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Quality Assessment of Tropospheric Delay Estimated by Precise Point Positioning in the Korean Peninsula

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ABSTRACT

Over the last decade, the Global Navigation Satellite System (GNSS) has been increasingly utilized as a meteorological research tool. The Korea Astronomy and Space Science Institute (KASI) has also been developing a near real-time GNSS precipitable water vapor (PWV) information management system that can produce a precise PWV for the Korean Peninsula region using GNSS data processing and meteorological measurements. The goal of this paper is to evaluate whether the precise point positioning (PPP) strategy will be used as the new data processing strategy of the GNSS-PWV information management system. For this purpose, quality assessment has been performed by means of a comparative analysis of the troposphere zenith total delay (ZTD) estimates from KASI PPP solutions (KPS), KASI network solutions (KNS), and International GNSS Service (IGS) final troposphere products (IFTP) for ten permanent GNSS stations in the Korean Peninsula. The assessment consists largely of two steps: First, the troposphere ZTD of the KNS are compared to those of the IFTP for only DAEJ and SUWN, in which the IFTP are used as the reference. Second, the KPS are compared to the KNS for all ten GNSS stations. In this step, the KNS are used as a new reference rather than the IFTP, because it was proved in the previous step that the KNS can be a suitable reference. As a result, it was found that the ZTD values from both the KPS and the KNS followed the same overall pattern, with an RMS of 5.36 mm. When the average RMS was converted into an error of GNSS-PWV by considering the typical ratio of zenith wet delay and PWV, the GNSS-PWV error met the requirement for PWV accuracy in this application. Therefore, the PPP strategy can be used as a new data processing strategy in the near real-time GNSS-PWV information management system.

Keywords: GNSS, tropospheric delay, network solution, precise point positioning, Bernese GNSS software

1. INTRODUCTION

Water vapor in the atmosphere is one of the primary greenhouse gases, and has a significant impact on climate change (Kiehl & Trenberth 1997). For research on climate change and numerical weather forecasting, it is important to have accurate estimates of the amount and the distribution of water vapor. However, this is difficult due to the high spatial and temporal variability of water vapor (Bevis et al. 1992). Zenith total delay (ZTD) estimates based on the Global Navigation Satellite System (GNSS) can be transformed into atmospheric water vapor content (Bevis et al. 1992, Ha et al. 2006). Moreover, since GNSS has no time or space constraints, information about water vapor can be obtained with high spatial and temporal resolution (Byun & Bar-Sever 2009). Because of its relatively low cost and the advantages mentioned above, GNSS has been utilized over the last decade as a cost-efficient research tool in meteorology (Ha et al. 2007, Sohn et al. 2012, 2013, Vazquez B & Grejner-Brzezinska 2013, Singh et al. 2014).

The Korea Astronomy and Space Science Institute (KASI) has been developing a near real-time GNSS precipitable water vapor (PWV) information management system since March 2014, and started a pilot experiment in August 2014. The system produces an accurate and precise PWV of the Korean Peninsula region using GNSS data processing and meteorological measurements to apply the PWV to practical applications, such as the initial value of a numerical weather model (NWM), research on fog phenomena, or the Air Force operational weather. Table 1 lists the major technical

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Table 1. Major technical requirements of the GNSS-PWV information management system.

Requirement	Value	Remarks
GNSS-PWV accuracy	< 2 mm	
Latency	10 - 15 min	Near real-time mode
Spatial Resolution	100 - 200 km 10 - 30 km	The 1st Stage (2014) The 2nd Stage (2015)

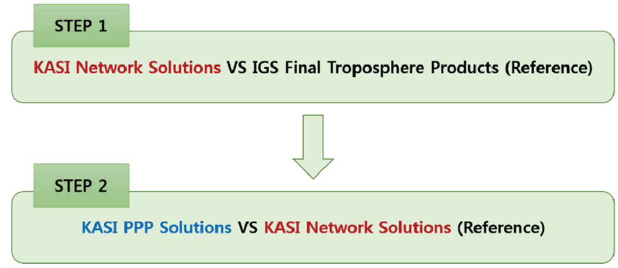

Fig. 1. Sequence of quality assessment for troposphere delay products.

requirements of the development project.

The GNSS-PWV information management system processes the network of GNSS stations consisting of KASI's nine permanent GNSS stations and the National Geographic Information Institute (NGII)'s one station in the Korean Peninsula, which creates a spatial resolution of 100 - 200 km. To meet the requirement for the spatial resolution at the 2nd stage as shown in Table 1, the GNSS network is going to be densified by 2015. To process the GNSS data for the densified networks in near real-time, it is necessary to find processing strategies that are more effective, with an adequate level of accuracy secured for the applications (Ahmed et al. 2014).

There are two representative GNSS data processing strategies: the double-difference (DD) strategy and precise point positioning (PPP) strategy (Zumberge et al. 1997). Since the DD strategy can achieve high accuracy by eliminating common errors between stations, it has generally been used in precise GNSS applications (Grinter & Janssen 2012). Meanwhile, the PPP strategy is more efficient in terms of its computational burden and thus enables the processing of larger networks in shorter time spans (Ahmed et al. 2014). Moreover, as the accuracy of the PPP has been improving while International GNSS Service (IGS) (2014) products such as GNSS orbit and clock have continuously improved, the PPP strategy has recently been considered for near real-time GNSS applications (Ha et al. 2012, Dousa & Vaclavovic 2014).

The goal of this study is to evaluate whether the PPP strategy can be used as a new data processing strategy for the near real-time GNSS-PWV information management system. Currently, the GNSS-PWV information management system employs the DD strategy to process the data from ten GNSS stations in near real-time. This strategy is easily applied when there is only a small number of GNSS stations. However, if the number increases, the DD strategy may not be adequate for near real-time processing. Thus, the quality of ZTD obtained from the PPP strategy is systematically assessed to validate the use of PPP as a substitute for the DD strategy when it is unavailable.

