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Tropospheric Data of KASI GNSS Network (2001-2014) Based on the CODE's 2nd Reprocessing Product

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ABSTRACT

The trend of water vapor contents in atmosphere is one of key elements for studying climate change. The tropospheric products, i.e., ZTD values achieved through GPS data processing can retrieve the amount of water vapor with higher temporal and spatial resolution than any other instruments. In this study, the tropospheric products of KASINET for a time period from 2001 to 2014 are reprocessed using PPP strategy and the products from the CODE's 2nd reprocessing campaign. For consistency with reprocessing activities of other networks like EPN, the VMF1 mapping function and non-tidal loading effect due to atmospheric pressure are applied in the process. The reprocessing results are investigated through comparing with the CODE's 2nd reprocessing products by including some IGS stations in the process and also calculating weekly coordinate repeatability to see the quality of the processing. After removing outliers based on the variation of averaged formal error, all processed stations have similar variations of formal error about 2 mm which is lower than that of the IGS final product. Comparison results with the CODE's 2nd reprocessing products show that the overall mean difference is found to be -0.28±5.54 mm which is similar level of the previous studies. Finally, the ZTD trends of all KASINET stations are calculated and the averaged trend is achieved as 0.19 mm/yr. However, the trend of each month shows different amounts and directions from -1.26 mm/yr in May to 1.18 mm/yr in August. In conclusion, the reprocessed tropospheric product and applied strategy of this study has enough quality as one of reliable solution for a reference product for Korean Peninsula which is needed to use GPS-based tropospheric product for climate change research.

Keywords: GPS, tropospheric delay, IGS, reprocessing campaign

1. INTRODUCTION

The present usages of Global Positioning System (GPS) are becoming more essential part for of our daily life especially in applications like positioning and navigation. Apart from its' practical usages, GPS are widely used as observation tools not only for geodesy but also for atmospheric researches like meteorology and climate change. For enhancing these scientific applications, the International GPS Service (IGS) was established in 1994 and have provided the highest-quality GPS data, products and services including satellite ephemerides, Earth rotation parameters, clock information, tropospheric zenith total delay (ZTD) and global ionospheric maps. These products enable access to the definitive global reference frame for various applications. Now, the services are extended to cover all available global navigation satellite systems (GNSS) and renamed to International GNSS Service.

The ZTD parameters from GPS are especially attractive because the understanding of tropospheric water vapor is essential to researches like climate change and numerical weather prediction (Guerova et al. 2016). GPS data works as an effective remote sensor with higher temporal and spatial resolutions than traditional instrument like radiosonde. As GPS data has been accumulated more than 20 years, the application of GPS for climate monitoring becomes

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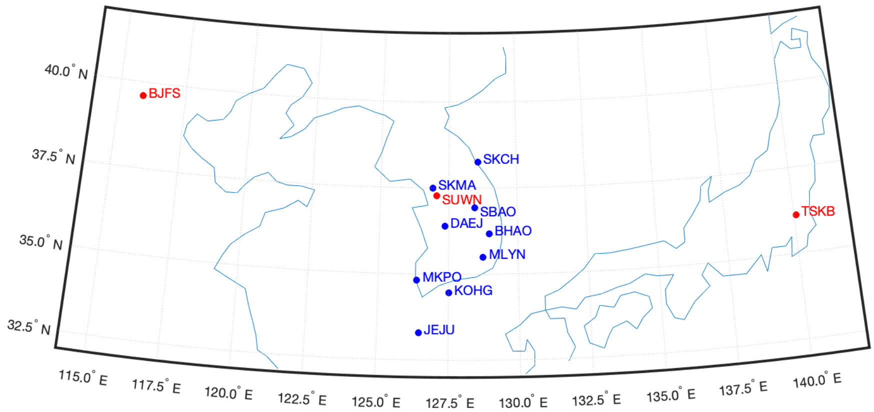

Fig. 1. Locations of KASINET (blue) and additional stations from IGS network (red).

