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Strengthening Severe Weather Prediction Using the Advanced Victorian Regional GPS Network − a Recent NDRGS Project

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Abstract.

The Natural Disaster Resilience Grants Scheme (NDRGS) is a grant program funded by the Commonwealth Attorney-General's Department under the Australian National Partnership Agreement on Natural Disaster Resilience signed by Prime Minister and state Premier of Victoria. Under the Agreement, Victoria develops an Implementation Plan, for approval by the Australian Commonwealth Minister for Justice, to receive continued funding for the NDRGS.

This contribution introduces the Victorian NDRGS project – "Strengthening Severe Weather Prediction Using the Advanced Victorian Regional Global Navigation Satellite Systems" awarded to a consortium led by RMIT University in 2013. This project aims to develop a smart GPS-based water vapour estimation system for disaster management users to reduce the risks and impact of natural weather disaster events. The regional precipitable water vapour measurements obtained predominantly from this new system using measurements from regional ground-based GNSS continuously operating reference stations (CORS) networks in Australia –will be assimilated into the Australian Community Climate and Earth-System Simulator (ACCESS) model.

In this paper, the main objectives, anticipated outcomes and research roadmap for this project are introduced. The key issues and challenges confronting innovative applications of GNSS for severe weather event prediction in Australia are emphasised. The key results achieved so far related to atmospheric remote sensing and atmospheric modelling etc. are briefly reported.

Keywords: GPS/GNSS, water vapour, severe weather event, Vicpos™, GNSS meteorology.

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Dr Suqin Wu is a research fellow at the SPACE Research Centre, RMIT University. Her areas of expertise include GPS precise positioning and its innovative applications, geodesy, precise orbit determination and prediction etc.. Dr Toby Manning is a lecturer at RMIT University and his area of specialty is in 4D tomographic modeling of GNSS-derived wet refractivity for regional severe weather applications. Mr Yubin Yuan and Mr Xiaoming Wang are PhD candidates at SPACE and their research topics mainly focus on real-time retrieval of tropospheric products from GNSS observations for severe weather monitoring and climate study, and on improving the accuracy of GNSS tropospheric products for severe weather monitoring and climate study, respectively. Associate Professor Allison Kealy is a staff member in the Department of Infrastructure Engineering at The University of Melbourne. Dr John le Marshall is a senior principal research scientist at the Bureau of Meteorology. Prof Kefei Zhang is Director of the SPACE Research Centre, RMIT University.

1. INTRODUCTION

Globally, severe weather events have caused substantial damage to properties and claimed many lives over the past decade. The frequency and severity of the severe weather events are amplified by climate change and increased societal dependencies on costly and complex infrastructure. Statistics from the last 20 years of disaster management data (www.disasters.ema.gov.au) show that in Victoria alone, 2.5 million people have been affected by severe storms and flooding, resulting in over $1.9 billion in losses. These statistics highlight the pressing need for a reliable and robust severe weather monitoring and predicting system, coherent with current disaster management risk reduction solutions. The ability to monitor and predict the development of severe storms, in particular those that have the potential to produce heavy rainfalls, is highly dependent on the availability of precise water vapour (WV) information. The amount of WV contained in the troposphere has significant implications in determining the intensity, time and extent of storm activities.

The most commonly used technique of sensing WV is through the use of radiosondes. Due to the high cost involved, only a small number of radiosonde stations regularly launch weather balloons with the typical frequency of just twice a day. This means only sparse WV measurements are available for meteorology, and this is true in particular for low tropospheric regions. To address this issue, Global Navigation Satellite Systems (GNSS) have been considered to offer significant potential for improved atmospheric remote sensing for both weather and climate monitoring. This is a direct result of its unique advantages of global availability in any weather and any time. Many regional and national ground-based permanent continuously operating reference stations (CORS) networks have been established all over the world predominantly for geodetic applications. GNSS observations from a CORS network have become a valuable and rich data source for estimating atmospheric variables, especially PWV in the troposphere, for the region covered by the network. Applying GNSS-derived products to meteorological applications (termed GNSS meteorology) is promising.