One of the biggest challenges of the assessment is the fact that there is no reference data to be compared with. Therefore, in this study, the quality assessment is performed through a comparative analysis of the troposphere ZTD estimates among KASI PPP solutions (KPS), KASI network solutions (KNS), and IGS final troposphere products (IFTP) in two steps, as shown in Fig. 1. The KPS and KNS are the navigation solutions estimated by the PPP strategy and the DD strategy, respectively, for all ten GNSS stations. The IFTP are the solutions estimated by the PPP strategy for only DAEJ and SUWN, which are the IGS reference stations (Byram & Hackman 2012).

In Step 1, the troposphere ZTD estimates of the KNS are compared to those of the IFTP for DAEJ and SUWN, in which the IFTP are used as a kind of reference. Because IGS has been producing and formally servicing the IFTP for a long time (Byun & Bar-Sever 2009), they are reliable. In addition, the formal errors for solutions and the coordinate repeatability are analyzed in both the KNS and IFTP. In Step 2, the KPS are compared to the KNS for all ten GNSS stations in the Korean Peninsula. In this step, the KNS are used as a new reference instead of the IFTP.

This paper is organized as follows. Chapter 2 presents the architecture and features of the GNSS-PWV information management system developed by KASI. Chapter 3 addresses the troposphere ZTD estimation systems and GNSS data. In Chapter 4, the quality of the ZTD estimated from the KNS is evaluated with IFTP. Chapter 5 presents the results of the comparison between KPS and KNS. Finally, Chapter 6 summarizes and discusses the results.

2. A NEAR REAL-TIME GNSS-PWV INFORMATION MANAGEMENT SYSTEM

2.1 The Architecture

A near real-time GNSS-PWV information management system has been built on three high performance computers and the latest version of Bernese GNSS software 5.2. The architecture and the specific features are shown in Fig. 2 and Table 2, respectively. As shown in Fig. 2, the system largely

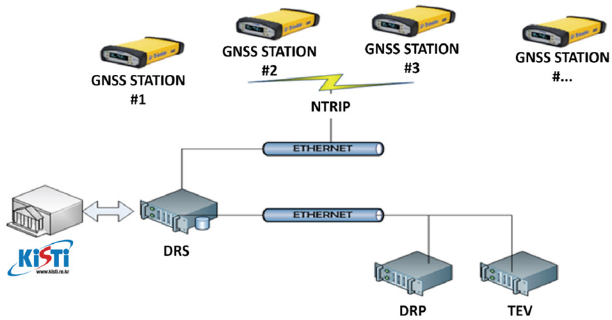

Fig. 2. The architecture of the near real-time GNSS-PWV information management system.

Table 2. Specifications of the GNSS-PWV information management system.

Title	Description
Computers	Three servers - Data receive and service server (DRS) - Data processing server (DPR) - Test and evaluation server (TEV)
Specification of DPS	Model: HP ProLiant DL360p Gen8 - 2 Intel Xeon E5-2640 (2.0 GHz, 8-core) - 64 GB RAM - 512GB SSD 4EA
Number of GNSS stations	Step 1: 10 (nine KASI stations and one NGII station) Step 2: More than 80 (in 2015)
Data Collection	Near real-time - NTRIP (for KASI stations): Less than 1 min interval - FTP (for IGS stations): Less than 4 min interval
O/S	LINUX (Ubuntu 12.04 LTS)
Data processingengine	Bernese GNSS software 5.2

consists of a Data Receive and Service Server (DRS), a Data Processing Server (DPR), and a Test and Evaluation Server (TEV), which are functionally divided. The GNSS-PWV information management system receives data from a GNSS network, processes the data, and provides the results to the Korea Institute of Science and Technology Information (KISTI).

The DRS stores observation data and data processing results, and provides GNSS-derived PWV to KISTI. The DPR estimates a troposphere ZTD parameter through GNSS data processing using Bernese GNSS software 5.2, and then derives a PWV from the ZTD using the pressure and temperature from each given GNSS station. Finally, the TEV is in charge of the DPR redundancy as well as testing and evaluation for this system.

In addition, Networked Transport of RTCM via Internet Protocol (NTRIP) has been adopted on the DRS, as shown in Fig. 2, which allows the DRS to receive RINEX files from GNSS stations in real-time. This data communication system makes it possible for the GNSS-PWV information management system to produce a GNSS-derived PWV in near real-time, as well as in post-processing.

Finally, the GNSS-PWV information management system allows the processing of GNSS data using a PPP approach for station-wise processing as well as a DD approach for a GNSS network. As mentioned before, the DD approach is generally more accurate but imposes a higher computational load. Meanwhile, the PPP approach has a lower computational burden and is advantageous for the near real-time processing of larger networks (Ahmed et al. 2014).

2.2 A Permanent GNSS Network

The GNSS network of the GNSS-PWV information management system consists of KASI's nine permanent GNSS stations and NGII's one station in the Korean Peninsula, which has a spatial resolution of 100 - 200 km. To meet the spatial resolution requirement in the 2nd stage, as shown in Table 1, KASI plans to increase the number of GNSS stations to more than eighty by including the stations of other agencies, such as NGII. Then, the spatial resolution will be highly improved, to 10 - 30 km.

Fig. 3 shows the GNSS network, where the diamond marker denotes KASI's GNSS station, the square marker denotes NGII's station, and the circle marker denotes the IGS reference station. Because DAEJ and SUWN are the only IGS reference stations among the ten GNSS stations, three IGS stations - BJFS, TSKB, and WHUN - around the Korean Peninsula have been added to the network to define the local datum. Note that defining the local datum is only required in the DD approach. Therefore, adding the three IGS stations is not necessary when using the PPP approach.