an emerging field of research (Gradinarsky et al. 2002, Jin et al. 2008, Heise et al. 2009, Sohn & Cho 2010, Pacione et al. 2017). However, the time-series of GPS data are affected by inconsistencies caused by update of reference frame and processing strategies and therein models like updating mapping functions. Inhomogeneities are also caused by changing receiver or antenna even an update of receiver firmware. Therefore, for long-term analysis, it is important not only to calculate products using consistent processing strategies but also to define time histories of physical or environmental changes related to reference stations. Steigenberger et al. (2007) showed that the lack of inconsistencies in data processing can cause deviation of integrated water vapor up to several mm. For this reason, IGS launched a reprocessing campaign and now a third campaign is under process (Griffiths 2019).

The motivation of this article to provide GPS tropospheric data set for a network operated by Korea Astronomy and Space Science Institute (KASINET). Reprocessing ZTD product for regional or local networks is required, since this reprocessing campaign focuses on orbit and clock products of GNSS satellite and reference stations registered in the IGS network. The reprocessed tropospheric products for the EUREF Permanent Network (EPN) are the representative example (Pacione et al. 2017, Dousa et al. 2017). The EUREF is a reference frame maintained by International Association of Geodesy Reference Frame Sub-Commission for Europe (http://www.euref.eu). In this study, the ZTD products for KASINET are calculated using the orbit and clock information provided by the 2nd reprocessing campaign and applying the strategies recommended by the 2nd reprocessing campaign of IGS.

The KASINET is one of the oldest GNSS network in the Korean peninsula and now consists of 9 stations. Sohn & Cho (2010) conducted a trend analysis for the KASINET data from 2000 to 2009 and showed that the GPS-based water vapor can be a effective tool for climate research. However, the solutions were achieved using the original IGS products. In this study, the time span is expended to 2014 according to the 2nd reprocessing campaign strategy of IGS. Additionally, from this reprocessing for the KASINET, it is possible to find inconsistency in data set of KASINET due to various physical or environmental reasons. The processing strategy used in this work is described in Sec. 2 including introduction of KASINET and the reprocessing results are presented in Sec. 3. Lastly, the summary and future work are drawn in Sec. 4.

2. REPROCESSING STRATEGY FOR KASINET

2.1 KASINET

The first site of the KASINET is DAEJ installed in 1995. DAEJ is also one the first the IGS station in the Korean Peninsula. Currently, the KASINET consists of 9 stations and most of them have started operation from end of 2000 except KOHG site which was installed 2008. Fig. 1 shows the locations of the KASINET and its' four-character code along with 3 IGS stations. Namely, BJFS, SUWN and TSKB are belong to the IGS reference station and they are processed for comparison purpose with the products from the Analysis Center of IGS. The most distinguished feature of the KASINET is that all stations are installed on bed rock and its' own pillar above 1~2 meters from the ground as can be seen Fig. 2 for some of the KASINET station.

There are some additional advantages of KASINET for long-term analysis. KASINET uses one receiver and antenna vendor, i.e., Trimble and changes receiver model only two or three times. Since the antennas are installed independently

Fig. 2. Pictures of the KASINET stations.

Table 1. Processing options and models.

Item	Method (or Model)
Software	Bernese 5.2
Interval	300 sec
Timespan (YYYY-DOY)	2001-001 ~ 2014-365
Mapping function	VMF1 (Boehm et al. 2006, Kouba 2008)
Atmospheric pressure loading	APL
Ocean tidal model	FES2004
Orbit & clock products	CODE's 2^{nd} repro (CO2)
Elevation cutoff	5
Reference frame	IGb08
ZTD interval	Every 2 hour

from pre-existing buildings, the effects from environmental changes are minimized. However, there can be effects caused by receiver change or firmware update, therefore these effects need to be identified using consistent processing strategies throughout the full data span.

