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Kinematic GNSS Estimation of Zenith Wet Delay over a Range of Altitudes

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ABSTRACT

Atmospheric water vapor estimates from static ground-based Global Navigation Satellite System (GNSS) receivers are now operationally assimilated into numerical weather prediction models, either as total precipitable water vapor (PWV) or zenith total delay. To extend this concept, the estimation of water vapor using kinematic GNSS has been investigated for over a decade. Previous kinematic GNSS PWV studies suggest a 2–3-mm PWV measurement agreement with radiosondes, almost commensurate with static GNSS PWV measurement accuracy, but the only comprehensive experiments undertaken have been shipborne. As a first step toward extending sea level–based studies to airborne experiments that obtain atmospheric profiles, the authors considered the kinematic GNSS estimation of atmospheric water vapor along a repeatable trajectory spanning substantial topographic relief, namely, the Snowdon Mountain Railway, United Kingdom. The atmospheric water vapor was indirectly quantified through the GNSS estimation of zenith wet delay (ZWD). Static GNSS [GPS + Globalnaya Navigatsionnaya Sputnikovaya Sistema (GLONASS)] reference receivers were installed at the 950-m-altitude profile’s extremities, providing ZWD reference values that were interpolated to the train’s altitude, together with profiles from 100-m-resolution runs of the Met Office Unified Model. Similar GNSS ZWD accuracies to those from shipborne studies are demonstrated, namely, 12.1 mm (RMS) using double-difference relative kinematic GPS and 16.2 mm using kinematic GPS precise point positioning (PPP), but which is improved to 11.6 mm when using kinematic GPS + GLONASS PPP, commensurate with the relative kinematic GPS. The PPP solution represents a more typical airborne estimation scenario, that is, without relying on nearby GNSS reference stations.

1. Introduction

The provision of measurements of atmospheric water vapor is a key requirement in meteorology and climate studies, with the highly variable spatial and temporal distribution of water vapor directly impacting precipitation patterns and energy transfer in the atmosphere. To improve the ability of numerical weather prediction (NWP) models to forecast precipitation, accurate atmospheric water vapor measurements are required for assimilation, particularly in otherwise data-sparse areas where NWP model precipitation performance is limited, such as deserts, mountains, and oceans. Previous studies (Baker et al. 2001; Karabatić et al. 2011; Smith et al. 2007) have suggested a total precipitable water vapor
(PWV) measurement accuracy approaching 1–2 mm is desirable for improving NWP models.

Meteorological applications of using static ground-based global positioning system (GPS) receivers have developed, since the conception of GPS as a PWV sensor in the early 1990s, to now operationally provide PWV observations for assimilation into NWP models in near–real time (Gutman et al. 2004). These observations complement more traditional sources of atmospheric water vapor measurements such as radiosondes, which suffer from poor spatial and temporal resolution. GPS PWV measurements may be obtained as often as once every 5–15 min, while the spatial resolution is governed solely by the number of receivers deployed. The use of GPS in network real-time kinematic applications (e.g., Edwards et al. 2010) and geophysical monitoring (e.g., Bock et al. 2004) has resulted in dense coverage of ground-based static GPS receivers in areas such as western Europe, North America, and Japan, with PWV measurements for use in meteorology also attainable from these instruments. Such ground-based networks have also started to log data from other satellite navigation systems such as Globalnaya Navigatsionnaya Sputnikovaya Sistema (GLONASS) and soon BeiDou and Galileo, which collectively are termed Global Navigation Satellite Systems (GNSS). Regardless of the system, the incoming GNSS radio waves are refracted nondispersively by the neutral atmosphere (troposphere and stratosphere), with the signal delays at particular elevation angles and azimuths usually mapped to form the zenith total delay (ZTD). The ZTD can be attributed to the hydrostatic and the nonhydrostatic components of the atmosphere, which are mapped to the zenith using separate hydrostatic and wet mapping functions, such as provided by Vienna Mapping Function 1 (VMF1) (Boehm et al. 2006b) and its empirical approximation, global mapping function (GMF; Boehm et al. 2006a). Because of the well-mixed nature of the hydrostatic gases in the atmosphere, the zenith hydrostatic delay (ZHD) can be accurately modeled using local surface pressure and temperature measurements (Tregoning and Herring 2006). The additional delay resulting from the water vapor, the zenith wet delay (ZWD), is much more spatially variable but can be calculated by subtracting modeled ZHD from stochastically estimated ZTD. If surface temperature is known at the receiver, then the mean atmospheric temperature can be inferred via a regionally tuned model [e.g., as developed for Europe by Emardson and Derks (2000)] and thus ZWD can be directly related to PWV (Bevis et al. 1992). For typical atmospheric conditions, ZWD (in length units) is roughly 6.5 times larger than the equivalent PWV measurement. Thus, ZWD may be assimilated into NWP models instead of PWV as the GNSS water vapor data type, as may ZTD, which is the quantity currently used by the Met Office (Bennitt and Jupp 2012) and Météo-France (Poli et al. 2007) in their operational near–real-time assimilations. In the results section of this paper, we will use ZWD as a proxy for atmospheric water vapor.

