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Advanced Weather Prediction and Severe Weather Monitoring Using National GNSS CORS Infrastructure – Preliminary Results

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Abstract

Atmospheric water vapour (AWV) plays an important role in the pursuit of weather research, in particular extreme weather phenomena. Conventional atmospheric sounding methods including radiosonde and water vapour radiometer (WVR)) have the disadvantages of low spatial or temporal resolutions or high cost. As an emerging remote sensing approach of AWV, GPS is an ideal complement due to its unique advantages of 24-hour availability, high accuracy and low cost. As a critical part of the Australian positioning infrastructure, several regional Continuously Operating Reference Stations (CORS) networks have been established in the past two decades. The huge amount of GPS measurements provided by these CORS infrastructures are a rich data source that can be used for many applications in addition to positioning. This research aims to use GPS observations from Australian CORS networks to derive values of local atmospheric variables for weather prediction and severe weather monitoring. Our initial research task was to investigate approaches to obtain the GPS-derived tropospheric zenith total delay (ZTD) which is directly related to AWV. Preliminary results from both Precise Point Positioning (PPP) and Double Difference (DD) approaches available in Bernese software are presented in this paper. GPS data for the periods of the three heavy storm events occurred in Victoria (2012), Queensland (2011) and Victoria (2010) were selected for testing. The results showed that the GPS-derived ZTD from both PPP and DD agreed with the ZTD derived or provided from other data sources, including IGS tropospheric products from Center for Orbit Determination in Europe (CODE), and synoptic and radiosonde data from the Australian Bureau of Meteorology, at the level of several millimetres. This implies that the use of GPS observations from the well-distributed national CORS infrastructure over Australia to complement the current atmospheric sounding systems is promising. It has great potential to use these GPS observations to obtain atmospheric variable values with high spatial-temporal resolution, thanks to the all-day GPS observability and the dense distribution of the CORS networks. The synthetic integration of the GPS-derived atmospheric results with meteorological data from other space- and ground-based atmospheric sensors has significance for severe weather monitoring and prediction for the Australian region.

Key words: Zenith Total Delay (ZTD), water vapour, PPP, CORS network, severe weather monitoring

Author biographies

Mr. Yubin Yuan is a PhD student at the Satellite Positioning for Atmosphere, Climate and Environment (SPACE) Research Centre, School of Mathematical and Geospatial Sciences (SMGS), RMIT University. His research area is the applications of ground-based GPS in weather prediction and severe weather monitoring. Dr. Witold Rohm and Dr. Suqin Wu are research fellows at the same Centre. Dr. Witold Rohm's current research areas are GPS tropospheric tomography and its meteorological applications. Dr. Suqin Wu's expertise lies in GPS data processing and GPS RTK. Professor Kefei Zhang is Director of the SPACE Research Centre and his current research involves innovative applications of Global Navigation Satellite System (GNSS) technologies for precise positioning, GNSS atmospheric studies, space tracking, satellite orbit determination, as well as people mobility and object tracking. Dr. Suelynn Choy is a lecturer at SMGS and her current research area is multi-GNSS PPP (based on QZSS, the Quasi-Zenith Satellite System) and using GNSS for atmospheric and ground remote sensing.

1. Introduction

Most countries have already built relevant infrastructures including CORS networks to facilitate existing GPS applications which are not restricted to the conventional positioning / navigation. Bevis (1992) proposed that GPS can also be utilised for the sounding of the atmosphere, i.e. GPS meteorology (GPS/MET). His results showed that GPS CORS measurements could be extremely useful for both operational weather forecasting and fundamental research into atmospheric storm systems, atmospheric chemistry and hydrologic cycles. Since then scientists from a number of institutes over the world have conducted research in these fields (Duan 1996; Gendt 2001; Hagemann 2003) and some products based on GPS observations, e.g. the atmospheric parameter profiles including temperature, pressure, water vapour and humidity, have been assimilated into the Numerical Weather Prediction (NWP) model in some countries (Bennitt 2012).

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Australia has a unique continent surrounded by the ocean and most of its population densely concentrates on several big cities along the coast. Australia also suffers from several types of natural disasters caused by severe weather such as thunderstorms and floods. For example, a series of floods hit Queensland since December 2010, forcing evacuation of thousands of people from towns and cities. Hence, it is of great significance to investigate the applications of national GPS infrastructures to meteorology such as severe weather monitoring, specifically, to assimilate GPS-derived atmospheric results into the NWP model, which has not been performed yet so far in Australia.

