Estimation of Local-scale Precipitable Water Vapor Distribution Around Each GNSS Station Using Slant Path Delay

Yoshinori Shoji, Hiroshi Yamauchi, Wataru Mashiko, and Eiichi Sato
Meteorological Research Institute, Ibaraki, Japan

Abstract

A procedure for estimating the precipitable water vapor (PWV) distribution around ground-based stations of the global navigation satellite system (GNSS) on a scale of several kilometers is presented. This procedure utilizes the difference between the zenith total delay above a GNSS station and the zenith mapped slant path delay (SPD). This difference can be used to estimate the PWV gradient in each SPD direction by assuming an exponential distribution for the horizontal water vapor gradient.

The procedure was tested using an estimation of the PWV variation associated with the parent storm of an F3 Fujita scale tornado that occurred in Ibaraki prefecture on 6 May, 2012. Differential reflectivity observed by a dual-polarimetric radar indicated the existence of a developed parent cloud approximately 1 h before the tornado occurred. A high-resolution numerical weather model simulation suggested the existence of a strong PWV gradient around the parent cloud, made evident by the co-existence of a strong updraft and downdraft within an approximately 5-km radius. The PWV gradient, calculated using the GNSS observation network with an average spacing of approximately 17 km, could not detect such a small-scale, strong-PWV gradient. The PWV gradient estimated using the proposed procedure revealed a strong PWV gradient and its enhancement. In this case, a higher-order inhomogeneity component of each SPD played a critical role.

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1. Introduction

In Japan, the Geospatial Information Authority of Japan (GSI) operates a nationwide permanent global navigation satellite system (GNSS) called the Earth Observation Network (GEONET) with an average spacing of 17 km. It is regarded as one of the densest GNSS networks in the world and covers all of Japan. Several studies have attempted to use GNSS-derived precipitable water vapor (PWV) measurements to monitor heavy rainfall (e.g., Kanda et al. 2000; Niimura et al. 2000; Inoue and Inoue 2007). These studies have confirmed the validity of measuring GNSS-derived PWV and its variation to monitor heavy rainfall. However, as vertically integrated water vapor, PWV does not provide vertical profile information; therefore, monitoring PWV with a 17-km spacing alone does not always provide sufficient information on precursors of severe storms.

Shoji et al. (2004) developed a retrieval procedure for signal delay along each ray path (slant path delay (SPD)). They decomposed the SPD into three components: an isotropic component, a first-order gradient, and a higher-order inhomogeneity. Shoji (2013) proposed two new indices using decomposed components of the gradient and higher-order inhomogeneity: the water vapor concentration (WVC) index, which represents the spatial concentration of water vapor 2 to 3 km above ground, and the water vapor inhomogeneity (WVI) index, which expresses the degree of water vapor variation around each GNSS station on a scale of several kilometers. Using SPD values derived from the procedure of Shoji et al. (2013), Kawabata et al. (2013) considered the impact of SPD assimilation on the reproduction of small-scale convective precipitation. Sato et al. (2013) compared PWV values measured by radiosonde with those derived from the GNSS SPD and found that the SPD closest to the radiosonde path exhibited better agreement than the estimated zenith total delay (ZTD). The WVI index is based on the standard deviation of the SPDs measured at a GNSS station, so directional information for each SPD is neglected. However, the results of Kawabata et al. (2013) and Sato et al. (2013) clearly demonstrate that the slant path direction does provide practical information.

This article presents a new approach for utilizing SPD to monitor severe storms. In Section 2, we describe a procedure for analyzing the PWV gradient around GNSS stations. Section 3 introduces application results for the F3 scale tornado which occurred in Japan on 6 May, 2012, and a summary and discussion are presented in Section 4.

2. Procedure for estimating PWV gradient around GNSS sites

The procedure for estimating the PWV distribution around GNSS stations can be divided into the following three steps.

2.1 Retrieval of ZTD and SPD at each GNSS station

The procedure for this step was identical to that described by Shoji (2013), except for the precise orbit and satellite clock correction data. The ZTD and SPD at each station were estimated by adopting the precise point positioning method (Zumberge et al. 1997) with GIPSY-OASIS II (Webb and Zumberge 1993) Version 6.1.

The GNSS-derived PWV at each station was converted from an estimated ZTD using the proportionality coefficient II (Aske and Nordius 1987). ZTD is the integrated refraction index (N) of the atmosphere in the zenith direction, where the refractivity is a function of temperature (T), partial dry-air pressure (P_d), and partial vapor pressure (P_v):

\[ \text{ZTD} = \int_0^\infty N(z) dz, \]  

\[ N = (n-1) \times 10^4 = K_1 \frac{P_d}{T} + K_2 \frac{P_v}{T} + K_3 \frac{P_v}{T^2}, \]  

where \( n \) is the refractive index and \( K_1, K_2, \) and \( K_3 \) are constants that have been determined theoretically or by fitting to the observed atmospheric data.