Besides the densification of static ground-based GNSS receiver networks, another option to widen the availability of ZWD data is to utilize GNSS on kinematic platforms. Such platforms include ships, commercial airplanes and trains, or platforms tasked with the collection of atmospheric data, such as unmanned aerial vehicles and research aircraft. A kinematic platform approach allows data collection where installing meteorological sites is not practicable, for example, over deep oceanic areas and deserts. Airborne kinematic platforms during ascent and descent from an airport could offer additional vertical profiling constraints for high-resolution weather models aimed at delivering mesoscale and microscale meteorology.

The possibility of estimating ZWD from a kinematic platform was first explored around a decade after static GPS meteorology was first introduced by Bevis et al. (1992). Kinematic GNSS must deal with the dynamics of a receiver, and being unable to constrain the position solution to a single location reduces redundancy in the system and therefore tends to worsen the accuracy of the estimated ZWD. Double-difference relative solutions were first explored with “levered” ZTD estimates (Rocken et al. 1995), whereby the ZTD at the static reference site is somehow known and fixed, and the difference in ZTD between reference and rover is then estimated. Dodson et al. (2001) considered a GPS unit on a moored boat and used a levered approach over a short baseline of ~200 m to obtain an agreement of 1–2 mm in ZTD. Kealy et al. (2012) found agreement in PWV of 2.2 mm for the levered approach from a 10-day shipborne experiment around Hawaii with baseline lengths up to 120 km but often shorter. Chadwell and Bock (2001) used a GPS buoy 8 km from a reference station, processed with a network-equivalent double-differenced ambiguity-fixed solution, obtaining an agreement of 1.5-mm PWV with radiosonde launches 8 km away.

An alternative approach to a relative GNSS solution is the use of precise point positioning (PPP), as introduced by Zumberge et al. (1997) for static GPS and later used for kinematic GPS (e.g., Kouba and Héroux 2001). PPP uses only data from a single receiver to estimate parameters that include ZTD, relying on the explicit minimization of the errors in the observables, and therefore requires accurate satellite orbit and clock data. Rocken et al. (2005) used a postprocessed three-step iterative kinematic PPP solution to analyze a 2-week-long GPS dataset collected on a Caribbean cruise, and found RMS errors for PWV of 1.5 and 2.8 mm when compared with onboard radiosonde launches and water vapor radiometers (WVRs),
respectively. Fujita et al. (2008) found a nighttime agreement of 2.3-mm PWV for GPS and radiosondes over a 2-month period on a cruise ship. Boniface et al. (2012) compared 4 months of shipborne GPS PWV estimates from a real-time network processing engine (RTnet) PPP solution to MODIS and the ALADIN 10-km NWP model, with an RMS agreement of 3.5 and 1.4 mm, respectively. Skone et al. (2006) explored the use of an airborne platform in the collection of PWV from a real-time GPS-only PPP solution. GPS ZWD was collected from a single 15-min upward trajectory covering ~5500 m of height change. The GPS estimates were compared to ZWD extracted from the Canadian Meteorological Centre’s Global Environmental Multiscale model, with agreement between methods of 10–2-mm ZWD.