2.2 Reprocessing of KASINET using Repro-2 Campaign Results

There are two distinctive methods to process GPS data including the ZTD parameters in the Analysis Centers of IGS. In here, the precise point positioning (PPP) method is chosen for the KASINET's 2nd processing campaign (KP2) since it has several advantages over the other strategy which use double differenced observations and often called network solution. The PPP technique processes original data without differencing, and it make the solutions to be estimated independently without correlation with parameters of other stations. The PPP method is highly dependent on external precise clock products unlike the network solution which can remove clock errors by differencing observations. However, the reprocessed clock information as well as orbit products are available in case of this reprocessing work for long-term data. And the KASINET's PPP-based ZTD values (KPS) were already investigated comparing solutions achieved through two methods and showed that the quality of ZTD values obtained through both strategies is comparable (Park et al. 2014). The processing is conducted using Bernese software with options and models used in most of the 2nd reprocessing campaigns (Dach et al. 2015). The detailed list of options and models are tabulated in Table 1. Since the repro2 products, i.e., orbit and clock solutions are provided with respect to IGb08 reference frame, data processing in this study is conducted in IGb08 frame. The most important updates in the 2nd reprocessing campaign related to tropospheric product are the mapping function from GMF to VMF1 and inclusion of atmospheric pressure loading model. These updates are recommended guideline of the repro2 campaign of IGS and also these updates showed the improved vertical repeatability in the previous studies (Pacione et al. 2017, Dousa et al. 2017).

The 2^{nd} reprocessing campaign by IGS used GPS observation data from 1994 to 2014, therefore reprocessing work in this study covered total 14 years of GPS data from 2001 to 2014. Though KASINET started to make observation from 1995, most of stations became on stable status from 2001. Since this study aims to investigate long-term trends, the starting epoch is chosen to 2001 to avoid unstable data. The site, KOHG was added in data processing from when the site was installed 24 Jun. 2008. Finally, reprocessing this study was conducted on a workstation with Intel Xeon Silver 4110 CPU (2.1 GHz, 8 Core) and 160 GB memory. Average processing time for 12 sites per one day is less than 2 minutes.

3. ANALYSIS OF RESULTS

3.1 Filtering Outliers

The reprocessing results are compared with the CODE's 2nd repro products, named CO2 hereafter, to validate the quality of the tropospheric products achieved in this study. It also aims to investigate the differences between the PPP method of this study and the network solutions of the CODE. Before comparison, the estimated ZTD values are filtered by eliminating possible outliers. There can be several ways to define outliers. The filtering method chosen in this study is to exclude epochs with higher standard deviation than a specified value calculated as follows:

$$Threshold = 3 \times \sigma(\sigma_{ZTD}) \quad (1)$$

where, σ_{ZTD} is the formal error calculated for each time epoch by the process of PPP. This value is only dependent on the amount of carrier phase measurements and the constellation of the satellites for a given site (Byun & Bar-Sever 2009) and listed in the TRO file with the estimated ZTD. Since the values, $\sigma(\sigma_{ZTD})$ has wide range as shown in Table 2, the

Table 2. Average coordinate repeatability of KASINET for 2014.

Station	Mean(σ_{ZTD}) mm	$\sigma(\sigma_{ZTD})$ mm	# of processed epoch	# of excluded epoch	Ratio of processed epoch (%)
DAEJ	1.8	4.6	112,134	7	99.994
SUWN	1.8	0.9	108,618	3	99.997
BJFS	1.5	11.0	107,179	18	99.983
TSKB	4.3	92.0	114,838	340	99.705
BHAO	2.0	22.7	92,773	30	99.968
MKPO	2.1	5.1	111,273	97	99.913
MLYN	10.9	142.2	96,799	2172	97.797
SBAO	1.8	0.7	103,278	3	99.997
SKMA	3.4	55.1	100,923	392	99.610
KOHG	1.5	13.3	51,161	4	99.992
SKCH	1.8	0.7	111,854	1	99.999
JEJU	1.9	13.9	112,462	2	99.998

site having median value among KASINET, i.e., KOHG is selected. The resultant 'Threshold' value is set to 39.9 mm. Through this filtering, the epochs with abnormally high standard deviation were eliminated from the comparison and the distributions of σ_{ZTD} of the processed sites become similar. Among the KASINET, MLYN has more than 2,000 epochs excluded through filtering process. However, the number of excluded epochs does not mean that the quality of observations is good or not. The number of the processed epochs also does not guarantee the quality when poor