3. GNSS DATA PROCESSING

3.1 ZTD Estimation Systems

The troposphere ZTD is estimated from the GNSS-PWV information management system and IGS for the same period. In the former, the ZTD estimates are obtained from KPS and KNS by using the PPP approach and the DD approach, respectively. Therefore, there are three versions of the ZTD estimation solutions, as shown in Table 3, where the characteristics of the solutions are listed in detail. Note that all solutions used in this study employed IGS final orbit and clock products for GNSS data processing. This means that all the solutions were obtained in post-processing mode.

IFTP is utilized as a kind of reference in the current study. Although the IFTP is not perfect, it is one of the most reliable and affordable sources, because IGS has been producing and formally servicing it for a long time (since 1997) (Byun

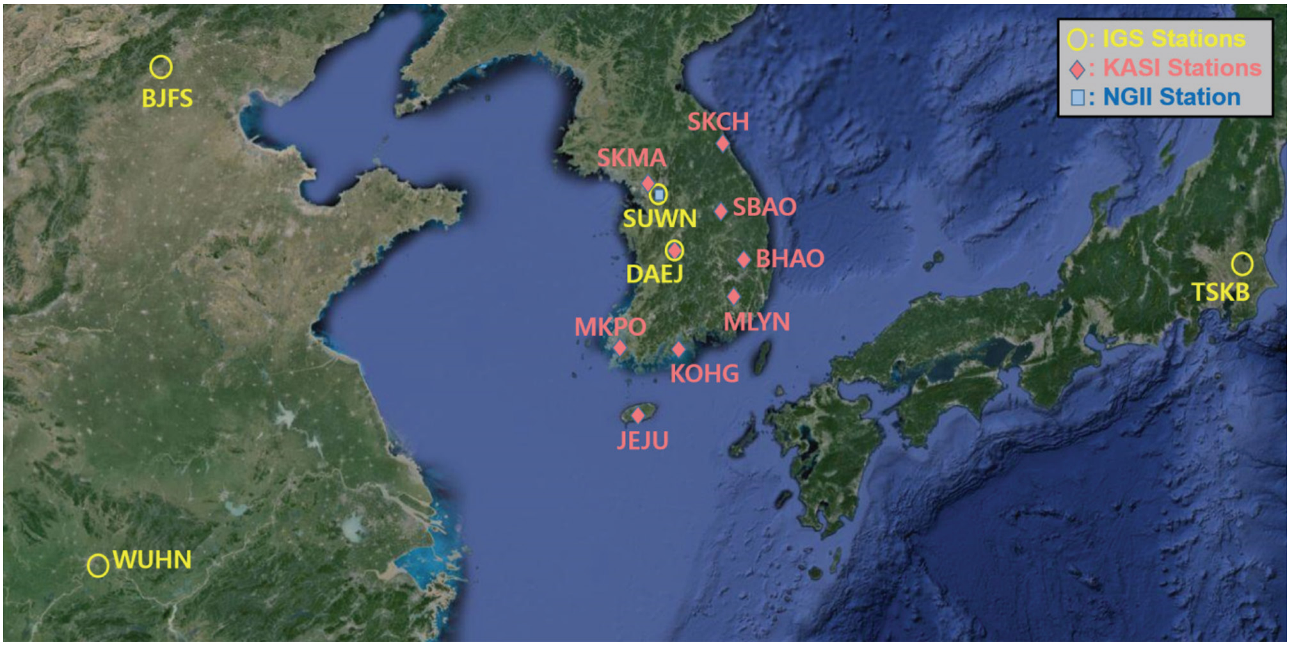

Fig. 3. The network of permanent GNSS stations in the Korean Peninsula and the surrounding area.

Table 3. Processing characteristics of the ZTD estimation systems.

Estimation System	KPS	KNS	IFTP*
Institute	KASI	KASI	IGS
Strategy	PPP	DD	PPP
Processing Engine	Bernese GNSS SW 5.2	Bernese GNSS SW 5.2	Bernese GNSS SW 5.0
Temporal Resolution (min)	15	15	5
Observation Window (hours)	24	24	27
GNSS Orbit/Clock Product	IGS Final	IGS Final	IGS Final
A Priori Troposphere Model	DRY_GMF	DRY_GMF	DRY_Niell

*Byram & Hackman (2012), KPS: KASI PPP Solutions, KNS: KASI Network Solutions, IFTP: IGS Final Troposphere Products

& Bar-Sever 2009), and a number of researchers have verified the IFTP and have compared it with their research results (Ahmed et al. 2012, Moeller et al. 2012). Moreover, the IFTP can be converted to PWV with a margin of error within 2 mm if accurate pressure and temperature data are available (Rocken et al. 1995).

The major differences between KASI's solutions and IFTP include the temporal resolution, the observation window, and the *a priori* troposphere model. First, the temporal resolution of KASI's solutions is 15 min, while for IFTP it is 5 min. The lower temporal resolution causes a higher computational load, because the number of estimating parameters increases. It is even more important in the DD approach. The temporal resolution of 15 min has been determined by considering the trade-off between computational load and accuracy. Second, the observation window of KASI's solutions is 24 hours, while for IFTP it is 27 hours. Although it is daily processing, IFTP uses a time window of 27 hours. Therefore, an overlap of three hours might be eliminated in the final products. The time window is set to minimize the effect of the daily processing batch, which has a jump in ZTD at the day boundaries (Ahmed et al. 2014). However, it also causes a higher computational load due to the extended period. Considering the trade-off in the effect-jumping ZTD and the computational load, KASI adopted an observation window of 24 hours. Finally, KASI's solutions employ the dry global mapping function (DRY_GMF) as the *a priori* troposphere model, while the IFTP employ the dry Niell model (DRY_Niell) as the one (Byram & Hackman 2014). In addition, both employ wet global mapping function (WET_GMF) as mapping function used for the computation of the partial derivatives of the troposphere ZTD parameters (Byram & Hackman 2014). Bernese 5.2 recommends using DRY_GMF in combination with the WET_GMF mapping function (Dach et al. 2007). Also, the GMF model was an improvement over the Niell model in terms of regional height biases and annual errors (Boehm et al. 2006).