A recent development in kinematic PPP has been the inclusion of GLONASS as well as GPS observations. The use of a combined system solution is beneficial due to increased redundancy and the increased chance of good satellite geometry, especially in high-latitude areas and those with an obstructed sky view, and can reduce solution convergence times (Cai and Gao 2013). However, to date there has not been a comprehensive assessment of ZWD retrieval from a multisystem GNSS solution using a moving platform. The purpose of this paper is therefore to assess the retrieval of ZWD using an extensive kinematic multisystem GNSS (GPS+GLONASS) dataset, collected over a range of altitudes as experienced by potential future platforms such as trains and airplanes, rather than at sea level only as used in previous publications based on shipborne experiments (Webb et al. 2014).

To allow a rigorous assessment to be undertaken, GNSS (GPS+GLONASS) data were collected from a moving platform with a repeatable trajectory over a 50-day period, during which a range of meteorological conditions were experienced. The use of interpolated ZWD from static GNSS sites at the extremities of the trajectory, and the use of a high-resolution NWP model, enables quality control of the kinematic GNSS solutions. The use of absolute positioning techniques (PPP) with multiple GNSS (combined GPS and GLONASS solutions) compared to GPS-only solutions as used in previous studies is explored, together with results from relative GPS-only solutions.

2. Dataset

A 50-day experiment was conducted utilizing the Snowdon Mountain Railway (SMR), located in Snowdonia National Park, North Wales (Fig. 1), to permit an extensive analysis of ZWD retrieval from GNSS solutions over a range of altitudes. SMR is a tourist railway operating between the town of Llanberis and the summit of Snowdon, the highest mountain in England and Wales. The railway operates over an altitude range of 950 m, with an average traveling speed of around 2–3 m s⁻¹. Samples were collected along this repeatable trajectory between 28 August and 16 October 2011 [days of year (DOY) 240–289].

A Leica GS10 GNSS receiver was mounted with its AS10 antenna on the roof of an individual SMR carriage which, depending on the conditions and demand, could make up to four return journeys per day. This moving receiver will be referred to as SNTR (“Snowdon train”). GPS and GLONASS dual-frequency carrier phase data were collected at 1-s intervals by SNTR during normal SMR working hours. Pressure data were collected every 2 min using a collocated Paroscientific model 745 sensor. Static GNSS receivers (also Leica GS10s with identical Leica AS10 antennas) were installed at the height extremities of the trajectory, that is, the Llanberis base of

FIG. 1. (left) The location of Snowdon (red box in inset) in comparison to the rest of the United Kingdom. (right) The location of the reference stations SNLB (altitude: 115 m MSL) and SNSU (altitude: 1065 m), and the ~6-km trajectory of the railway (thick black line), displayed on a topographic plot of the area.
Snowdon (SNLB) 115 m MSL and Snowdon summit (SNSU) with an altitude of 1065 m. Near-continuous 1-Hz dual-frequency carrier phase GPS+GLONASS data were collected from these receivers: data were collected daily from midnight to 2250 UTC, except on 5 days during the experiment arising from fortnightly site visits for manual downloading, when logging stopped at around 1500 UTC. Both of the static sites SNLB and SNSU had calibrated Paroscientific Met4 pressure and temperature sensors collocated (mounted ~100 mm below the GNSS antenna), logging at 5-min intervals.

3. Reference zenith wet delay values

ZWD values were established at the static sites SNLB and SNSU as follows. We used the NASA JPL GPS-Inferred Positioning System (GIPSY) 6.1.2 software, which has been widely used in atmospheric studies, with GIPSY GPS-estimated ZWD values shown to agree with those from radiosondes and WVRs at the 6–20-mm level (e.g., Braun et al. 2003; Niell et al. 2001; Ning et al. 2012), and also used to generate the International GNSS Service (IGS) tropospheric product (Byun and Bar-Sever 2009). We computed GPS estimates of ZTD at 5-min intervals using established GIPSY processing options (Williams and Penna 2011), although using European Space Agency (ESA) final precise orbit and clock products (held fixed), and then averaged the ZTDs to one value every 15 min to be commensurate with the NWP model estimates described below. As pressure measurements with an accuracy of 0.3 mbar allow ZHD to be determined to within 1 mm when the atmosphere is in hydrostatic equilibrium (Bevis et al. 1992), ZHD calculated from the collocated pressure and temperature measurements (Saastamoinen 1972; Tregoning and Herring 2006) was subtracted from the ZTDs to provide ZWD. The ZWDs from SNLB and SNSU, together with their differences, are shown in Fig. 2.