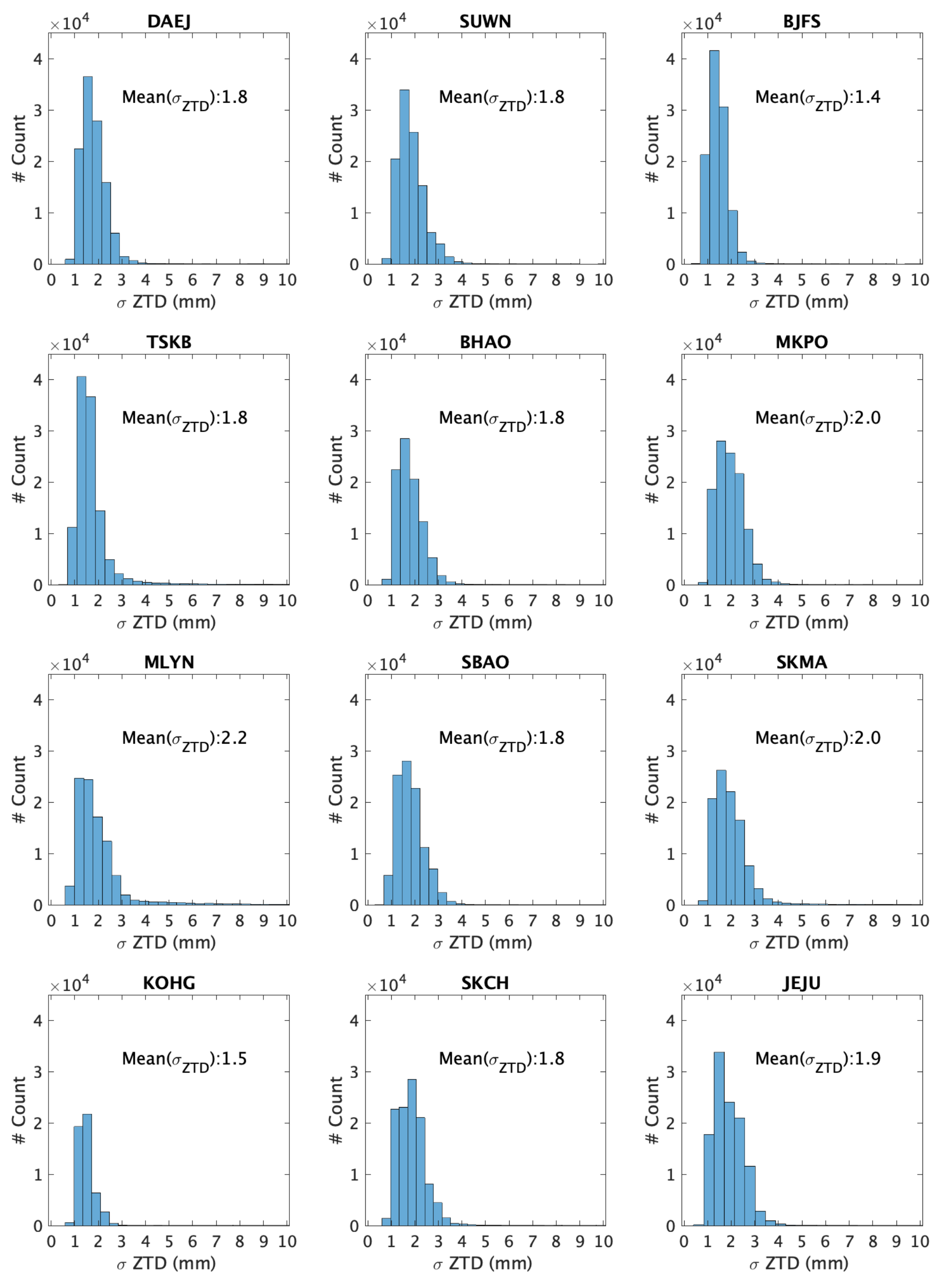

Fig. 3. Histogram of formal error distribution.