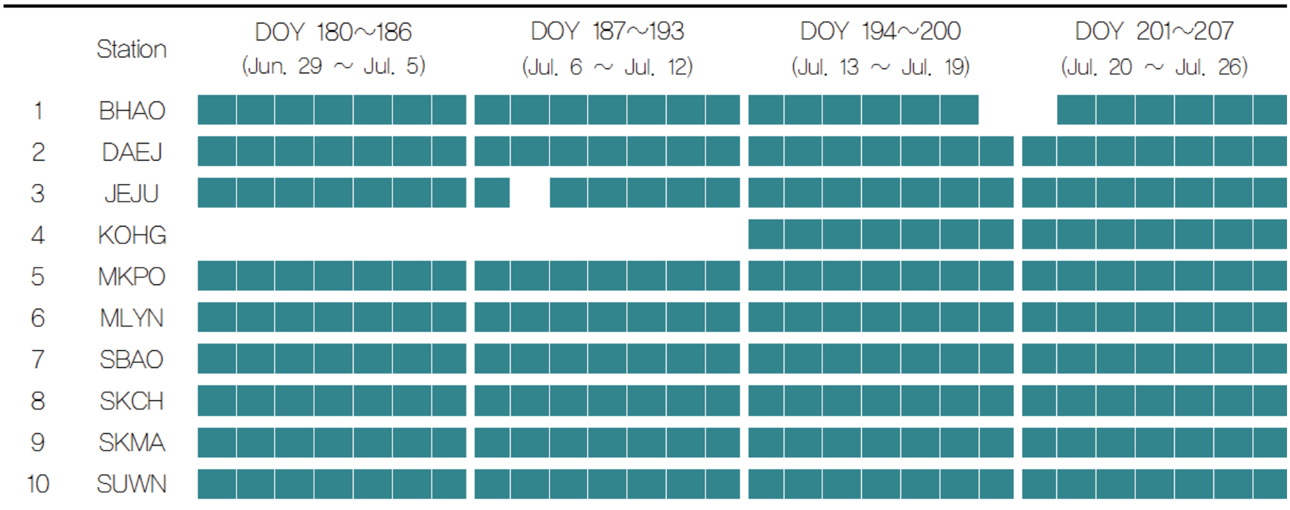

Fig. 4. GNSS data from ten GNSS stations in the Korean Peninsula during the time period 2014-06-29 00:00:00 UTC to 2014-07-26 23:59:30 UTC.

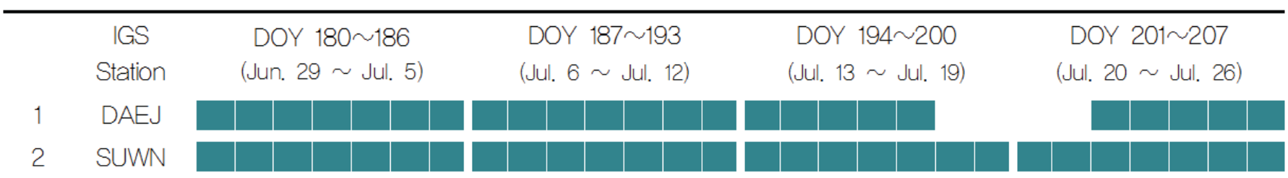

Fig. 5. IGS final troposphere products from DAEJ and SUWN during the time period 2014-06-29 00:00:00 UTC to 2014-07-26 23:59:30 UTC.

3.2 GNSS Data

GNSS data processing was performed for ten GNSS stations in the Korean Peninsula from June 29, 2014, to July 26, 2014. As was previously mentioned, the GNSS network consists of KASI's nine GNSS stations and NGII's one station (SUWN). Although the SUWN station is not KASI's station, its data were included, because it is an IGS reference station located in Korea.

Fig. 4 shows the GNSS data for each station during the period of data processing. BHAO and JEJU do not display GNSS data for two days (19 - 20 July) and for one day (7 July) respectively, because of a data communication fault. KOHG station's GNSS data was received from 13 July. Fig. 5 shows the IFTP during the same period. As can be seen in this figure, the IFTP for DAEJ were not produced for four days, from 13 July to 16 July. IGS processes more than 300 stations per day (Byram & Hackman 2014). However, some stations are screened out due to post-processing data quality screening (Byram & Hackman 2012).

4. QUALITY ASSESSMENT FOR KNS

The quality of the troposphere ZTD estimates from the KNS are assessed by means of an overall comparative analysis of the KNS and IFTP. The quality assessment proceeds in three stages. In Section 4.1, the ZTD estimates of the KNS for DAEJ and SUWN are directly compared to those of IFTP during the same period. Section 4.2 discusses the histogram of the formal errors for solutions. Finally, the repeatability of the coordinates estimated by the GNSS data processing is evaluated in Section 4.3. The validated KNS will be used as a new reference in the next chapter.