A comparator ZWD acting as a reference for SNTR was obtained by interpolating the GIPSY-estimated ZWDs from SNLB and SNSU. At each epoch an empirical decay coefficient (EDC) was computed [Eq. (1)] following Kouba (2008), inputting the known heights \( h \) and ZWD estimates from SNLB and SNSU. The SNTR ZWD was then computed using Eq. (2):

\[
\text{EDC}(t) = -(h_{\text{SNSU}} - h_{\text{SNLB}}) \ln[ZWD_{\text{SNSU}}(t)/ZWD_{\text{SNLB}}(t)].
\]

\[
ZWD_{\text{SNTR}}(t) = ZWD_{\text{SNLB}}(t) \times e^{(h_{\text{SNTR}} - h_{\text{SNLB}})/\text{EDC}(t)}.
\]

To validate this approach, we extrapolated the ZWD values from SNLB to SNSU and from SNSU to SNLB.

![Fig. 2. (top) GIPSY GPS-estimated reference ZWDs for the static reference sites SNLB and SNSU, and (bottom) the differences between them for the entire 50-day dataset.](image-url)
respectively, with a fixed EDC of 1980 m—this being the mean EDC value from our dataset and comparable with the 2000 m used by Kouba (2008), and compared each with the GIPSY-estimated reference ZWD values. The differences between the extrapolated and GIPSY reference ZWD values for SNLB and SNSU for a 5-day subset of the dataset are shown in Fig. 3. For the whole 50-day dataset, the standard deviation and bias of the differences are 18.0 and 0.2 mm, respectively, for SNLB, and 11.1 and 0.1 mm, respectively for SNSU. Because these statistics are for extrapolated ZWD over the full altitude range of the railway, using a fixed EDC, they provide very conservative upper bounds on the quality of the SNTR reference ZWD values derived using Eq. (2), since the latter are interpolated using a variable EDC and there is a much smaller altitude difference from the nearest static site. We note also that this exponential interpolation is not strictly appropriate for the lateral variations that exist in ZWD. However, for typical ZWDs at SNLB and SNSU, the difference between linear and exponential interpolation is on the order of 2 mm, which is again a conservative bound on its effect on the interpolation error in the normal situation where vertical variations are dominant at these lateral scales. We infer that the actual quality of our SNTR reference ZWD is subcentimeter (RMS), with negligible bias.

4. Zenith wet delay estimation methods for a kinematic platform

In this paper we compare three kinematic GNSS solutions—two PPP (GPS+GLONASS and GPS only) and one relative (GPS only)—to the reference ZWD estimates for SNTR derived as above. We also compare ZWD derived from a high-resolution NWP model, the Met Office Unified Model, which is completely independent of the Snowdon GNSS data. For each technique tested, ZWD difference values greater than 5 times the mean absolute deviation were considered outliers and excluded from the analysis, with the proportion of outliers not exceeding 0.7%, except for the long baseline relative solution (described in section 5b), which was up to 2.2%. This section describes these kinematic ZWD estimation methods, including the tuning of process noise values used in the GNSS solutions.

a. Kinematic GNSS PPP

We processed dual-GNSS (GPS and GLONASS) data using PPP software developed in-house (Martin 2013), which uses an extended Kalman filter to process a time-ordered stream of carrier phase and code pseudorange observations and satellite data, estimating receiver positions, clocks, and ZWD as time-varying random-walk parameters, and real-valued carrier phase biases and the GPS-GLONASS system time offset as constant parameters. The ionosphere-free observations were processed at 1-s intervals with ESA final precise orbits and clocks held fixed, a positional process noise of 1 m s−0.5 and a ZWD process noise of 0.1 mm s−0.5. The atmospheric and positional process noise values used in the study were optimized by tuning a 7-day subset of the ZWD estimates for SNTR against the GIPSY-based interpolated reference ZWDs. The GMF (Boehm et al.
cloud microphysics (Wilson and Ballard 1999). A pseudoreal-time approach could not be implemented because the railway track is bordered by trees for a small section near SNLB, causing loss of lock, and so a forward-only solution does not converge for the majority of each trajectory. We then also generated a GPS-only kinematic PPP solution using the same processing approach but without any GLONASS observations.