This research is the preliminary study for the project aiming to investigate the improvement of weather prediction accuracy and predictability under severe weather using GPS CORS networks deployed in Australia. We started from deriving water vapour from GPS data using Bernese software (Dach 2007). Three severe weather events, i.e. the heavy storms occurred in Victoria (2012), Queensland (2011) and Victoria (2010) were used as case studies. GPS observables from CORS networks in Victoria, New South Wales, part of Queensland and South Australia were processed. GPS-derived ZTD obtained from two strategies – PPP and DD – were compared, and then both were compared with ZTD from synoptic and radiosonde data for the validation of the results from the two strategies.

2. GPS data sources

A GPS CORS network consists of several tracking stations and it is a basic positioning infrastructure for the region covered. CORS networks can be classified as global, regional, national and local level based on the covered region,. The International GNSS Service (IGS), formerly the International GPS Service, is a voluntary federation involving more than 200 worldwide agencies to provide GPS & GLONASS (GLObal NAvigation Satellite System) station data to generate precise GPS & GLONASS products. The IGS is committed to providing the highest quality data and products as the standard for GNSS in support of Earth science research, multidisciplinary applications and education. More importantly, the IGS core stations were built complying with rigid rules and regulations and recognised as relatively more stable than stations from other CORS networks. In GPS data processing, IGS core stations are often used as constraints and reference frames. In this research, several IGS stations located in the study region were selected for reference stations and they are ADEL, ALIC, CEDU, HOB2, MOBS, PKVL, RSBY, SYDN, TID1, TIDB and TOW2. Another GPS data source used in this research was the Asia-Pacific Reference Frame (APREF) project. This project was to create and maintain an accurate geodetic framework to meet the growing needs of industries, science programs and the general public for positioning applications in the Asia-Pacific region. Recognising the importance of improving the regional geodetic framework, the member countries of the 18th United Nations Regional Cartographic Conference for Asia and the Pacific (UNRCC-AP; October 2009, Bangkok) agreed to improve the reference frame in the Asia-Pacific region (Geoscience Australia 2012). This involves using several existing CORS networks operated by national mapping agencies and private sector organisations. Almost all states in Australia either have established or are in the process of enhancing their local CORS networks. Thus, GPS data from the Vicmap Position in Victoria, CORSnet in New South Wales and SunPos in Queensland were tested in this study. All the GPS stations from the aforementioned IGS, APREF, Vicmap Position, CORSnet and SunPos are shown in Figure 1.

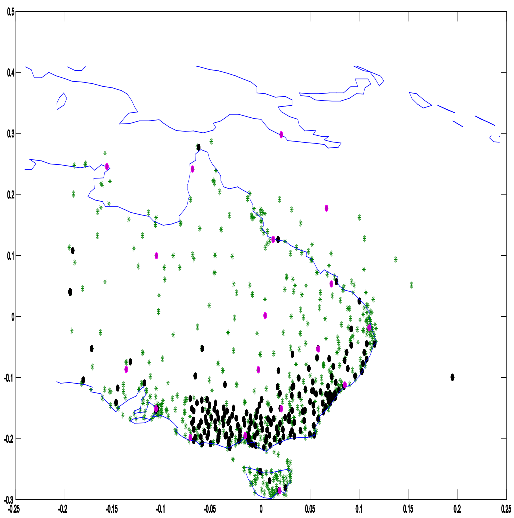

Figure 1. GPS CORS stations from various sources deployed and distributed in Australia. The pink dots represent the IGS stations, the green dots represent APREF GPS stations and the black dots represent VICmap GPS stations

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3. Using PPP and DD to derive tropospheric delays

The troposphere is located at the altitude region above the surface of the Earth up to 20 km. It contains most of the mass of the neutral atmosphere and almost all of water vapour. Due to the fact that the troposphere affects GPS signals causing delays or biases, we can use GPS observations to derive the tropospheric delays. ZTD is an important quantity and is commonly used in many application areas. The ZTD can be divided into dry component − Zenith Hydrostatic Delay (ZHD), and wet component − Zenith Wet Delay (ZWD), as expressed by Equation (1) for a specific station. The ZHD can be accurately estimated by an empirical model, which is based on local meteorological data such as surface pressure, temperature profile, height and ellipsoidal latitude of the GPS station, whereas the ZWD cannot be accurately estimated by any empirical models due to the characteristic of its volatility with time. In this research, after estimating the ZTD from the GPS data processing, the ZWD was obtained by subtracting the model-derived ZHD from the GPS-derived ZTD.

