Estimation of Local-Scale Precipitable Water Vapor Distribution Around Each GNSS Station Using Slant Path Delay: Evaluation of a Severe Tornado Case Using High-Resolution NHM

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

Abstract
Precipitable water vapor (PWV) derived from a ground-based global navigation satellite system (GNSS) can be regarded as a representative value of the PWV above each GNSS station. It is inherently difficult to capture local-scale water vapor distribution using GNSS-derived PWV.

Shoji et al. (2014) proposed a new method that utilizes GNSS slant path delays (SPDs) to estimate the PWV distribution around each GNSS station. To evaluate this new method, we simulated GNSS SPDs using a high-resolution numerical weather prediction model result, emulated GNSS analysis, retrieved PWVs, and compared their accuracy with the conventional method for a severe tornado that occurred in Japan on 6 May, 2012.

Comparison results demonstrate the validity of the new method for this case. The conventional procedure introduces a 0.3 to 0.7 mm root mean square error (RMSE) at the GNSS site. Errors made by simple extrapolation increased with distance and reached 1.5 mm at about 1 to 3 km. The distance dependency of PWV errors in the new procedure varied with SPD elevation angle. Using SPD with an elevation angle exceeding 15°, we were able to estimate PWV with 1.5 mm or better RMSE within 6 km from a GNSS station.

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1. Introduction
Since the development of global positioning system (GPS) meteorology, application of slant path delays (SPDs) along ray paths from GPS receivers to GPS satellites have been studied to determine local water vapor variation and its role in the development of hazardous cumulus convection. One such approach is to retrieve a three-dimensional (3D) structure of water vapor by applying the tomographic method. Several dense GPS observation campaigns have been conducted with successful results (Hirahara 2000; Noguchi et al. 2004; Seko et al. 2004). However, reproduction of 3D water vapor structures using only GPS SPDs has been difficult when applied to permanent GPS observation networks, due to the small number of SPDs, insufficient density of the receiver network, and slow movement of GPS satellites.

Another approach is to improve the initial field of numerical weather prediction (NWP) models by applying GPS SPDs to advanced variational assimilation techniques. A GPS SPD assimilation experiment conducted by Kawabata et al. (2013) significantly improved both rainfall timing and intensity for a line-shaped local heavy rainfall event that occurred on 19 August, 2009, over Okinawa Island, Japan.

In recent years, the term global navigation satellite system (GNSS) has been used with increasing frequency. GNSS is a generic term for satellite navigation systems, whereas GPS is specific to the GNSS operated in the United States. The Geospatial Information Authority of Japan (GSI) operates a nationwide GNSS array known as the GNSS Earth Observation Network (GEONET). In May 2013, GSI started providing GEONET observed signals disseminated through the Japanese Quasi-Zenith Satellite System (QZSS) and the Russian global navigation satellite system (GLONASS), in addition to GPS. With an increased number of available SPDs, several studies have proposed utilizing SPDs to retrieve the local distribution of precipitable water vapor (PWV) near each GNSS receiver. Sato et al. (2013) compared the results of such studies with those of radiosonde observations and determined that zenith-scaled GNSS SPD, in which the path is closest to a radiosonde path, exhibited better agreement than zenith total delay (ZTD) retrieved using standard GNSS analysis. Utilizing the decomposed components of each SPD (i.e., gradient and higher-order inhomogeneity), Shoji (2013) proposed two new indices to express the degree of water vapor variation near each GNSS station, and Shoji et al. (2014) proposed a new method for estimating PWV distribution near ground-based GNSS stations on a scale of several kilometers. The new method demonstrated the capability to capture a strong PWV gradient associated with the parent storm of the F3 tornado that struck Tsukuba City in Ibaraki Prefecture, Japan, on 6 May, 2012 (hereafter, Tsukuba tornado).

For practical monitoring of severe convection, we must carefully assess the accuracy of PWV distribution using the new method. The purpose of this study is to quantitatively evaluate the method of Shoji et al. (2014) using the simulation results of a high-resolution NWP model. Section 2 describes our methodology for evaluating the new method. Section 3 presents the evaluation results, and Section 4 provides a summary and discussion.

2. Emulation of PWV retrieval using model atmosphere
In this study, we evaluate the new method using a simulated atmospheric state expressed in high-resolution NWP model results for the Tsukuba tornado. During the tornado, C-band polarimetric radar of MRI (MRI-C) observed both the parent storm and the vertical structure of the tornado at a range of 13 to 17 km (Yamauchi et al. 2013).