**b. Double-difference kinematic GPS**

A relative double-difference solution was obtained at 1-s intervals from Massachusetts Institute of Technology (MIT)’s GPS Analysis MIT/global Kalman filter (GAMIT/GLOBK) module Track, version 1.24 (Chen 1998; Herring et al. 2010). ESA final precise orbits were held fixed, co-ordinates and ZWD estimated using GMF with a cutoff angle of 7° (the default value of relative humidity in the GMF was altered from 0 to 0.5, similar to an update available in Track version 1.27), and an elevation-angle-dependent observation weighting was used. A position process noise of 4 m s$^{-0.5}$ was applied, and a ZWD process noise of 0.01 mm s$^{-0.5}$ plus 0.23 mm s$^{-0.5}$ (m s$^{-1}$)$^{-1}$ of vertical speed. As with the PPP solution, a back-smoother was applied and the applied process noise values were tuned from a 7-day subset of the reference ZWD estimates for SNTR. A levered troposphere approach was used, with collocated pressure-derived ZHD and GIPSY-derived ZWD values at the fixed end of the baseline being fed into the solution. To do this, Track was modified to accept separate ZHD and ZWD values and to use the hydrostatic and wet GMF, respectively, with these input delays. Because Track does not process GLONASS data, only the GPS [L1 and L2 carrier phases, and coarse acquisition code (C/A) and Precision 2 code (P2) pseudoranges] observations were used. The L1 and L2 carrier phase signals were combined linearly to mitigate ionospheric effects, and double-difference carrier phase ambiguities were resolved to integer values using a wide-lane linear combination.

**c. 100-m-resolution NWP model**

The Met Office Unified Model solves the non-hydrostatic, deep-atmosphere equations of motion on a rotated latitude–longitude grid using a semi-implicit, semi-Lagrangian numerical scheme (Davies et al. 2005). It uses Arakawa C grid staggering in the horizontal and a terrain-following hybrid-height Charney–Phillips vertical grid. A comprehensive set of physical parameterizations is used, including surface (Best et al. 2011), boundary layer (Lock et al. 2000), and mixed-phase cloud microphysics (Wilson and Ballard 1999).

The configuration used in this study consists of a set of one-way nested domains with horizontal grid lengths of 4 km, 1 km, 333 m, and 100 m. The 4-km-resolution domain is the Met Office UK4 model, which covers the whole of the United Kingdom and includes a full data assimilation system and hence generates operational analyses every 3 h. The 1-km domain is based on the Met Office operational U.K. 1.5-km model [the U.K. variable-resolution (UKV) model] but uses a smaller domain covering only a 100 km × 100 km domain centered on Snowdon. The 1-km model uses the standard boundary layer scheme for vertical subgrid mixing but, unlike the UK4 configuration, uses a stability-dependent Smagorinsky–Lilly diffusion scheme in the horizontal. The 333- and 100-m models cover 50 km × 50 km and 20 km × 20 km, respectively, and both use the Smagorinsky–Lilly diffusion scheme in the vertical as well as in the horizontal, since at these microscale resolutions, with the exception of the very smallest eddies, the three-dimensional nature of boundary layer eddies is resolved. All the models use 70 levels in the vertical, the spacing of which increases quadratically with height up to the domain top at 40 km. The majority of the levels are located near the surface, with five levels in the lowest 100 m and 16 levels in the lowest 1 km of the atmosphere.

The nested model set was run as a “dynamical adaptation” of the UK4 model, keeping the simulation as close as possible to the operational analysis. The 4-km model was rerun from the operational analysis every 3 h, to provide the lateral boundary condition (LBC) data for the 1-km model, which provided LBC data for the 333-m model, which in turn provided LBC data for the 100-m model. The 1-km, 333-m, and 100-m models were all initialized with the interpolated 4-km analysis but were then free-running, such that no further reinitialization took place. Hereafter, the NWP model refers to the data output by the 100-m model.