To leverage developments towards an Australian national positional infrastructure (NPI) via the National Collaborative Research Infrastructure Strategy (NCRIS) AuScope, SPACE at RMIT initiated GNSS for severe weather research in 2010 through the Australian Space Research Program (ASRP) platform technology project. In 2012 RMIT, as an international collaborator, was also involved in a major international initiative of the European Cooperation in Science and Technology (COST) 1206 − Advanced Global Navigation Satellite Systems tropospheric products for monitoring severe weather events and climate (GNSS4SWEC). Most recently, a new collaborative project “Strengthening Severe Weather Prediction Using the Advanced Victorian Regional Global Navigation Satellite Systems” was funded by the Victorian government via the Natural Disaster Resilience Grants Scheme (NDRGS) of Victoria. The partner organisations of this project include RMIT University, the Bureau of Meteorology (BoM), the Department of Environment and Primary Industries (DEPI), the University of Melbourne, and Australia’s Cooperative Research Centre for Spatial Infrastructures (CRCSI). This one-year (2014−2015) project aims to utilise the advanced Victorian GNSS infrastructure – the CORS network, i.e. Vicpos™, as a new source of WV to improve severe storm predictability. Vicpos™ is currently the most dense and most mature state-wide CORS network, used mainly for high accuracy positioning in Victoria, Australia. Tens of millions of dollars have been invested by the Victorian government over the last two decades to build this homogenous, state-wide positioning infrastructure, which is important for spatial science activities in Victoria. Vicpos™ is coordinated, operated and maintained by the Victorian Government – through the Department of Environment and Primary Industry (DEPI).

This project addresses a number of risks that have been identified as a high priority for natural disaster events by the Victorian state government. These include: severe storms, flash flooding and flooding. All three are related to synoptic weather patterns and strongly correlated with the WV content in the troposphere. The most efficient and effective (precise, frequent and unbiased) estimation of WV content from this research will underpin our capability and capacity in dealing with severe weather phenomena in Victoria and beyond. It is expected that this research will play an important role in assessing the severity of these risks and mitigating their impact, both socially and economically.

This research will also leverage the existing Vicpos™ infrastructure for meteorological studies, in particular for estimating the tropospheric Zenith Total Delay (ZTD), from which the amount of integrated water vapour (IWV), also known as PWV, in the troposphere can be derived. The dense distribution of Vicpos™ stations provides a unique opportunity to use advanced GNSS technology for meteorological studies. Cutting-edge GNSS meteorology techniques will be used as a new type of GNSS sensor to investigate WV content in addition to currently available alternate atmospheric WV observation systems. In this project, in collaboration with the BoM, the ZTD/PWV derived from Vicpos™ will be assimilated into the Australian Community Climate and Earth-System Simulator (ACCESS) model for an investigation of potential improvements in the predictability of severe weather.

2. AIMS AND OBJECTIVES

This project aims to develop an unprecedented GNSS-based system that can be used by disaster management stakeholders to reduce the risk and impact of natural disaster events. This will be carried out by:

- Precisely and continuously monitoring the amount of PWV in the troposphere over the Victorian region obtained from the Vicpos™ measurements along with selected AuScope stations;
- Fostering partnerships between research institution like the RMIT, BoM and regional authorities like DEPI;
- Effectively using heavily invested NPI, i.e. VicPos™, in Victoria for extended services and products in severe weather prediction;
- Positioning Victoria as a leading state and research hub in using the advanced GNSS for severe weather services and potential reduction of risks; and
- Providing an important guide/role model for other states who have heavily invested in establishing their state-wide CORS networks.