4.1 Troposphere ZTD Estimates of KNS and IFTP

The troposphere ZTD estimates of the KNS and IFTP are compared and analyzed overall. Fig. 6 shows the ZTDs of DAEJ and SUWN, which are IGS stations in the Korean Peninsula, and the difference between the two ZTDs for four weeks (2014-06-29 - 2014-07-26). In the upper plot of Fig. 6, the solid line represents the ZTD time series of KNS, and the dotted line represents that of IFTP. In the

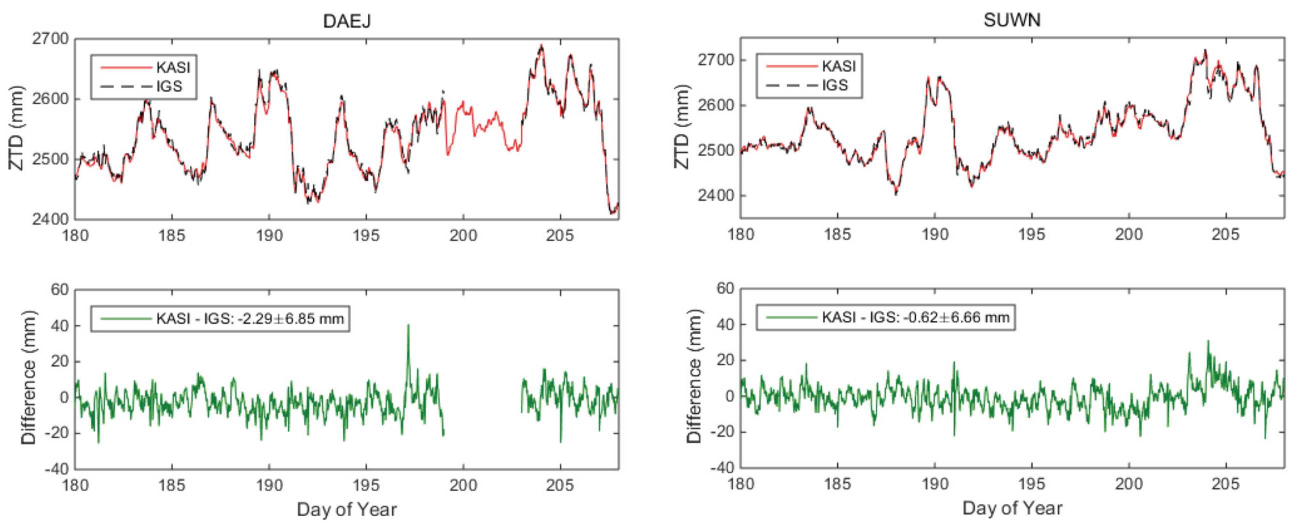

Fig. 6. The troposphere ZTD of KNS and IFTP for DAEJ and SUWN during the time period of four weeks.

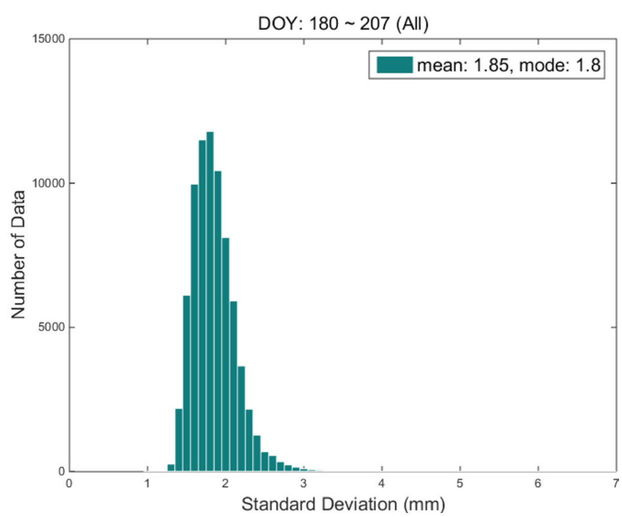

Fig. 7. Histogram of the formal errors reported for KNS for all ten GNSS stations in the Korean Peninsula.

lower plot of Fig. 6, the solid line represents the difference between the two ZTDs. The ZTDs from both the KNS and IFTP follow the same pattern overall. The comparison yields an overall mean difference of -1.46 ± 6.76 mm, which translates to an error of about 1 mm in PWV. Without validation using other techniques, it cannot be determined which series is more reliable. Therefore, the accuracy assessment of the ZTD of KNS and IFTP will be performed in Sections 4.2 and 4.3.

4.2 Histogram

For the quality assessment, the formal errors were obtained from the difference between the estimated ZTD and ZTD calculated by *a priori* troposphere model (Dach et al. 2007) and were analyzed through histogram. Note that the formal error does not represent the actual error because it does not include systematic errors in the GNSS orbit and clock (Byun & Bar-Sever 2009). Nevertheless, the formal error was employed for the quality assessment, because it can show the internal consistency (Byun & Bar-Sever 2009).

Fig. 7 shows the histogram of the formal error for the KNS for four weeks. The formal errors were centered around 1.8 mm, and its mean was approximately 1.85 mm. DAEJ and SUWN are GNSS stations located in the Korean Peninsula and are also IGS reference stations. Therefore, we can directly compare the IFTP for both of the stations with those of the KNS during the same period. As shown in Fig. 8, the formal errors were centered around 1.9 mm and 2.0 mm for the KNS and the IFTP, respectively. Overall, the formal errors of the KNS were more concentrated in the center, and the mean value was slightly less than that of the IGS product. In addition, the KASI's maximum formal error was no more than 4.0 mm, while the formal errors for the IFTP were distributed over a larger range.

4.3 Coordinate Repeatability

The second methodology for assessing the quality of the ZTD is to check the repeatability of the coordinates estimated by GNSS data processing. Because the coordinates of a ground-based GNSS station vary little in the short term, we can determine the reliability of the GNSS data processing result by checking the coordinate repeatability (Rothacher et al. 1998).