Using model fields of pressure, temperature, and humidity, the wet and dry refractivity was calculated for each model grid point. The total refractivity was then used to find the contribution to the satellite signal delay for each model layer at each grid point. To obtain the ZTD for each surface grid point, we found the vertical total of all the layer delays above that point, and then added the contribution to the delay of the atmosphere above the model top, as detailed in Bennett and Jupp (2012). To calculate the ZWD, we used the wet refractivity at each grid point to calculate the contribution of a layer of atmosphere to the total ZWD, assuming the atmospheric refractivity decays exponentially with height from the surface. ZHD was calculated as the difference between the ZTD and ZWD.
Simulations were conducted for the 50-day study period, with outputs generated every 15 min for SNLB and SNSU, and at every 25 m of vertical interval of the SNTR trajectory. The NWP model ZHD and ZWD values were corrected for the difference between the height of the model surface (the digital elevation model used in the NWP model) and the actual GNSS instrument height above mean sea level, by the extrapolation methods outlined in Kouba (2008). The NWP model ZHD and ZWD outputs were linearly interpolated to the location of SNTR from the bounding NWP model time series to correct for differences in height and frequency of output.

5. Results

a. Validation of kinematic mode ZWD at stationary sites

ZWDs from each of the four kinematic estimation methods (GPS+GLONASS PPP, GPS-only PPP, relative GPS, and Unified Model) were compared to the GIPSY GPS-estimated reference values for SNLB and SNSU at 15-min intervals over the 50-day data span. The PPP solutions were obtained as for a dynamic platform, using the process settings outlined in section 4. For the relative GPS solution, the sites SNLB and SNSU were processed relative to each other, with the site of interest being processed as if dynamic and the alternate site being held fixed. The stationary sites SNLB and SNSU allow benchmarking of the optimal performance of the methods at the vertical extremities of the experimental domain, but in an idealized situation lacking vehicle dynamics (and less multipath than that experienced by SNTR). The quality of the GPS+GLONASS PPP, relative GPS and the Unified Model, is illustrated in Fig. 4 (we will consider GPS+GLONASS and GPS-only PPP differences in section 5c) for a sample 5-day period that experienced a large variation in ZWD, while the RMS, standard deviations, and biases (medians) of the differences, with respect to the reference values for the entire 50-day dataset (approximately 4250 data points, each with a duration of 15 min, after outlier removal at the 5σ level), are given in Table 1 for all four methods.

At the stationary sites SNLB and SNSU, kinematic GPS+GLONASS PPP ZWD minus GIPSY reference value differences show standard deviations and RMS values between 5.4 and 7.7 mm, and biases between 2.1 and 3.4 mm. These differences are commensurate with those given in Dousa and Vaclavovic (2014), who undertook similar “pseudokinematic” comparisons using a 44-day dataset (March–April 2012) for 11 European Reference Frame (EUREF) stations, and are an improvement on the ~12–18-mm ZWD RMS agreements of previous low-dynamic shipborne studies (Rocken et al. 2005; Boniface et al. 2012). The kinematic PPP solution quality is almost commensurate with those from static PPP solutions, even though some degradation might be expected, due to the weakened geometry caused by unknown receiver dynamics. Furthermore, the RMS differences of the ZWD from the reference values are very similar (within 2–3-mm ZWD, or 0.5-mm
PWV) to those for relative kinematic GPS, suggesting the GPS+GLONASS PPP solution is comparable to a relative GPS solution with a moderately short (~6 km) baseline. NWP model differences of 11.0-mm RMS in ZWD are commensurate with previous studies (Boniface et al. 2012; Skone et al. 2006), and they demonstrate the ability of the NWP model to be used as a quality control for the kinematic GNSS estimates along the trajectory. The NWP model biases are larger at SNSU than at SNLB, which we attribute to the altitude of the site. The strong winds at the summit make accurate modeling of the near-surface weather, and hence the ZWD, very difficult there. For instance, small errors in the subgrid turbulence scheme formulation could be amplified by the summit winds to produce large errors in the boundary layer representation, for example, its depth, at and close to the summit.

b. Assessment of ZWD for the kinematic platform

ZWD estimates at SNTR from the three techniques GPS+GLONASS PPP, relative GPS, and the Unified Model were compared to the interpolated reference ZWD at 15-min intervals. Because of equipment difficulties, no SNTR data were collected during DOY 271–280. RMS, standard deviations, and biases of the ZWD differences between the techniques for the entire 50-day data span are listed in Table 2, with around 650 data points available, each with a duration of 15 min, from the 39 days on which SNTR collected data. Differences were only included in the statistical analysis if they were recorded under truly kinematic conditions, that is, when SNTR was outside of the Llanberis and Snowdon summit railway stations at which it made lengthy stops (occasional brief pauses at intermediate stations were neglected). Estimated kinematic ZWD for SNTR and the interpolated reference values, and their differences, are shown for a sample day (DOY 264) in Fig. 5. The correlations between the estimates and the reference values can be seen in Fig. 6.