Mashiko (2012) conducted a high-resolution numerical simulation experiment using the Japan Meteorological Agency’s (JMA’s) nonhydrostatic model (NHM) (Saito et al. 2006, 2007). Downscale experiments were performed using JMA mesoscale analysis (MANAL) data for 09:00 JST on 6 May, 2012, as the initial field. The horizontal grid spacing of MANAL is 5 km, and that of the downscale experiments was set to 1km, 250 m, and 50m. Although the results were 30 min earlier than and several kilometers northward of the event observed by MRI-C radar, the 50 m resolution experiment (NHM50m) successfully reproduced a tornado for which the track and lifetime agreed well with the radar observation.

In this study, we used the 250m-resolution experiment (NHM250m) results because the area of NHM50m is too small for simulating low-elevation SPDs. Considering the model top height of about 20 km, in order to reproduce SPDs at elevation angles of 15° or higher, we need a 75 km radius area for one virtual GNSS station. The domain of NHM50m is 55km in the north-
Fig. 1. Domain of NHM250m (outer frame) and SPD simulation area (inner red frame). Topography in the outer frame is expressed by gray shaded contours at 0.2 km intervals, and that in the inner frame is expressed by black contours at 0.2 km intervals. The color shading in the inner frame represents the maximum of absolute elevation difference of the model surface within an 8 km radius of each grid point. Figure 3 is evaluated in the white flat area within the inner frame.

Fig. 2. Example of SPD distribution for (a) a grid point at a particular time and that of its decomposed components as an isotropic component (b), first-order gradient component (c), and a higher-order inhomogeneity component (d). The SPDs are scaled to zenith and were converted to PWV values by multiplying with coefficient. SPDs were calculated for elevation angles of at least 15°, and SPDs were 4 km apart at the model top height.

south direction and 65 km in the east-west direction. NHM250m’s domain is shown in Fig. 1. The horizontal dimensions were 1200 (1100) for the x (y) direction, 70 for the vertical level number, and 18.7 km for the model top height.

No tornado was reproduced in NHM250m because of limitations in the horizontal grid spacing. However, enhancement of vortices near the model surface was expressed, and an isolated area with a strong PWV gradient formed near the southern-central part of Saitama Prefecture 1h before the tornado struck (Shoji et al. 2014). The track of the strong PWV gradient area exhibited key features of the track of a high-Zdr area, as observed by MRI-C radar (Fig. 2 of Shoji et al. 2014).

Our approach includes the following steps.

2.1 Calculation of SPDs in model atmosphere

SPD is the integrated refractivity (N) of the atmosphere along a GNSS signal path. In the NWP model atmosphere, SPD can be expressed as the sum of refractivity along the path length (ds):

\[ SPD = \int_{\text{Model surface}}^{\text{Model top}} N \, ds. \]  (1)

Refractivity is a function of temperature (T), partial dry-air pressure (P_d), and partial vapor pressure (P_w):

\[ N = K_1 \frac{P_w}{T} + K_2 \frac{P_d}{T} + K_3, \]  (2)

where \( K_1, K_2, \) and \( K_3 \) are constants. We used 77.60 K hPa⁻¹ for \( K_1 \), 71.98 K hPa⁻¹ for \( K_2 \), and 3.754 × 10⁻³ K⁻¹ hPa⁻¹ for \( K_3 \) (Boudouris 1963).

In this study, we considered the effect of the Earth’s curvature but assumed a straight signal path. Because of limitations in the NHM250m horizontal domain, we calculated SPD within the inner frame of Fig. 1. We regarded each 250-m spacing grid point at the model surface as a virtual GNSS station. For every virtual GNSS station, we calculated the SPD in which the elevation angle was at least 15° for a duration of 140 min at 2-min intervals from 11:00 to 13:20 JST.

2.2 Emulation of GNSS PWV retrieval

In GNSS analysis (Shoji 2013), SPD at the elevation angle \( \theta \) and azimuth angle \( \phi \) is expressed as

\[ \text{SPD}(\theta, \phi) = m_d(\theta) \cdot \text{ZHD} + m_w(\theta) \cdot \text{ZWD} + \text{G}_n(\cos \phi + \text{G}_n \sin \phi) + \mu, \]  (3)

where \( m_d \) is the isotropic mapping function for dry atmosphere and \( m_w \) is isotropic mapping functions for water vapor. These mapping functions describe the scale factor of SPD and delay in the zenith direction (zenith path delay (ZPD)). We used the global mapping function (GMF) (Boehm et al. 2006) for both dry and wet mapping functions. Zenith hydrostatic delay (ZHD) [zenith wet delay (ZWD)], \( G_n, G_w \), and \( \varepsilon \) are delays in the zenith direction attributed to dry atmosphere [water vapor], delay gradient parameter in the north [east] direction, and higher-order inhomogeneity. Following Askne and Nordius (1987), ZHD was estimated from atmospheric pressure at each virtual GNSS station, and PWV was converted from ZWD using a proportional coefficient (II) estimated using the temperature obtained at each virtual GNSS station (Shoji 2013).