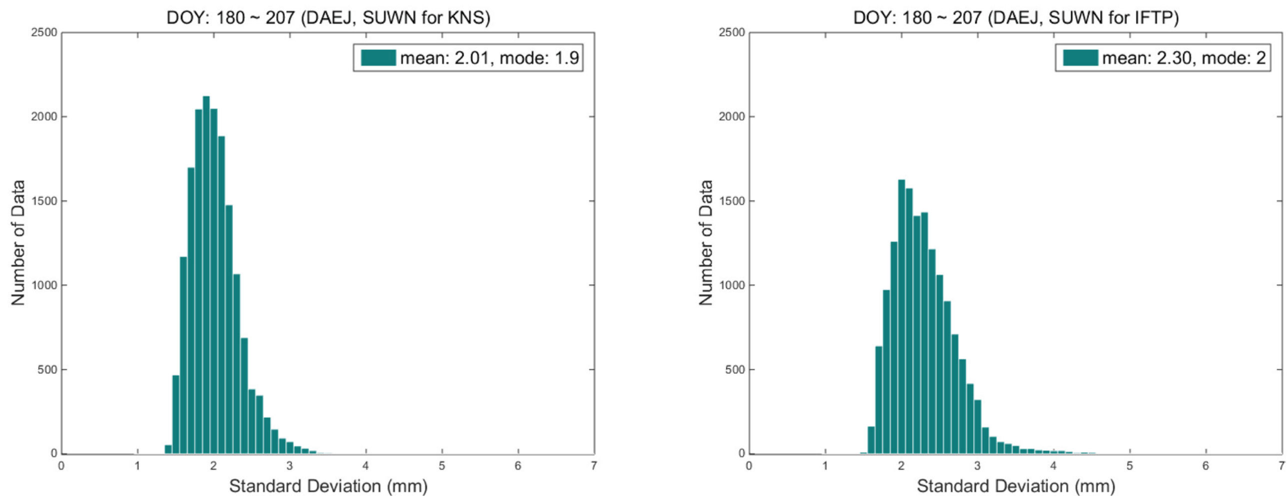

Fig. 8. Histograms of the formal errors for DAEJ and SUWN reported for KNS (left) and IFTP (right).

Table 4. Coordinate repeatability of KNS for all ten GNSS stations in seven-day increments.

DOY	N (mm)	E (mm)	U (mm)
180 - 186	1.24	1.31	4.46
187 - 193	1.68	2.56	3.48
194 - 200	1.13	1.17	4.12
201 - 207	1.86	1.53	4.56
Average	1.48	1.64	4.16

Table 5. Comparison of the coordinate repeatabiliy of KNS and IFTP with DAEJ and SUWN.

DOY	N (mm)		E (mm)		U (mm)	
	KNS	IFTP	KNS	IFTP	KNS	IFTP
180 - 186	1.24	1.97	0.54	2.17	3.41	6.62
187 - 193	1.11	2.53	2.44	2.48	1.44	2.93
194 - 200	0.88	2.38	0.67	2.86	3.37	5.94
201 - 207	0.43	1.06	1.00	1.24	2.91	4.15
Average	0.92	1.99	1.16	2.19	2.78	4.91

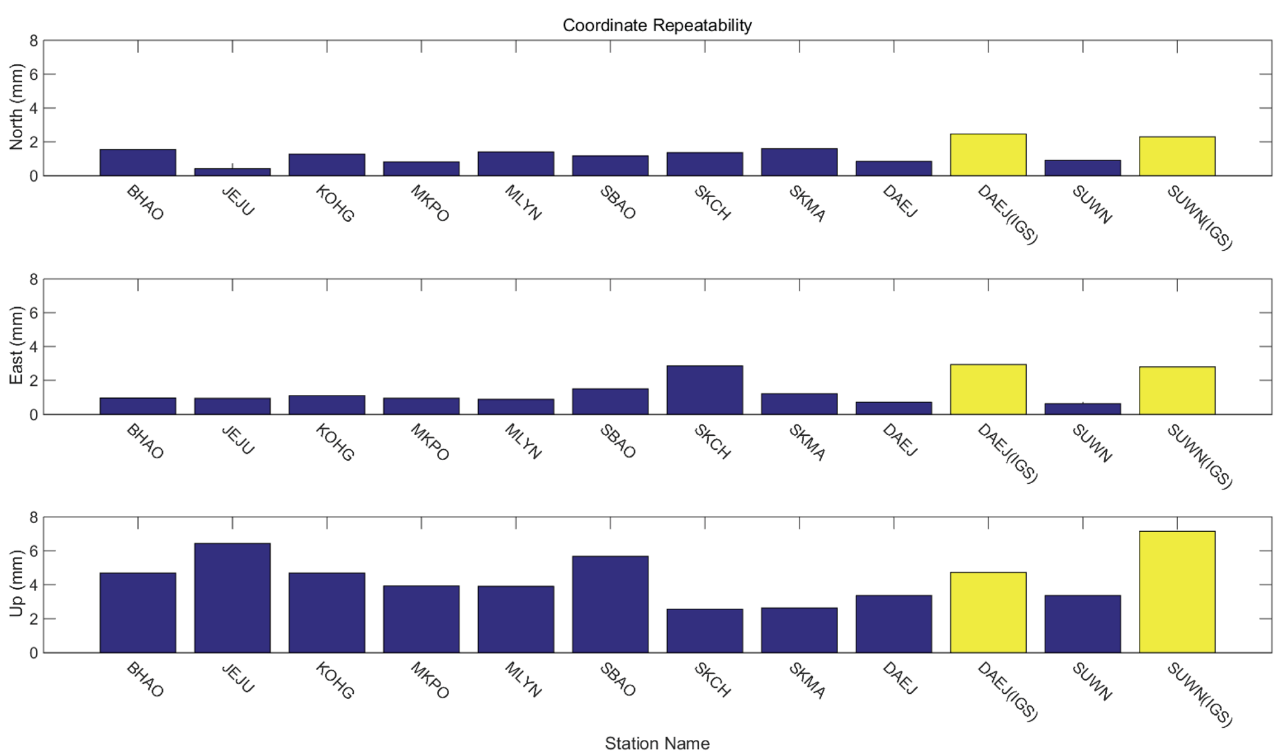

Fig. 9. Coordinate repeatabilty of KNS and IFTP.