The RMS of the differences between the kinematic GPS+GLONASS PPP ZWDs and the references values is 11.6 mm (correlation coefficient of 0.945), at least commensurate with previous GPS shipborne studies. Relative kinematic GPS provides similar accuracy to kinematic GPS+GLONASS PPP, with an RMS agreement of 12.1 mm. This compares with RMS agreements of about 6 mm for the kinematic processing of SNLB and SNSU, but apart from the receiver dynamics, teqc (Estey and Meertens 1999) analysis showed that the average of the daily running-mean RMS pseudorange multipath at SNTR is about twice that at SNLB and SNSU, so some degradation is expected. It is important to note that the relative positioning considered is a near optimal setup: a very local reference site SNLB is used, with a maximum baseline length of 6.1 km that is not routinely available for airborne positioning. When the same comparison was made to a solution computed relative to the nearest Ordnance Survey continuous GNSS site St Asaph (ASAP; Fig. 1; situated at a height above mean sea level of 103 m, similar to SNLB but 45 km away), there was a reduction in the RMS agreement to 23.0 mm. Processing relative to multiple base stations [ASAP and Aberdaron (ADAR)] yielded an RMS difference of 19.2 mm, an improvement over a single long baseline but still worse than the GPS+GLONASS PPP solution. The RMS difference between the NWP model and the interpolated GIPSY-based reference values is 10.8 mm.

### Table 1. RMS, standard deviation, and bias (median) of the differences between ZWDs estimated at 15-min intervals from kinematic GPS+GLONASS PPP, kinematic GPS PPP, relative kinematic GPS, and the Unified Model with respect to the GIPSY reference values, at the stationary sites SNLB and SNSU for the entire 50-day dataset (approximately 4250 data points after removal of outliers). All quantities are expressed in mm.

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### Table 2. RMS, standard deviation, and bias (median) of the differences between ZWDs estimated at 15-min intervals from kinematic GPS+GLONASS PPP, kinematic GPS PPP, relative kinematic GPS, and the Unified Model with respect to the interpolated GIPSY-estimated reference values for SNTR for the 39 operational days of the 50-day dataset (approximately 650 data points after removal of outliers). All quantities are expressed in mm.

<table>
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commensurate with the SNLB and SNSU validations. This gives further confidence in the quality of the interpolated reference values.

To assess any variation in the performance of the different ZWD estimation methods with height, the ZWD difference statistics were computed in 100-m height bins, and the RMS differences are shown in Fig. 7. There is no obvious degradation with height for any of the three methods. This provides further validation of the NWP model as a control in the experiment, and it indicates the potential for using kinematic GNSS ZWD estimates not just from ships and ground-based vehicles but also aircraft.

c. Impact of GLONASS on kinematic GNSS PPP performance

Previous shipborne studies of kinematic PPP ZWD estimation have used GPS only, whereas thus far the PPP results we have shown in this paper have used GNSS (GPS and GLONASS). Now we consider the differences between GPS-only and combined GPS+GLONASS kinematic PPP solutions, for SNLB, SNSU, and SNTR. At the stationary sites SNLB and SNSU, neither solution provided a notable improvement over the other, with RMS agreements and biases between GPS-only and GPS/GLONASS solutions of 1.1 and 0.4 mm,

![Graphs showing ZWD time series and differences](image1)

**Fig. 5.** (top) ZWD time series for SNTR on sample DOY 264 of 2011, obtained from kinematic GPS+GLONASS PPP (blue), relative kinematic GPS (green), Unified Model (red), and the GIPSY-based interpolated reference ZWD (gray with crosses at comparison epochs). (middle) Differences between each estimation method and the reference ZWD. (bottom) Height of SNTR above mean sea level.