Actual GNSS analysis simultaneously estimates the ZWD, gradient parameter, and site coordinates using parameter estimation techniques (e.g., Kalman filter and least-squares method) as unknown parameters. For convenience, we estimated the ZWD and gradient parameters by averaging zenith scaled SPDs as

\[ \text{ZWD}_{\text{est}} = \frac{\sum_{i=1}^{n} \left( \text{SPD}_{i} - m_d \cdot \text{ZHD} \right)}{n}, \]  (4)

\[ \text{ZWD}_{\text{est}} = \frac{\sum_{i=1}^{n} \left( \text{SPD}_{i} - m_w \cdot \text{ZWD}_{i} \right)}{n}, \]  (5)

and

\[ \text{G}_n = \frac{\sum_{i=1}^{n} \left( \text{SPD}_{i} - m_w \cdot \text{ZHD} - m_d \cdot \text{ZWD}_{i} \right)}{n}, \]  (6)

where \( n \) is the number of GNSS satellites observed at one time. Higher-order inhomogeneity (\( \varepsilon \)) is defined as a residual of the above estimation. Here, ZWD represents the isotropic component of the SPDs. As indicated in Eq. 2, SPD is affected by both dry air and water vapor distributing along the ray path. However, in this study, we ignore such 3D distribution of refractivity because our aim is to emulate conventional GNSS analysis which ignores 3D variation of refractivity. The effect of 3D variation of dry air
refractivity might be much smaller than that of water vapor. For precise analysis, we should consider the effect of 3D variation of dry air refractivity, however, we think this is the subject of future study. To discriminate the estimated ZWD from the actual ZWD at a virtual GNSS station, we added the subscript \( \text{ZWD}_{\text{EST}} \) for estimated ZWD. In actual GNSS analysis, some analysis software and tools have the capability to assign different weight for SPDs depending on elevation angles. However, for convenience, we treat every SPD with the same weight in the present study.

Figure 2 presents an example of SPD distribution at a virtual GNSS station at a particular time and distributions of decomposed components. Here, 1225 (35 \( \times \) 35) SPDs are calculated for elevation angles of at least 15°. The SPDs are 4 km apart at the model top height of 18.7 km. The virtual GNSS station is at the center of each circle. Zenith-scaled SPDs (Fig. 2a) expressed complicated distribution. The true PWV value at the virtual GNSS station located at the center grid in Fig. 2a is 32.64 mm, while the simulated GNSS-derived PWV value (Fig. 2b) is 32.48 mm. Thus, usually, GNSS-derived PWVs are not identical to true PWV at the site. Also, here we define one more type of PWV, which is estimated from SPD (Fig. 2a). Again, true PWV is defined as PWV estimated from SPD of 90° elevation angle located at the center grid in Fig. 2. To distinguish GNSS-derived PWVs from those obtained from zenith-scale SPDs, we refer to the former as PWV\(_{\text{EST}}\) and the latter as PWV\(_{\text{SPD}}\).

\[
\text{PWV}_{\text{SPD}} = \frac{\text{SPD} - \text{m}_i \cdot \text{ZHD}}{\text{m}_i}. \tag{7}
\]

2.3 Evaluation method

Because the purpose of this study was to evaluate the validity of using PWV\(_{\text{SPD}}\) to estimate PWV distribution near each GNSS station, we compared both PWV\(_{\text{EST}}\) and PWV\(_{\text{SPD}}\) with the actual PWV value at each virtual GNSS station and in the surrounding area within 8 km radius. We then examined the distance dependencies of error.

We calculated the satellite elevation and azimuth angle at each virtual GNSS station, using the GPS and GLONASS satellite coordinates recorded on 6 May, 2012, as described in precise ephemeris provided by the Center for Orbit Determination in Europe (CODE). The SPDs of each GNSS satellite were then determined. PWV\(_{\text{EST}}\) was calculated using the procedure described in Section 2.2. For PWV\(_{\text{SPD}}\), we calculated 1225 SPDs (35 slant paths for the east-west direction and 35 slant paths for the north-south direction) for each virtual GNSS station (Fig. 2b). Both PWV\(_{\text{EST}}\) and PWV\(_{\text{SPD}}\) were compared with actual PWV values within a radius of 8 km from each virtual GNSS station. Because PWV depends strongly on station altitude, comparison was conducted in only flat areas to avoid the effects of height difference in stations. Flat area is defined as an area where altitudes of the model surface are identical within 8 km range centered on each grid point. The white area in the inner frame in Fig. 1 is a flat area. As described in Section 3, SPDs of 15° elevation angle or higher would be relocated within a 7 km area around each virtual GNSS station. Therefore, we set an 8 km range as the threshold for our flat area definition.