$$ZTD = ZWD + ZHD \tag{1}$$

Based on the derived ZWD, atmospheric water vapour, the main parameter applied in GPS/MET, can be obtained. For example, Integrated Water Vapor (IWV), which gives the total amount of water vapor that a signal from the zenith direction would encounter, can be calculated from Equation (2) (Bevis 1992).

$$IWV = \frac{ZWD}{10^{-6} \cdot R_w \cdot (K_2' + \frac{K_3}{T_M})} \tag{2}$$

where K_2' and K_3 are two empirically determined constants, R_w is the specified gas constant, and T_M is the integrated mean temperature accurately estimated from surface temperature.

In this research, two GPS data processing approaches were used to estimate the ZTD: PPP and DD. Both approaches utilised the ionosphere-free combinations of dual-frequency GPS pseudorange (P) and carrier-phase observations (φ). The observation equations for PPP are (Kouba 2003):

$$l_p = \rho + c(dt - dT) + T_r + \varepsilon_P \tag{3}$$

$$l_\varphi = \rho + c(dt - dT) + T_r + N\lambda + \varepsilon_\varphi \tag{4}$$

where:

- l_P is the ionosphere-free combination of pseudoranges P1 and P2 at both frequencies,
- l_φ is the ionosphere-free combination of carrier phases L1 and L2 at both frequencies,
- dT is the receiver clock error,
- dt is the satellite clock error, which can be corrected by IGS precise clock products,
- c is the speed of light in a vacuum,
- T_r is the tropospheric delay, which is the focus of this study,
- λ is the wavelength of the carrier-phase combination,
- ε_P and ε_ϕ are the noise of the ionosphere-free combinations of pseudorange and carrier phase measurements respectively,
- N is the ambiguity of the ionosphere-free combination of carrier phase measurements.

The DD observation equation is performed by two steps. For observations from two satellites (k,l) observed by two stations (i,j), the first step is single-differencing between the two observations from two stations to a same satellite and the second step is further differencing between a pair of single-differenced observation equations formed from the previous step. Equations (5) and (6) are the DD ionosphere-free combination (from Equations (3) and (4)) observation equations between (i,j) and (k,l). It should be noted that both the receiver and satellite clock biases, the two terms of dT and dt in Equations (3) and (4), are eliminated.

$$l_{Pij}^{Kl} = \Delta\rho_{ij}^{kl} + \Delta T_{rij}^{kl} + \Delta\varepsilon_{Pij}^{kl} \tag{5}$$

$$l_{\varphi ij}^{kl} = \Delta\rho_{ij}^{kl} + \Delta T_{rij}^{kl} + \Delta N_{ij}^{kl}\lambda + \Delta\varepsilon_{\varphi ij}^{kl} \tag{6}$$

where $\Delta(.)_{ij}^{kl}$ denotes the double-difference operator.

The PPP approach can estimate station coordinates in both static and kinematic modes using GPS data from only one station. However, the accuracy of its position estimates is usually poorer than those obtained from the DD approach. The reasons for that are, 1) it is unlikely to resolve the integer value of the phase ambiguities even using ionosphere-free combinations; 2) satellite clock errors cannot be eliminated as done in DD; and 3) the introduction of the satellite clock corrections in the PPP approach

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makes it impossible to decorrelate the residual satellite clock error and station coordinates. Therefore, the effect caused by the introducing of IGS products could not be accounted for in the later stage of data processing (Dack 2007).

However, PPP has its advantages in terms of the way and time to estimate the ZTD. First, there is no need for any reference stations and GPS data is processed independently for each station. So data processing time is in proportion to the number of GPS stations. This is a big advantage particularly when large number of data is processed. For example, in each of our three case studies, there were more than 100 stations tested. It is especially critical for the applications that require near real-time solutions. In addition, the tropospheric delay parameters are estimated epoch-by-epoch in PPP, while the DD approach commonly adopts the batch processing mode, in which a time period of data, e.g. hourly data or every half an hour data are post-processed to obtain the "mean" results of the whole time period. Therefore, using PPP is beneficial greatly for retrievals of ZTD (and thus also water vapour), especially for near real-time applications.