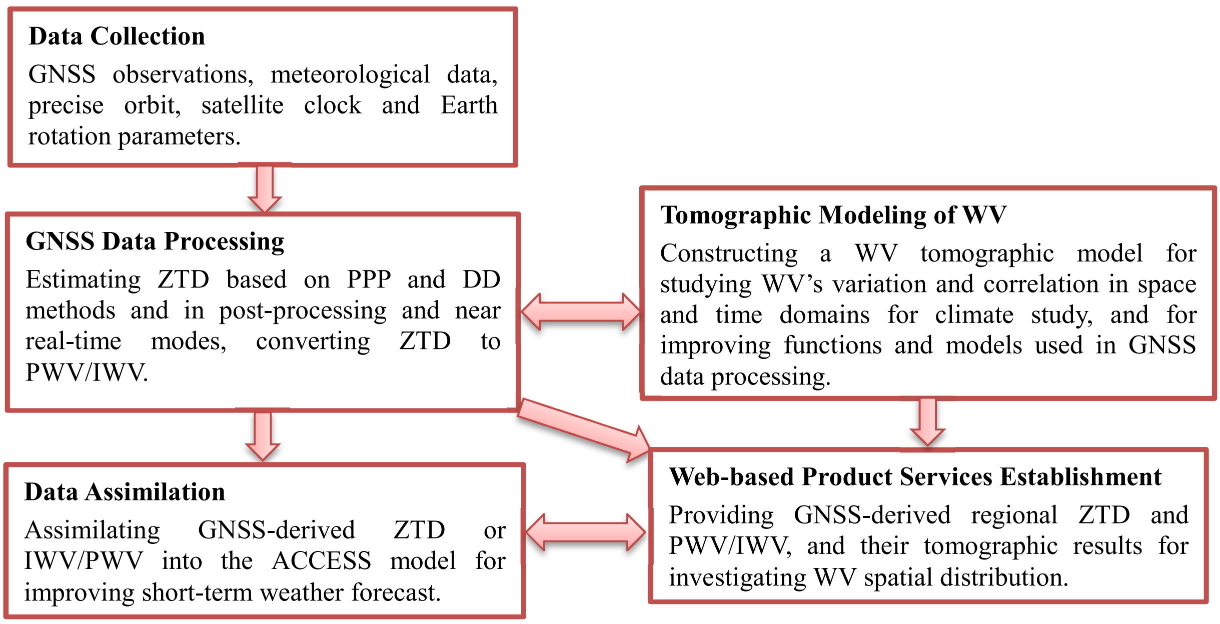
This research will demonstrate the potential of using the Australian NPI i.e. GNSS CORS networks as a novel, active, IWV sensing system for strengthening the predictability of severe storms. The outputs of this research will help to identify and mitigate the social and economic impacts of severe storms and heavy rainfalls in conjunction with existing disaster management policies and practices. Tangible outputs include:

- Incorporating a new GNSS NPI-based data source into the assimilation scheme of the Australian ACCESS model;
- Continuously estimating regional PWV for short term, near real-time and long-term climate studies; and
- Developing a new interactive web-based product dedicated to WV distribution on the SPACE Research Centre's server.

The workplan to achieve the above mentioned tasks or outputs is:

- Generating a GNSS database related to a few selected recent severe storms;
- Assimilation study of post-processed GNSS data;
- Developing near real-time GNSS processing capability; and
- Assimilating near real-time GNSS results (to the ACCESS model).

The research roadmap is outlined in the diagram below.



3. METHODOLOGY

The standard products obtained from GNSS data processing are mainly the optimal estimates of the coordinates of GNSS stations (if the coordinates are unknown) and the ZTD. The GNSS-derived ZTD is attributed to two constituents of the troposphere: gases that obey hydrostatic equilibrium and those that do not. The first constituent is composed of all major gases in the troposphere while the second is linked only with WV. Thus the ZTD is usually divided into a hydrostatic part – zenith hydrostatic delay (ZHD), and a non-hydrostatic part – zenith wet delay (ZWD), i.e.

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

The ZHD is very stable and so can be determined at a high accuracy using an empirical model and the surface meteorological measurements near the station. The Hopfield or Saastamoinen models are the most commonly used such empirical models (Hopfield, 1969; Saastamoinen, 1972). The ZHD accounts for more than 80% of the ZTD. However, the ZWD cannot be calculated at a high accuracy using any empirical model due to its dynamic nature. This is the reason for the ZWD being treated as an unknown parameter and being estimated in GNSS data processing. There are a few dedicated software packages available to do the GNSS data processing such as BERNESE, from which the algorithms of solving for the unknown parameters including the ZWD from GNSS observations systems can be found in Hugentobler et al., 2007.

In this research, GNSS data will be processed in near real-time, e.g. every 30 minutes, for high temporal resolution ZTD/PWV results over Victoria, which will then be transferred to the BoM for data assimilation studies. To achieve this, several types of data including precise satellite orbits, satellite clock corrections, earth rotation parameters, especially for GNSS precise point positioning (PPP), are needed. Moreover, for the standard GNSS network solution, the original strategies need to be modified to allow for sliding windows or stacked processing (Bosy et al., 2011; Dousa, 2010) so that high accuracy, high resolution and robust solutions can be obtained from a set of 30-minute-period observation data.