3. Evaluation results

The three panels in Fig. 3 plot an evaluation results at three different moments spaced at 32 min intervals (1104, 1136, and 1208 JST). The thick gray lines represent the root mean square (RMS) difference of PWV\(_{\text{EST}}\) against the true PWV field around each virtual GNSS station. As described in Section 2.2, PWV\(_{\text{EST}}\) is not equal to the true PWV at virtual GNSS stations. In Fig. 3a, the RMS difference of PWV\(_{\text{EST}}\) is 0.3 mm at the GNSS site. When we extrapolated PWV\(_{\text{EST}}\) as the PWV value near a virtual GNSS station, the RMS increased with distance and exceeded 1.5 mm at a distance of 3 km. The thin colored lines in the figure represent distances at which the RMS error (RMSE) became smallest. The distance increases as the elevation angle decreases. For PWV\(_{\text{SPD}}\) with a 77.6° elevation angle, the RMSE was smallest within 1 km of a virtual GNSS station. In Fig. 3a, for PWV\(_{\text{SPD}}\) with a 17.6° elevation angle, RMSE was the smallest (0.7 mm) at a distance of 5.5 km. The red dots in the figure represent the distance and elevation dependency of minimum RMSE. In Figs. 3b, c, we can see changing relation of the distances and RMSEs where RMSEs become minimum. Overall, the conventional procedure introduces a 0.3 to 0.7 mm RMSE at the GNSS site location, and error caused by simple extrapolation increases with distance, reaching 1.5 mm at 1 to 3 km. The distance dependency of PWV errors in PWV\(_{\text{SPD}}\) varies with elevation angle. Using SPD with an elevation angle exceeding 15°, we are able to estimate PWV with better than 1.5 mm RMSE within 6 km from a GNSS station. Essentially, with PWV\(_{\text{SPD}}\), we can estimate the PWV distribution around each GNSS station with less than half the RMSE of that using the conventional GNSS PWV retrieval method (PWV\(_{\text{EST}}\)).

The panels in Fig. 4 plot the minimum error distance as a function of the elevation angle of SPD at times corresponding to Fig. 3. According to Shoji et al. (2014), the distance where the error becomes the minimum is related to SPD elevation angle. Red circles represent raw data. The figure above each red circle represents the RMSE value presented in Fig. 3. The blue line represents the fitting result determined using the cotangent of the SPD elevation. The coefficient is analyzed as 1.80 (1104), 1.73 (1136), and 1.62 (1208).
\[ d = H_w \cdot \cot(\theta), \]  

(8)

where \( H_w \) is water vapor scale height. We analyzed the results of least squares fitting applied to the red dots in Fig. 4, in which scale height gradually decreases from 1.8 km to 1.6 km with time. We also calculated water vapor scale height expressed in NHM250m at each 250 m grid interval by applying least squares fitting for the water vapor profiles. The results of the water vapor scale height distribution expressed in NHM250m are presented in Fig. 5. The area of less than 1.65 km scale height (violet) gradually expands with time. The averaged (median) scale height for each panel is (a) 1.67 km (1.67 km), (b) 1.68 km (1.67 km), and (c) 1.67 km (1.66 km). The true water vapor scale height distribution indicates much smaller change than those estimated from the least square fit of Eq. 8.

The panels in Fig. 6 depict the PWV fields during the development phase of the tornado parent cloud as reproduced by NHM250m, which in this study were regarded as true fields; GNSS fields retrieved using the conventional procedure and GNSS fields retrieved using the new procedure. To allocate the PWV fields near each GNSS station, we first determined water vapor scale height, as described in Eq. 8. Following Shoji (2013), we used the following statistically obtained equation:

\[ H_w = 8.64679 \cdot \text{PWV} + 1657.91, \]  

(9)

In panel (a), a large PWV area is visible, coinciding with the wind convergence area that formed southeast of the parent cloud at 1142 JST. The largest PWV value exceeded 40 mm and increased as time progressed. We also detected a small PWV area just behind the parent storm. Shoji et al. (2014) attributed this PWV gradient enhancement to the co-existence of a strong updraft and downdraft within a radius of 5 km. In panel (b), with a 250-m spacing of virtual GNSS stations, the characteristics depicted in panel (a) are weakened. In panel (c), despite the considerably smaller GNSS station spacing of 5 km, a stronger PWV gradient is evident, and the features are more similar to those in (a) than to those in (b).