Using Eq. (2), the contribution of dry atmosphere \( (N_{dry}) \) and water vapor \( (N_{vap}) \) can be derived as follows:

\[ N_{dry} = K_1 \frac{P_d}{T}, \quad N_{vap} = K_2 \frac{P_v}{T} + K_3 \frac{P_v}{T^2}. \]  

As described by Shoji (2013), the relationship between ZTD and SPD is

\[ \text{SPD}(\theta, \phi) = m(\theta) \cdot (\text{ZTD_{EST}} + \cot \theta (G_x \cos \phi + G_z \sin \phi)) + \varepsilon \]  

where ZTD_{EST} is the ZTD value estimated from the GNSS analysis. ZTD_{EST} can be regarded as a representative value of ZTD.
Estimation of Precipitable Water Distribution Using GNSS Slant Path Delay

We call this ZTD\textsubscript{SPD} to distinguish it from ZTD\textsubscript{EST} (Fig. 1).

2.2 Estimation of PWV gradient using SPDs

Using Eq. (4), we mapped each SPD to the zenith direction. We call this ZTD\textsubscript{SPD} to distinguish it from ZTD\textsubscript{EST} (Fig. 1).

\[ ZTD\textsubscript{SPD} = \frac{\text{SPD}(\theta, \phi)}{m(\theta)} = ZTD\textsubscript{EST} + \cot(\theta)G_x \cos(\phi) + G_x \sin(\phi) + \frac{e}{m(\theta)} \] (5)

We make the following three assumptions.

1. The horizontal gradient of dry refractivity (\(N_{dry}\)) is small enough to be negligible.
2. The difference between ZTD\textsubscript{EST} and ZTD\textsubscript{SPD} is due to the several-kilometer horizontal gradient of water vapor refractivity (\(N_{wet}\)) alone.
3. The horizontal \(N_{wet}\) gradient (\(g_{wet}\)) decreases exponentially with height.

\[ g_{wet}(z) = g_{wet}(0) \cdot \exp\left(-\frac{z}{H}\right) \] (6)

Here, \(g_{wet}(z)\) is the horizontal water-vapor gradient at altitude \(z\) and \(H\) is the scale height of \(g_{wet}\).

In this study, we ignore height differences among the various GNSS stations for simplicity. ZTD and PWV depend heavily on the altitude of the observation site. Practical and/or more precise application may need careful consideration of height differences.

If the above assumptions are met, \(N\) along each SPD can be expressed as a function of the refractivity at the GNSS site and \(g_{wet}\) as schematically depicted in Fig. 1. ZTD is the integrated refractivity (\(N\)). Therefore, ZTD\textsubscript{SPD} can be expressed by the following equation.

\[ ZTD\textsubscript{SPD} = \int_{0}^{\infty} \{N(z) \cdot 10^6 + g_{wet}(z) \cdot \cot(\theta)\} \, dz = ZTD\textsubscript{EST} + \cot(\theta) \int_{0}^{\infty} (g_{wet}(z) \cdot z) \, dz \] (7)

Here, the second term of the right side denotes the contribution of \(g_{wet}\).

Following Ruffini et al. (1999), we acquire the following relationship:

\[ \int_{0}^{\infty} (g_{wet}(z) \cdot z) \, dz = H \cdot \nabla ZTD, \] (8)

where \(\nabla ZTD\) is the horizontal gradient of the ZTD distribution.

According to Askne and Nordius (1987), PWV is proportional to the delay in the zenith direction caused by water vapor (Zenith Wet Delay: ZWD). In this study, we assume that the difference between ZTD\textsubscript{EST} and ZTD\textsubscript{SPD} is due to the several-kilometer horizontal gradient of water vapor refractivity (\(N_{wet}\)) alone. Therefore, combining Eqs. (7) and (8) gives

\[ \nabla PWV = \Pi \cdot \nabla ZTD \approx \Pi \cdot \nabla ZWD = \Pi \cdot \frac{ZTD\textsubscript{SPD} - ZTD\textsubscript{EST}}{H \cdot \cot(\theta)}, \] (9)

where \(\Pi\) is the proportionality coefficient. The horizontal gradient of PWV is expressed as a function of the ZTD difference, elevation angle, and scale height. In this study, we used the following relationship between water vapor scale height (\(H\)) and PWV, which was determined by the statistical comparison of Shoji (2013).

\[ H \cdot \cot(\theta) = 8.64679 \cdot \text{PWV} + 1657.91. \] (10)