![Graphs showing correlation between ZWD and interpolated reference values](image2)

**Fig. 6.** Correlation between ZWD as estimated by each method and the interpolated reference values: (left) kinematic GPS+GLONASS PPP, (middle) relative kinematic GPS, and (right) Unified Model (UM). Terms $R$ and $y$ (and $x$) represent the correlation coefficient and the linear line of best fit, respectively.
respectively. However, it is important to note that these are “clean” sites, with clear sky views, and so the improved satellite geometry of a GPS+GLONASS solution is expected to have less impact.

The RMS, standard deviation, and biases of ZWD differences, with respect to the interpolated SNTR reference values, from GPS-only PPP and GPS+GLONASS are displayed in Fig. 8 for each day of the complete 50-day dataset. Kinematic GPS-only PPP has an RMS, standard deviation, and bias difference of 16.2, 15.3, and 4.9 mm, respectively, and a correlation coefficient of 0.906 with respect to the interpolated reference. In this respect, our kinematic GPS-only PPP solution collected over a range of altitudes is closely comparable to previous shipborne studies such as Boniface et al. (2012) and Rocken et al. (2005). The inclusion of GLONASS offers appreciable improvement, with a correlation coefficient of 0.945 and an RMS, standard deviation, and bias of 11.6, 11.6, and 1.8 mm, respectively, with respect to the reference ZWD, equating to an RMS PWV agreement of about 2 mm. Such an improvement is commensurate with the improved position dilution of precision (PDOP) in the GPS+GLONASS solutions (median of 1.13 compared with 1.51 for GPS only for the data difference points) and is likely due to the higher number of visible satellites, coupled with a better distribution of these satellites, resulting in more redundancy in the solution. This suggests that a combined GPS+GLONASS solution should be adopted for the optimal kinematic estimation of ZWD.

6. Discussion and conclusions

Over a 50-day period, multiple ZWD estimation techniques using a kinematic platform undergoing nearly 1 km of height change per trajectory were compared and validated using an interpolated reference

ZWD derived from static GPS and a high-resolution NWP model. The RMS ZWD difference between the NWP model and the GIPSY GPS-estimated reference ZWD is 10.8 mm, demonstrating the high quality of the high-resolution Unified Model and its value as a control in the experiment. The improvement of a multisystem GNSS solution in kinematic PPP has been shown, with the GPS+GLONASS combination showing an RMS agreement in ZWD of 11.6 mm compared to 16.2 mm for the GPS-only solution, with respect to the reference ZWD.

The GPS+GLONASS PPP-derived ZWD show similar RMS agreements to short-baseline relative GPS, with respect to the reference ZWD (within 2-mm PWV, 11.6–12.1-mm ZWD). When baseline lengths of 40–50 km were tested that are more representative of kinematic positioning of sea- and air-going vehicles, the relative PWV agreement worsened by 1.0–1.5 mm. A further advantage of the absolute PPP solution is that it is applicable globally, with the relative solution constrained by the existence of fixed surface reference stations. The fact that these solutions are of comparable accuracy suggests that a PPP solution would be the preferred option for collecting PWV data from kinematic platforms.

A major use of a PWV product derived from kinematic GNSS would be to constrain NWP models. The NWP model used in this experiment offered good agreement to the kinematic and reference solutions, but it should be noted that the model is operating in an area with dense meteorological measurements and in a postprocessed setting. The impact of assimilating GNSS-derived estimates into NWP models is an ongoing field of study (Bennitt and Jupp 2012; Gutman et al. 2004; Macpherson et al. 2008; Poli et al. 2007), but it has shown the potential to improve weather forecasting. The timeliness requirements for assimilation into operational NWP models would require predicted orbit and clock products to be used as opposed to final precise
products. Comparisons of near-real-time ZTD observations from static receivers to postprocessed ZTDs using final orbit and clock products show some degradation in ZTD of 3–6 mm in precision and 1–2 mm in accuracy (Dousa and Bennitt 2013); therefore, further study is required to assess the quality of ZWD estimates using the kinematic approach with predicted orbits and clocks. Once kinematic near-real-time ZWD estimates with a suitable level of accuracy compared with postprocessed estimates can be attained, a study could be performed to assess the impact of assimilating these estimates on the NWP analysis. Kinematic PWV measurements collected at an accuracy of 2 mm or better could be used to improve predictions from NWP models and in the calibration of satellite microwave instruments, with particular advantages in sparsely populated areas that serve as major air/sea transport routes and for very high-resolution NWP models in the vicinity of major airports.

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