4. Test results

4.1 Comparison of GPS-derived ZTD against CODE

Figures 2 − 4 show the values of the differences between the PPP- and DD-derived hourly ZTD and the ZTD from CODE of the three study cases. In the data processing, IGS final orbit and satellite clock corrections were used. From results of the same station during all the three events, it can be seen that that the DD strategy performed similarly with agreements with CODE solutions of less than 20mm. Nonetheless, the PPP approach performs differently in the same time periods. In 2010 and 2011, the differences between the PPP-derived ZTD and CODE solutions are at the level of 20mm, while in 2012 the differences are less than 10mm. This is probably resulted from the more stable orbit products and satellite clock products from IGS.

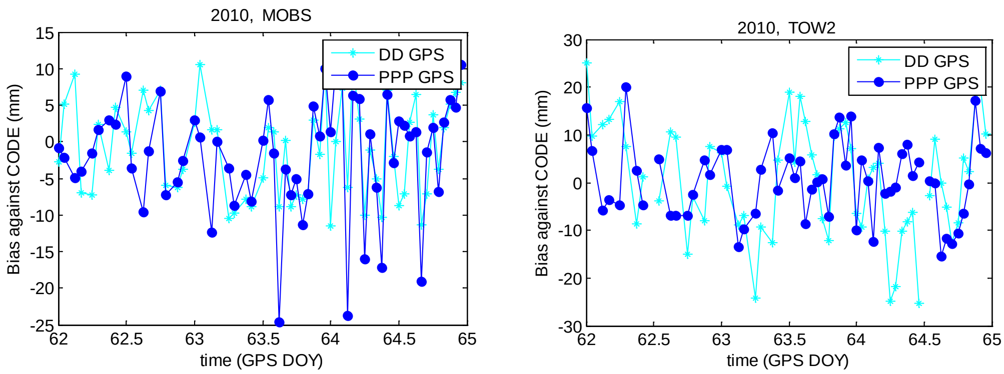

Figure 2. Difference values between GPS-derived ZTD and CODE products for storm 2010 at station MOBS (left) and TOW2 (right).

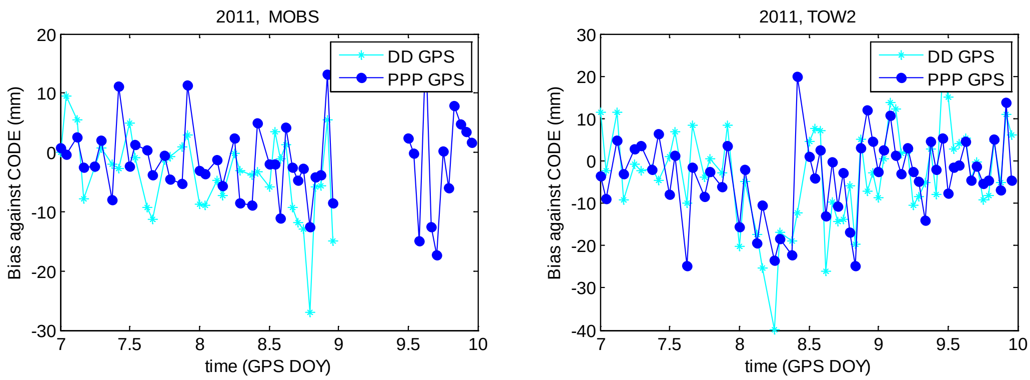

Figure 3. Difference values between GPS-derived ZTD and CODE products for storm 2011 at station MOBS (left) and TOW2 (right).

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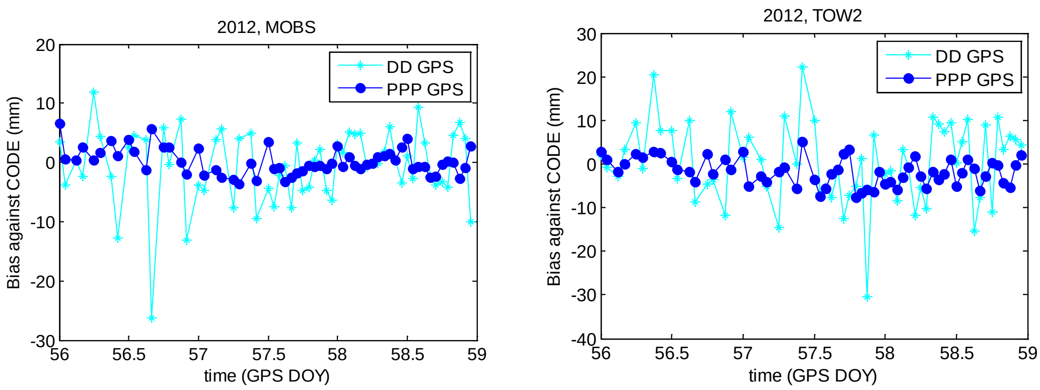