2.3 Analysis of PWV distribution around GNSS stations using retrieved PWV and PWV gradient

We can more finely estimate the PWV distribution around each GNSS station by using the several-kilometer PWV gradient described in Section 2.2. In this procedure, ZTD in the azimuth direction of each SPD is expressed as a function of distance from each GNSS station (Fig. 1):

\[ ZTD(d) = ZTD\textsubscript{EST} + d \cdot \nabla ZTD = ZTD\textsubscript{EST} + d \cdot \frac{ZTD\textsubscript{SPD} - ZTD\textsubscript{EST}}{H \cdot \cot(\theta)}, \] (11)

Thus, ZTD\textsubscript{d} becomes equal to ZTD\textsubscript{SPD} when \(d = H \cot(\theta)\), the distance at which the slant path reaches the scale height \(H\). Hereinafter, we refer to this distance as \(d_0\). Furthermore, according to Shoji (2013), \(\nabla PWV\) is most affected by the \(N_{wet}\) gradient at its scale height \(H\) assuming an exponential distribution of the \(N_{wet}\) gradient in the vertical direction.

The assumptions we made in Section 2.2 are approximate, so we need to refrain from excessive use of the estimated gradient. In this study, we set a virtual GNSS station around each GNSS station in each slant path direction at a distance \(d_0\) and set the ZTD\textsubscript{SPD} as the virtual station’s ZTD for convenience. Virtual GNSS stations were not set when \(d_0\) exceeded 5 km. By applying this qualification, SPDs of 20° elevation or less were excluded in this analysis. For more precise study, the applicability of the above restrictions should be investigated further. PWV at each virtual station was converted from ZTD\textsubscript{SPD} multiplied by \(\Pi\) at the actual GNSS station. PWVs at both actual and virtual GNSS stations were interpolated into a 2.5 × 2.5 km\textsuperscript{2} grid space using Cressman’s objective analysis (Cressman 1959). Hereinafter, we refer to PWVs at virtual GNSS points as PWV\textsubscript{SPD}.

3. Application for monitoring the development of the parent storm of the F3 tornado on 6 May, 2012, in Tsukuba, Japan

From 12:35 to 12:51 JST (Japan Standard Time: +9 UTC) on 6 May, 2012, an F3 scale tornado passed through the northern part of Tsukuba City (Fig. 2). The tornado caused extensive damage including one fatality, and 37 injuries.
3.1 Parent storm track observed by a dual-polarized Doppler radar

During the Tsukuba tornado, a C-band polarimetric radar of the Meteorological Research Institute (MRI-C) observed both the parent storm and the vertical structure of the tornado at close range (13 to 17 km) (Yamauchi et al. 2013). According to Yamauchi et al. (2013), this parent storm developed at the south end of a meso-β scale rainband. The storm moved northeast at a speed of 20 m s\(^{-1}\). The horizontal (vertical) scale of the storm was 20 (12 km). The storm lasted from 11:50 to 13:30 JST (1 h 40 min). The track of the parent storm was captured well by the differential (12 km). The storm lasted from 11:50 to 13:30 JST (1 h 40 min). The track of the parent storm was captured well by the differential area with a strong PWV gradient was formulated around the area with a strong PWV gradient was formulated around the and lifetime were well reproduced.

The reproduced hook-shaped precipitation system was approxi-

\[ r(i) = \frac{Z_{\text{obs}}}{Z_{\text{ref}}} \]

mately 30 min earlier and several kilometers northward from the approximate 30 min earlier and several kilometers northward from the event observed by the MRI-C radar. However, the tornado track event observed by the MRI-C radar. However, the tornado track

\[ Z_{\text{dr}} = \left( \frac{Z_{\text{H}} - Z_{\text{V}}}{Z_{\text{H}} + Z_{\text{V}}} \right) \]

was reproduced. The reproduced hook-shaped precipitation system was approximately 30 min earlier and several kilometers northward from the event observed by the MRI-C radar. However, the tornado track was reproduced. The reproduced hook-shaped precipitation system was approximately 30 min earlier and several kilometers northward from the event observed by the MRI-C radar. However, the tornado track was reproduced. The reproduced hook-shaped precipitation system was approximately 30 min earlier and several kilometers northward from the event observed by the MRI-C radar. However, the tornado track was reproduced. The reproduced hook-shaped precipitation system was approximately 30 min earlier and several kilometers northward from the event observed by the MRI-C radar. However, the tornado track was reproduced. The reproduced hook-shaped precipitation system was approximately 30 min earlier and several kilometers northward from the event observed by the MRI-C radar. 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a finer distribution of PWV than can be expressed by the network of GNSS stations.

Finally, Fig. 7 presents the PWV distribution before and after the tornado touchdown, (a) reproduced by NHM50m, (b) expressed by interpolation of PWV\textsubscript{EST} and PWV\textsubscript{SPD}, and (c) expressed by interpolation of only PWV\textsubscript{EST}. An area of large PWV contrast centered on strong precipitation implies a strong upward wind in front of and a strong downdraft behind the parent storm.