The next step is to convert the GNSS-derived ZWD to PWV using a dimensionless conversion factor, the so-called Π parameter (Askne and Nordius, 1987) which is dependent on the weighted mean temperature of the atmosphere (Davis et al., 1985) above the station:

$$\mathrm{PWV} = \mathrm{ZWD} \cdot \Pi \tag{2}$$

$$\Pi = \frac{10^6}{\rho_w \cdot R_v \left(\frac{k_3}{T_m} + k'_2\right)} \tag{3}$$

where,

Π	is the scale factor ($\mathrm{kgm^{-3}}$);
ρ_w	is the density of liquid water ($\mathrm{kgm^{-3}}$);
R_v	is the specific gas constant of WV ($\mathrm{Jkg^{-1}K^{-1}}$);
m_w	is the molar mass of WV (m_w=18.01528 $\mathrm{kgkmol^{-1}}$);
k_3 and k'_2	are two physical constants ($\mathrm{K^2hPa^{-1}}$), defined by Askne and Nordius (1987); and
T_m	is the weighted mean temperature of the atmosphere above the station (K).

For the Australian region, T_m can be calculated by Hunter (2010) (Choy et al. 2013):

$$T_m \approx 70.03 + 0.726 Ts \tag{4}$$

where *Ts* is the temperature observation at the station.

For deriving wet refractivity from the GNSS-derived wet signal path delay (SPD_w) from ground GNSS station *a* to satellite x, the following formula can be used (Troller et al., 2006):

$$SPD_w = 10^{-6} \cdot \int_a^x N_w \, ds \tag{5}$$

where ds and N_w are the integral increment and wet refractivity along the SPD_w (m) from a to x respectively.

To resolve the spatial structure of wet refractivity using a tomographic model, the atmosphere is divided into a number of 3D voxels, and each voxel *i* is assumed to have a constant refractivity N_{wi}, then equation (5) can be approximated by (Troller et al., 2006):

$$SPD_w = 10^{-6} \cdot \sum_i N_{wi} \Delta si \tag{6}$$

where Δsi is the length of the ray in voxel i. It is noted that the ray bending effect is commonly ignored as an elevation cut-off angle of 10 degrees is usually applied.

Using all SPD_w derived from a regional GNSS CORS network in a tomographic model system, all the voxels' wet refractivity can be estimated and these results can be used to investigate the spatial distribution of WV. If a time series of such models are derived then a 4D tomographic model can be established for the study of the spatio-temporal variation of WV over the network region.

In the step of assimilating atmospheric sensing data into a numerical weather prediction (NWP) model for weather forecasting, the regional PWV/IWP is a very important input. If accurate PWV can be converted from the GNSS-derived ZTD then this PWV can be used for weather forecasting by assimilating them into the NWP model. Via the collaboration with the BoM, more accurate atmospheric parameters such as refractivity and temperature, which are required in the conversion for high accuracy PWV, can be obtained. The resulting PWV with high accuracy is then used in the assimilation process.

3. RESULTS TO DATE

A range of new developments and progresses related to this project have been achieved during the last few years. Results from the following two studies are summarised here.

3.1 Using GPS to capture the signature of severe weather events in Australia

The distribution and dynamics of WV is closely associated with meteorological phenomena, such as long persistent rainfalls, tropical cyclones, mid-latitude cyclonic storms and thunder storms that are ongoing challenges for synoptic meteorology (Ahrens and Samson, 2010). Improving the understanding of WV distribution is important for meteorology (Le Marshall et al., 2010). The tomographic model, as a general model based on the inverse Radon transform theory, has been intensively used to investigate the spatial distribution of WV over a region by a number of researchers and organisations across the globe (Bender et al., 2011; Perler et al., 2011; Brenot et al., 2012; Flores et al., 2000; Rohm et al. 2014b). The standard approach to establishing GNSS-derived-troposphere tomographic models is to divide the spatial tropospheric region of interest into a 3D voxel structure. The intercepted distance of the GPS signal passing through the voxel of concern is used in the design matrix for the estimation of the tomographic model (Rohm et al. 2014b).

For investigating the performance of using the Victorian regional GNSS CORS network, for near real-time monitoring and forecasting of severe weather, two case studies were selected to investigate the signature of GPS-derived PWV and also the wet refractivity field derived from a 4D tomographic model under the influence of severe mesoscale convective systems (MCS). The two cases were from the storm period during 3–8 March, 2010 and the severe precipitation period during 1–15 January, 2011, both occurred in Melbourne. Results showed strong spatial and temporal correlations between the variations in the ground-based GPS-derived PWV and the passage of the severe MCS, suggesting that the GPS-derived PWV can resolve the synoptic signature of the dynamics and precursors to severe weather (Zhang et al., 2014).