Finally, panels in Fig. 7 compare statistical errors (mean error (ME) and RMSE) in PWV_{SPD} and PWV_{EST} for the entire duration of the NHM250m simulation (1100 to 1320). Error distributions in each moment are presented in supplement 1 with 2 min intervals. The storm passed in the northern half of the panels from west to east. Errors become large along the storm track for both PWV_{SPD} and PWV_{EST}. However, PWV_{SPD} exhibits smaller errors for both ME and RMSE than for PWV_{EST}. Figure 7b indicates a concentric ring structure in RMSE distribution. In the southern part (far from the storm), PWV_{SPD} exhibits good accuracy, with better than 1.5 mm RMSE for most of the area. In the northern part (near the storm), RMSE grows rapidly with distance from the center grid. This result suggests that the accuracy of PWV_{SPD} varies with meteorological conditions. Under meteorological disturbances, the accuracy of PWV_{SPD} becomes worse. Still, PWV_{SPD} can provide more reliable information than the conventional method.

4. Summary and discussion

We have quantitatively evaluated the method proposed by Shoji et al. (2014) to estimate PWV distribution near ground-based GNSS stations using high-resolution (250 m horizontal grid
reduce such error caused by steep topography may be to correct

did not evaluate the effect of height differences. One technique to

Therefore, it is anticipated that error increases with steep topogra-

spacing) NWP model results for a tornado parent cloud.

The results demonstrate the validity of the new method. The con-

ventional procedure inherently includes RMSE of 0.3 to 0.7

mm in the PWV at the GNSS site. When we extrapolated these

errors to estimate the surrounding PWV field, they increased with
distance, reaching 1.5 mm at 1 to 3 km. The distance dependency
of PWV errors with the new procedure varied with SPD elevation
angle. Using SPDs with elevation angles of at least 15°, we were
able to estimate PWV with less than 1.5 mm accuracy within 6 km
of a GNSS station. PWV distribution retrieved using the con-

ventional method was expressed as a rather smooth feature of the

PWV gradient even with densely located GNSS. Using the new

method, however, GNSS stations spaced 5 km or less apart can
capture local PWV variation associated with hazardous cumulus
convection.

One major error source of this new method is the limitation of
uncertainty in the water vapor scale height. As illustrated in
supplement 2, the error of estimated scale height was between
−0.2 and 0.3 km at 1104, 1136, and 1208 JST. Small-scale vari-
ation occurs near a well-developed cumulus convective system.
An error of 0.5 km in estimated scale height causes location errors
of 0.5 km in PWV at an elevation angle of 80°, 1 km in PWV at an

elevation angle of 30°, and 2 km in PWV at an elevation
angle of 15°. To reduce the error caused by scale height uncer-
tainty, a dense GNSS observation network and usage of only
high-elevation angle satellites are essential.

An additional major error source is height difference. Because
PWV depends on SPD generated along the GNSS signal path,
the value strongly depends on the altitude of each GNSS station.
Therefore, it is anticipated that error increases with steep topog-
raphy. In this study, we limited the evaluation to flat areas and
did not evaluate the effect of height differences. One technique to
reduce such error caused by steep topography may be to correct
PWV using the horizontal gradient of PWVEST because two-
dimensional distribution (2D) of PWV reflects topography to
some extent.

To apply this new method for practical monitoring of con-

vection, further investigation is required, particularly regarding
the two aforementioned concerns. This is only one case study.
As we discussed, the accuracy of PWVEST depends on meteo-

rological conditions. Statistical study with more cases using cloud

resolving numerical prediction model results should be conducted.

Nevertheless, for local water vapor monitoring, our new method
can maximize the potential of GNSS SPD, particularly with dense
GNSS observation networks.

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Supplement

Supplement 1. Error distribution of PWV and PWVEST and its
time variation from 1100 to 1320.

Supplement 2. Error of water vapor scale height caused by the
estimation procedure in this study at 1104, 1136, and 1208 JST.
The true field is depicted in Fig. 5. Estimations are calculated fol-

lowing Shoji (2013) as $H_0 = 8.64679PWV + 1657.91$ (in meter).
Black thick contours denote 10 mm h$^{-1}$ rainfall intensity repro-
duced by NHM250m.

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