Figure 4. Difference values between GPS-derived ZTD and CODE products for storm 2012 at station MOBS (left) and TOW2 (right).

We also performed another test, in which the same PPP strategy but IGS orbit and satellite clock corrections from CODE were adopted for the 2010 case. Figure 5 shows the results of the difference between the PPP-derived ZTD using CODE orbit and clock products and ZTD from CODE. Obviously, the biases of this solution against CODE ZTD were large – to several decimetres at both MOBS and TOW2 stations.

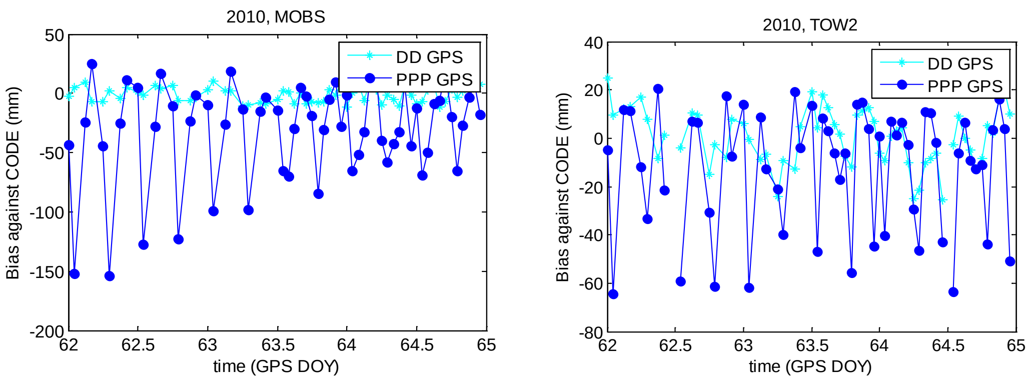

Figure 5. Difference values between GPS-derived ZTD and CODE products for storm 2010 at station MOBS (left) and TOW2 (right), IGS products from CODE were used.

It is notable that in the 2012 case, the accuracies of the PPP solutions are better than the DD by several millimetres when compared with references from IGS products. Two factors may contribute to this accuracy difference. The first one is that more GPS observables are used in the PPP strategy since observables from any pair of satellites that do not have simultaneous observations cannot be used in the DD strategy. The PPP approach can use observables from all satellites in view. Aother factor is that, for a network with short baselines like what we processed, the tropospheric parameters between sites are highly correlated in DD processing, In fact the accurately estimated tropospheric parameters are the relative values between the stations and the reference station. The absolute tropospheric value can be obtained using any priori models or from other sources. As a result, the error in the absolute tropospheric value will be brought to the final DD ZTD results.

4.2 Comparison of GPS-derived ZTD against meteorological data

To further validate our GPS-derived ZTD, our results were also compared against the ZTD derived from synoptic data and radiosonde data observed from those meteorological stations that are surrounding and closest to the GPS stations. Figure 6 shows hundreds of meteorological stations distributed all over south-eastern Australia. Most of those stations have a long history of meteorological data.

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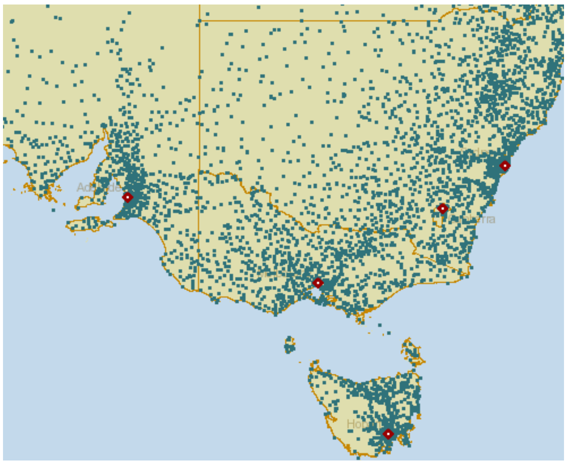