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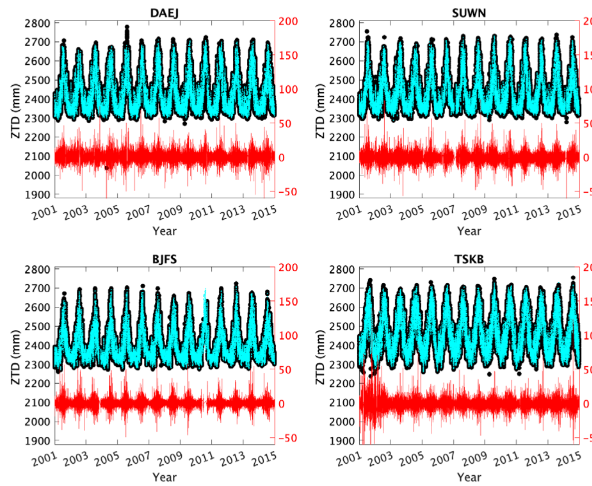

Fig. 4. Tropospheric ZTD from KPS and CO2 and their differences.

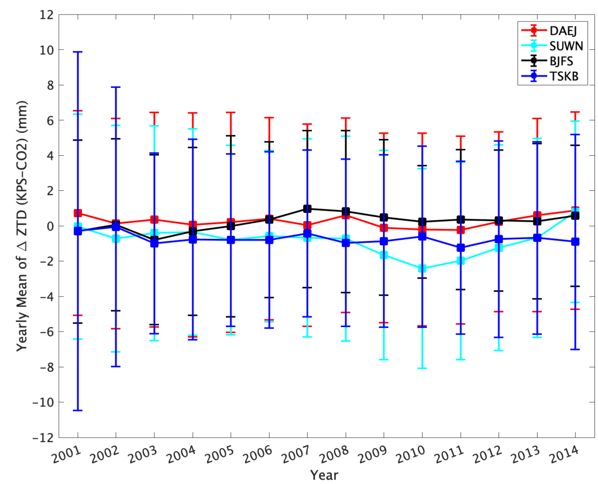

Fig. 5. Yearly mean and its' error for ZTD of KPS and CO2.

observations are not removed properly. At this moment, the variation of formal error, i.e., $\sigma(\sigma_{ZTD})$ can be an indicator to guess quality of a station. Fig. 3 shows the distribution of σ_{ZTD} for all processed stations after the filtering process and the mean of σ_{ZTD} has similar values around 2.0 mm. One thing should be noted that these formal errors improved from 2.62 mm (2001–2007) to 1.49 mm (2008–2014) after updating receiver to Trimble NetRS from Trimble 4000SSI. These receiver updates were conducted during the period from 28 Feb. to 24 Mar. 2008. These features indicate that logging and managing site history is very important to understand and analysis process results. The analysis results in the following section are all based on this filtered data.

3.2 Comparison with the CODE's Products

Verification of the tropospheric products in this work, i.e., KP2 is conducted by direct comparison with the ZTD values and their formal errors in the CODE's products (CO2). Total 4 IGS reference stations are compared including DAEJ which is also belong to KASINET. The ZTD values from KP2 (black dot) and CO2 (cyan dot) are plotted in Fig. 4 for the full timespan along with the differences (red line), ΔZTD ($=ZTD_{KP2}$-ZTD_{CO2}). The overall ZTD trends are quite similar and there are clear seasonal variations in the differences that need to be investigated in future work. The yearly mean of the difference along with its' error boundary (1-σ) are presented in Fig. 5. One thing should be noted in here is that the standard deviation in here is calculated by direct comparison between the two different solutions, while the σ_{ZTD} in Sec. 3.1 means error level of the ZTD value itself, namely, formal error. The average differences for 4 stations and 14 years is -0.28±5.54 mm. This value is comparable with the value in the previous study by Park et al. (2014), i.e., -0.38±5.38 mm which was calculated by comparing two solutions achieved through the PPP and network methods for one week of the KASINET data.