The coordinates of the ten stations are compared over each one-week period for four weeks (2014-06-29 - 2014-07-26). Table 4 shows the station repeatability. The values are the root mean square (RMS) of the differences between the coordinates and average coordinates for the north (N), east (E), and up (U) directions. Recently, Byram & Hackman (2014) also checked the coordinate repeatability for IFTP. The values were 1.45, 2.43, and 4.75 for N, E, and U respectively. For the KNS, the values were 1.48, 1.64, and 4.16 for N, E, and U, respectively, as listed in Table 4.

Table 5 shows the direct comparison of the coordinate repeatability of KNS and IFTP with DAEJ and SUWN. The IFTP's repeatability was almost twice that of the KNS for the same data. Fig. 9 shows the coordinate repeatability of KNS for each station. For DAEJ and SUWN, the coordinate repeatability of IFTP was also included.

In conclusion, it was found that the ZTD estimates of the KNS and IFTP had almost the same pattern as each other overall. In the additional assessment, it was found that the quality of the KNS was higher than that of the IFTP with regard to the histogram of the formal error and the coordinate repeatability. These results mean that KNS are reliable, and they can be used as a reference.

5. QUALITY ASSESSMENT FOR KPS

ZTD estimates from KPS are compared to those from KNS for all ten GNSS stations. In Chapter 4, the ZTD estimates from the KNS were validated as a reference.

5.1 ZTD Time Series

Figs. 10 - 12 show the ZTD time series obtained from the KPS and KNS for all ten permanent GNSS stations for four weeks (2014-06-29 - 2014-07-26). In these figures, the dotted line and solid line are the ZTD estimates from KPS and KNS, respectively, the values for which can be found in the left vertical axis. In addition, the lower dash-dot line represents the difference between the ZTD estimates from the KPS and KNS, the values for which can be found in the right vertical axis.

It can be seen that the ZTD time series from both the KPS and KNS follow the same pattern, and most stations show a jump in ZTD at the day boundaries. As mentioned previously, this is an effect of the daily processing batch.

5.2 ZTD Comparison Results

The statistics for this comparison were calculated during the same period in each solution. The overall mean difference between the ZTD estimates from KPS and KNS was found to be -0.38 ± 5.37 mm, with an average RMS of 5.38 mm. Table 6 shows the statistics for all ten GNSS stations.

The average RMS of 5.38 mm in ZTD can be approximately converted into an error of GNSS-PWV by considering the typical ratio of zenith wet delay and PWV. The typical ratio ranges from 6 to 7 (Schuler 2001) and is assumed as 6.5 in the current study. Therefore, the error of GNSS-PWV is about 0.83 mm. The error is significantly less than the 2 mm in PWV. In conclusion, the accuracy of the GNSS-PWV meets the requirement for PWV accuracy in Table 1.

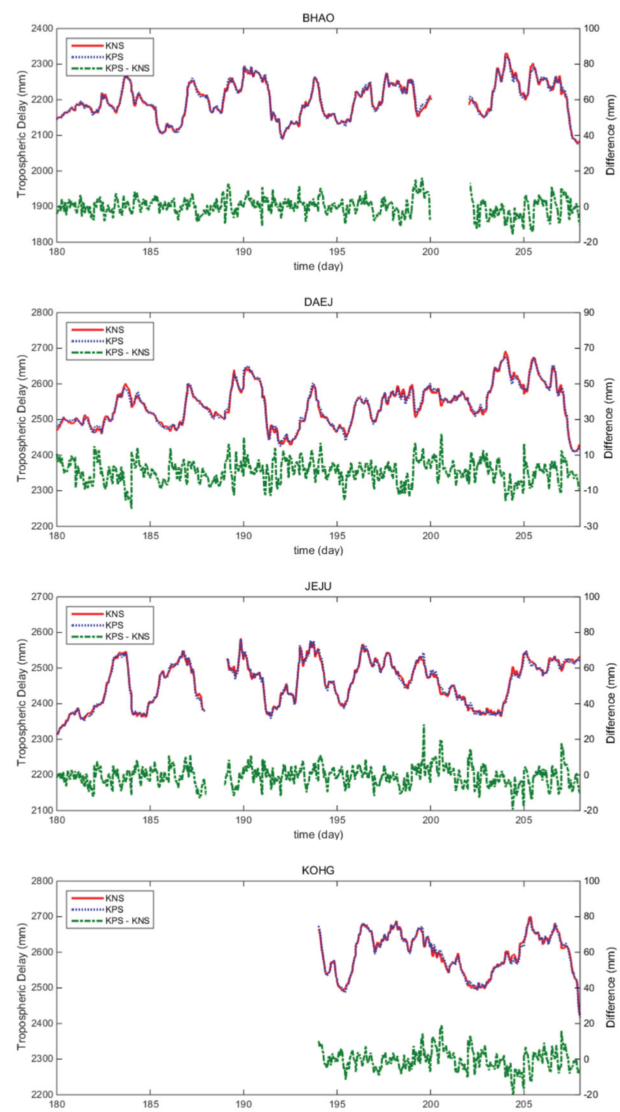

Fig. 10. ZTD estimates from KPS and KNS and the difference between the two ZTDs for BHAO, DAEJ, JEJU, and KOHG during the time period of four weeks.