Figure 6. Distribution of meteorological stations in south-eastern Australia (Australian Bureau of Meteorology 2012)

The procedure of obtaining the ZTD result from meteorological data for the location of a GPS station tested is: 1) using interpolation of atmospheric variables including surface temperature, pressure and humidity from four synoptic stations that are closest to and surrounding the GPS station; 2) using the interpolated values and the following Saastamoinen formulae (Saastamoinen 1972) to calculate the values of ZHD and ZWD; and 3) summing the ZHD and ZWD values from the second step to obtain the ZTD.

$$ZHD = \frac{0.002277 \cdot P}{f(B,h)} \tag{7}$$

$$ZWD = \frac{e}{f(B,h)}\left(\frac{0.2789}{T} + 0.05\right) \tag{8}$$

$$f(B,h) = 1 - 0.00266 \cdot \cos 2B - 0.00028 \cdot h \tag{9}$$

In the above equations, B and h are the latitude and height of the GPS station respectively, T and P are the surface temperature and pressure respectively, and e is the water vapour partial pressure.

The accuracy of the ZHD value estimated by formula (7) is a few millimetres or better. However, the ZWD estimated by formula (8) has low accuracy due to its variability in both spatial and temporal domains.

The ZTD derived from another source – radiosonde, was also calculated using the interpolation of atmospheric variable values from three closest radiosonde stations. Details on this can be found in (Vedel 2001).

Figures 7 − 9 show the comparison of the ZTD derived from all the four data sources discussed above: IGS products, synoptic data, radiosonde data and GPS. Note that the synoptic data from internet was only a small part of the several hundreds of meteorological stations in Australia and their sample rates were not uniform − varying from one to several hours. This implies that the temporal resolution of the synoptic data is low. Therefore, the accuracy of the synoptic-data-derived ZTD was not expected to be good. For the radiosonde data, only several radiosonde stations were available in the studied regions. As a result, the agreement or difference between the GPS-derived and the radiosonde-derived ZTD is highly related to the distance between the GPS station and radiosonde stations. Those GPS stations that are closer to the radiosonde stations would have better agreement. This can be seen from the ZTD time series of station MOBS, which is only several kilometres away from the radiosonde station located at Melbourne Airport in Victoria. In all the three events, the agreements of ZTD derived from GPS DD and radiosonde data is at the level of several millimetres.

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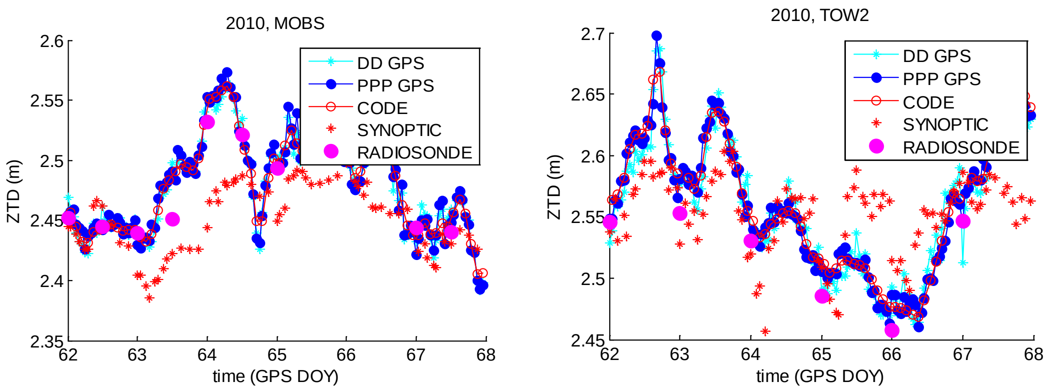

Figure 7. Comparisons of ZTD derived from GPS DD, GPS PPP, CODE products, synoptic data and radiosonde data for storm 2010 at station MOBS (left) and TOW2 (right).