The 4D wet refractivity tomographic modelling results suggest that the state-wide tomographic solution can be used to identify the signature of convection in the vertical layers at the front of the storm and also gradients of rear inflow jets in the stratiform region. Compared with the co-located radiosonde-derived wet refractivity under the influence of severe weather, the tomographic models achieved an accuracy/RMS of 8.58 ppm. These findings suggest that ground-based-GPS-derived PWV and tomographic modelling for wet refractivity fields have the potential to increase the ability of early detection and forecasting when assimilated into a NWP model and to depict the 3D signature of wet refractivity for the convective and stratiform processes evident in the MCS events (Zhang et al., 2014).

This research indicated that ground-based GNSS is a highly effective and robust observing technique for detection of the dynamics of water vapour during formation and lifecycle of severe weather. Using GNSS-derived tropospheric products to complement conventional meteorological observations for studying, monitoring and potentially predicting severe weather events is significant for meteorology, especially in the Australian context and also the southern hemisphere, where other atmospheric sensors are spatially and temporally sparse.

3.2 Using GPS-PPP to retrieve PWV in real-time

For obtaining high accuracy GNSS-derived ZTD or PWV, several data processing approaches or strategies can be used. For example, 1) double-differencing (DD), which includes short-baseline-network solution, long-baseline-network solution, and baseline-by-baseline solution — run but not considered; and 2) precise point positioning (PPP) (float ambiguity) (Rohm et al. 2014a). The DD approach can eliminate satellite and receiver clock errors but it needs simultaneous observations between two satellites and two receivers. Whilst the PPP approach only needs one receiver so it does not need simultaneous observations, but it needs precise satellite orbit and clock corrections. In fact, in terms of determining PWV, both DD and PPP approaches do not have significant differences in the resultant accuracies (1−2 mm)(Choy et al., 2013).

Modern weather forecasting systems have an ever increasing demand for PWV retrieval in terms of (1) short latency or no latency, (2) higher spatial resolutions of GNSS stations but relatively low computational resources, and (3) higher temporal resolutions specifically for severe weather nowcasting [Li et al., 2009]. This research took these three aspects into account and investigated the retrieval of the ZTD and PWV from the real-time PPP approach (Yuan et al., 2014). The test data included (1) real-time GPS data from 20 globally distributed IGS stations, (2) the ZTD products from the Center for Orbit Determination in Europe (CODE) and the United States Naval Observatory (USNO), and (3) radiosonde data from stations within 60 km from the selected IGS stations for the validation of the GPS-derived tropospheric results.

The test result of the real-time ZTD retrievals from a one-month period GNSS observations at the 20 stations showed that the accuracies of the GPS-PPP-derived ZTD at most of the stations agreed well with that from the International Global Navigation Satellite Systems Service, with a root-mean-square error (RMSE) <13 mm. This accuracy of the results meets the threshold value of 15 mm if ZTDs are to be assimilated into a NWP system. The RMSE of the retrieved PWVs in comparison with the radiosonde values were ⩽3 mm which is the threshold RMSE of PWVs as inputs to weather nowcasting. This implies that GNSS-PPP-derived real-time tropospheric products can be complementary to current atmospheric sounding systems, especially for nowcasting of extreme weather. More details on this study can be found in the contribution by Yuan et al. (2014).

4. CONCLUDING REMARKS

The development of a strategic plan towards an Australian NPI has resulted in the establishment of regional CORS networks such as the Victorian "VicPOS™". The temporal and spatial density of GNSS observations offered by these networks offers a significant opportunity to improve our characterization of the atmosphere. These GNSS observations can be used to derive tropospheric products including precipitable water vapor and wet refractivity etc. for the network covered region. As an important supplemental meteorological sensor, GNSS plays an increasingly important role in meteorological studies, e.g. severe weather monitoring and prediction and climate. This NDRGS project is well aligned with national priority areas in natural disaster resilience and the VicPOS™ network has provided a valuable data source. Preliminary results achieved to date are promising and future work will focus on validation and quality control algorithms and techniques for using GNSS data for weather prediction. The outcomes of this project will be significant for Australia and also the southern hemisphere where conventional meteorological observations are sparsely distributed and severe weather events are ongoing phenomena.

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