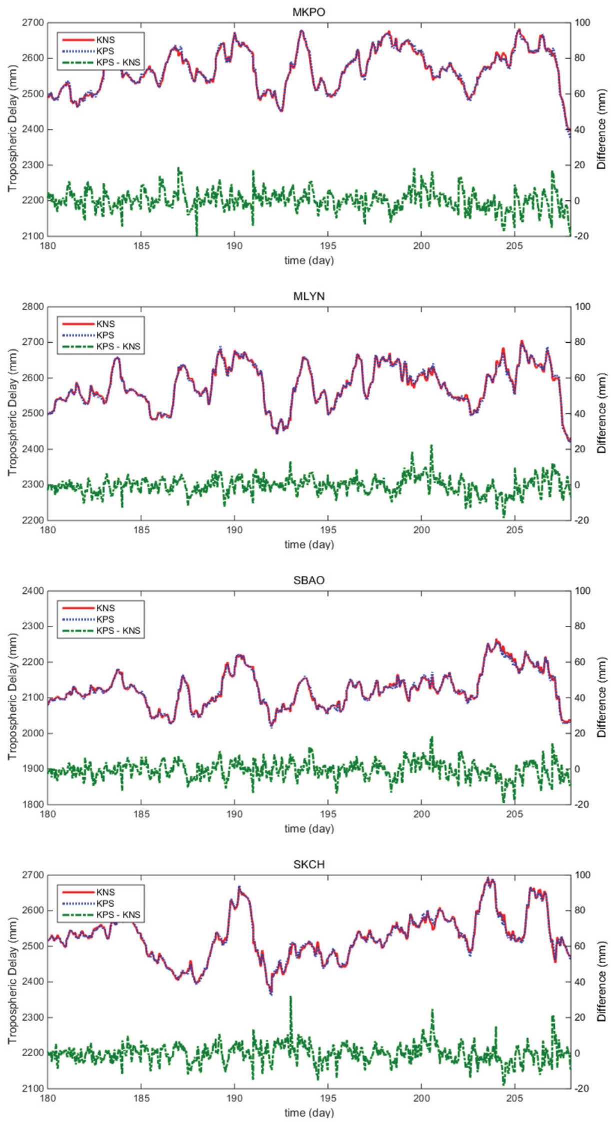

Fig. 11. ZTD estimates from KPS and KNS and the difference between the two ZTDs for MKPO, MLYN, SBAO, and SKCH during the time period of four weeks.

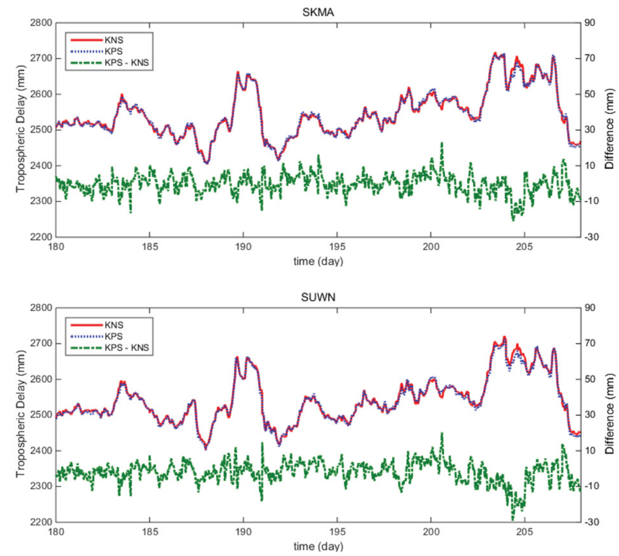

Fig. 12. ZTD estimates from KPS and KNS and the difference between the two ZTDs for SKMA and SUWN during the time period of four weeks.

6. CONCLUSIONS

The troposphere ZTD estimates from the KPS were compared with those from the KNS and IFTP using a regional GNSS network in the Korean Peninsula during the same time period (2014-06-29 - 2014-07-26). At first, when the ZTD estimates of the KNS were compared to those of the IFTP, the overall pattern was almost the same, and the mean difference was -1.46 ± 6.76 mm with an average RMS of 7.14 mm in ZTD. In this study, although the IFTP was used for the reference, it cannot be determined which one is more accurate without a proper quality assessment. Therefore, the formal error for the solutions and the coordinate repeatability were analyzed in both KNS and IFTP. As a result, the quality of the KNS is slightly higher than that of the IFTP. In the second step, the KPS were compared to the KNS, where the KNS was used as a new reference instead of the IFTP. The KPS corresponded well with the KNS for all ten GNSS stations. The overall mean difference was -0.38 ± 5.37 mm, with an average RMS of 5.38 mm in ZTD. The average RMS can be approximately converted into an error of GNSS-PWV by considering the typical ratio of zenith wet delay and PWV. In the current study, the ratio was assumed as 6.5. Therefore, the GNSS-PWV error was approximately 0.83 mm. Even though other systematic errors were considered, this value is small enough to meet the accuracy requirement in GNSS-PWV, as shown in Table 1. In conclusion, the PPP strategy has been validated as a new data processing strategy, and it can replace the previous DD strategy in the near real-time GNSS-PWV information management system.

Table 6. Difference between the ZTD estimates in the KPS and KNS.

	Total	BHAO	DAEJ	JEJU	KOHG	MKPO	MLYN	SBAO	SKCH	SKMA	SUWN
Mean	-0.38	0.00	0.70	-0.67	-0.42	0.17	-0.44	-0.55	-0.18	-0.32	-2.04
Std.	5.37	4.64	6.12	5.36	5.55	5.46	4.65	4.70	5.17	5.51	5.89
RMS	5.38	4.64	6.16	5.40	5.57	5.46	4.67	4.73	5.17	5.52	6.23

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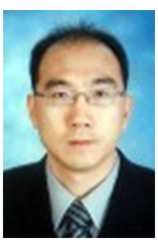

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