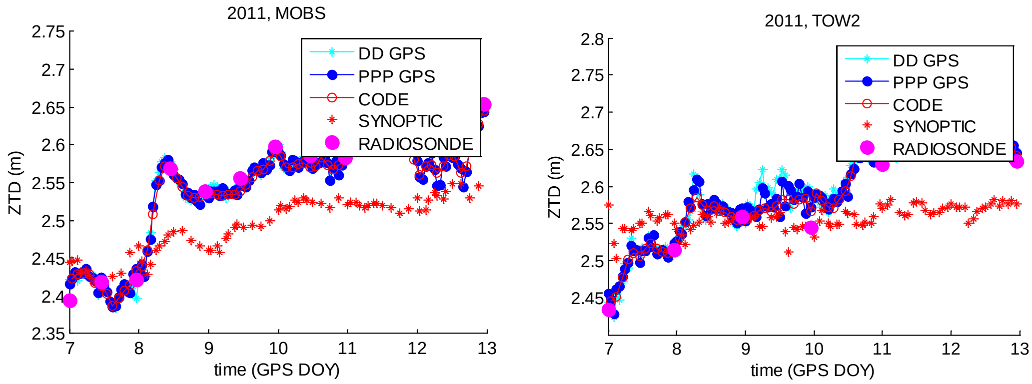

Figure 8. Comparisons of ZTD derived from GPS DD, GPS PPP, CODE products, synoptic data and radiosonde data for storm 2011 at station MOBS (left) and TOW2 (right).

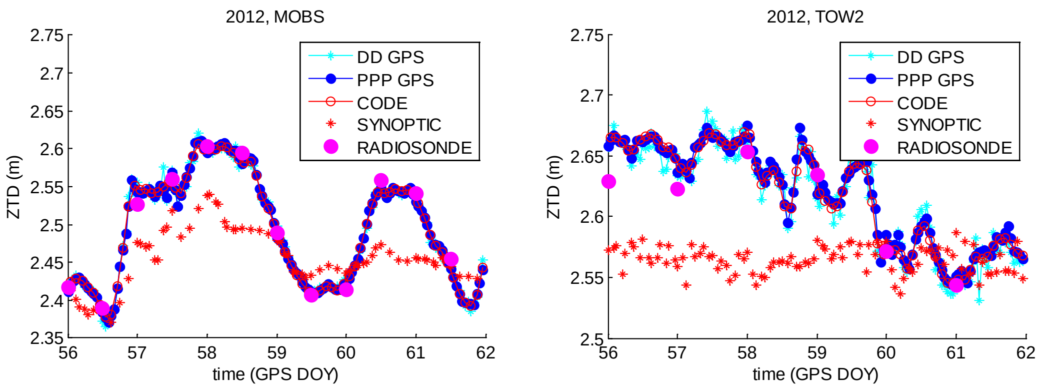

Figure 9. Comparisons of ZTD derived from GPS DD, GPS PPP, CODE products, synoptic data and radiosonde data for storm 2012 at station MOBS (left) and TOW2 (right).

5. Conclusions

In this research, GPS-derived ZTD for three severe weather events – three storm events occurred in Australia in 2010–2012 – were tested using the PPP and DD approaches and their results were compared with various meteorological data for their performance assessment and validation. The results indicate that GPS-derived ZTD from both PPP and DD approaches agree with ZTD from other data sources at the level of several millimetres. If using GPS-derived ZTD with this level of accuracy to further derive IWV, the results is expected to have good accuracy as well. This is promising for weather prediction and severe weather monitoring.

Experimental results suggest that DD solutions are more consistent while PPP solutions are largely affected by the quality of orbit and satellite clock products from IGS. Thus, when PPP is adopted, it may be essential to check the quality of IGS products before performing data processing. Another significant finding is that in the case of the 2012 storm, the accuracies of the PPP solutions

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are better than the DD by several millimetres when compared with references from both IGS products and radiosonde data. Two factors, as discussed in section 4.1, may contribute to this accuracy difference.

The higher accuracy of the PPP-derived ZTD estimates is encouraging because PPP has some other advantages against the DD approach, e.g. processing time of PPP is linearly proportional to the number of GPS receivers. Moreover, ZTD can be estimated on an epoch-by-epoch basis, which is useful for applications that require high temporal resolutions. Therefore, PPP can be an efficient approach for GPS-derived ZTD using ground-based GPS CORS networks, which is further for the sounding of atmospheric water vapour. Our future work will target to obtain PPP-derived ZTD for much shorter data intervals with accuracy under 5 mm for investigation of temporal variation in water vapour distribution.

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