Fig. 5. Time series of PWV\textsubscript{EST} (thick green line), PWV\textsubscript{SPD} of each observed satellite (thin gray lines along PWV\textsubscript{EST}), the magnitude of the PWV gradient estimated from the gradient parameter \((G_E(G_S))\) (thick red line at the bottom of each graph), and the magnitude of the PWV gradient estimated by the difference between PWV\textsubscript{SPD} and PWV\textsubscript{EST} (thin blue lines at the bottom of each graph). The locations of stations 3011, 3008, and 0583 are plotted in Fig. 2.

Fig. 6. Distribution of PWV\textsubscript{SPD} (colored triangles) of each GNSS station at its virtual position described in Section 2.3. Red circles represent the high ZDR area, and thick black lines represent 40 dBZ radar echo intensity at 4 km height. The locations vary with time depending on the GNSS satellite azimuth and elevation, and on the scale height of the water vapor gradient.

Fig. 7. PWV fields before and after the tornado. (a) Reproduced by NHM50m. (b) Expressed using both PWV\textsubscript{EST} and PWV\textsubscript{SPD}. (c) Expressed by PWV\textsubscript{EST} only. Black lines in (a) are 40 mm h\textsuperscript{-1} rainfall intensity reproduced by NHM50m; those in (b) and (c) are the 40 dBZ echo intensity at the 0.5° elevation angle of the MRI-C. As described in Section 3.2, though the timing differs by about 30 minutes, the NHM simulation succeeded in reproducing the movement and development of the parent storm.
storm. Neither (b) nor (c) expresses such a strong PWV contrast. However, enhancement of the PWV contrast toward the tornado is expressed in (b). In Fig. 7c, no such PWV gradient is expressed at all. However, the gradient in (c) was weaker than the NWP simulation. In NHM simulation (a), the area of PWV less than 24 mm distributes westward of the storm. In our new analysis (b), decreasing PWV behind the storm is expressed rather more weakly than in NHM. The possible cause of this difference is discussed in the next section.

4. Summary and discussion

We have presented a procedure for estimating the PWV variation around GNSS ground-based stations on a scale of several kilometers. The procedure utilizes differences between the estimated ZTD (ZTD_{SVP}) and the zenith-mapped SPD (ZTD_{SPD}). By assuming an exponential distribution for the horizontal water vapor gradient, this difference can be used to estimate the PWV gradient. Shoji (2013) proposed the WVI index, which is defined as the standard deviation of PWV_{SVP}. The retrieved PWV gradient in this paper can be regarded as another utilization of PWV_{SVP}. The WVI index does not utilize ray-path direction data. The PWV gradient proposed in this paper utilizes both the deviation of PWV_{SVP} and information on its direction.

The procedure was tested for the parent storm of the F3 tornado that struck on 6 May, 2012, in Tsukuba, Japan. During the tornado, both radar observation and high-resolution numerical weather prediction (NWP) model simulation revealed the existence of well-developed cumulus convection (the parent storm) at the southern tip of a line-shaped precipitation system approximately 1 h before the occurrence of the tornado. The NWP model simulation also revealed that the PWV gradient was enhanced as the storm approached the area where damage occurred. The Japanese nationwide dense GNSS network, with approximately 17 km spacing, cannot depict such a strong PWV gradient on a scale of several kilometers. Our estimated PWV gradient exhibited better agreement with the NWP model simulation. It was also confirmed that most of the improvement came from several-kilometer, higher-order inhomogeneity components.

However, the gradient was weaker than in the NWP simulation. This might be partly because of insufficient observation density. The horizontal scale of the higher-order inhomogeneity component of each SPD is several kilometers, and we adopted a distance cutoff of 5 km. In order to analyze several-kilometer PWV distributions, we need a denser GNSS network with at least 10-km horizontal spacing. Another possible reason for the weaker gradient may be the insufficient and inhomogeneous coverage of GPS satellites. As of 2012, from six to twelve GPS satellites could be observed simultaneously at each GNSS site in Japan. This might be insufficient for estimating the water vapor gradient in all directions. Also, we need to carefully check the quality of each SPD. In this study, we tried to eliminate the effects of the satellite clock error and multi-path (reflected-wave) error following Shoji (2013). However, it is difficult to distinguish atmospheric signals from these noises, especially under locally severe weather conditions.

The number of GNSSs has been increasing. As of December 2013, 24 satellites of the Russian GLONASS are in operation. The European Union’s GNSS (Galileo) is in the experiment phase, and China is developing an independent GNSS system named COMPASS. Furthermore, a number of space-based augmentation systems (e.g., Japan’s QZSS) and regional navigation satellite systems (e.g., the Indian Regional Navigation Satellite System, or IRNSS) will contribute further satellites and signals to the multi-constellation GNSS. In the next step of this study, we will assess the impact of the increased number of SPDs on multigNSS.

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