Table 3. Average coordinate repeatability of KASINET for 2014.

Site	North RMS (mm)	East RMS (mm)	Up RMS (mm)
BHAO	1.46	2.34	3.92
DAEJ	1.53	2.63	4.56
JEJU	1.5	2.67	5.43
KOHG	1.59	3.02	4.48
MKPO	1.44	3.24	4.13
MLYN	1.46	2.94	4.05
SHAO	1.23	2.09	3.78
SKCH	1.7	3.25	5.04
SKMA	1.42	2.87	4.22

The formal errors for all the KASINET have less than 2 mm. Standard deviation between KP2 and CO2 has ranges from 4 to 10 mm. Pacione et al. (2017) showed that the agreement in ZTD at the level of 8 – 9 mm in the work for the EPN's repro2 product. Considering the level of the formal error in Fig. 3 and the comparison results with the CODE's 2nd reprocessing products, the 2nd reprocessing results for the KASINET in here can be concluded to have reasonable accuracy for long-term trend analysis.

3.3 Repeatability

Repeatability of the coordinates estimated by the data processing can be used for checking the quality of the ZTD products. Generally, 9 mm of repeatability in the up direction are required to retrieving integrated water vapor at an accuracy level of 0.5 kg/m^2 (Bevis et al. 1994, Ning et al. 2016). Table 3 summarizes the average weekly repeatability of the KASINET stations for 2014 and their time histories are drawn

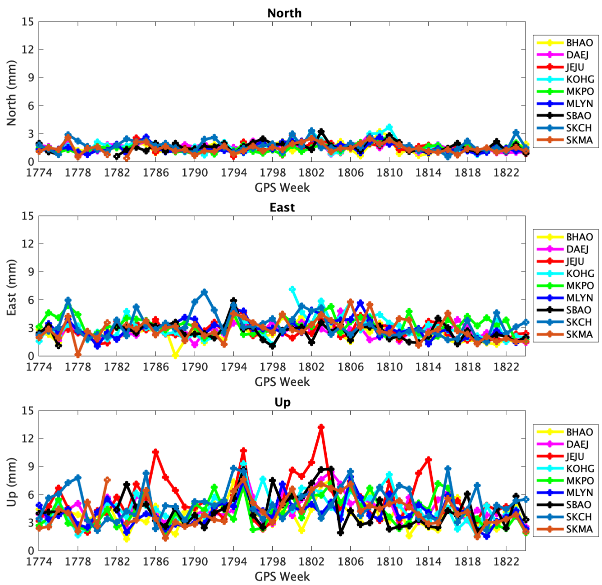

Fig. 6. Weekly coordinate repeatability for 2014.

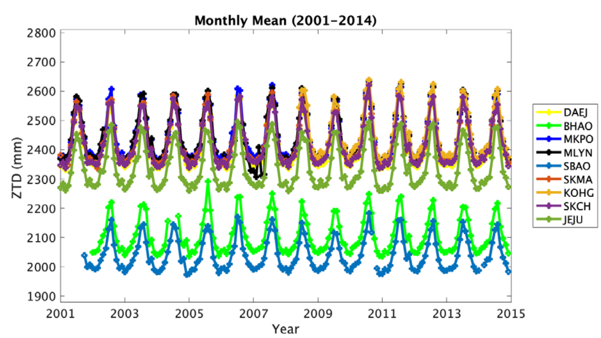

Fig. 7. Time series of ZTD monthly mean (2001-2014).

in Fig. 6. The results show the up components do not exceed this 9 mm threshold. However, there are several times of exceeding this 9 mm threshold at JEJU station as can be seen in Fig. 6. When this KP2 solution is used one of combination products for a reference tropospheric product of the Korean Peninsula, it will be needed to eliminate these outliers properly.

3.4 ZTD Trend of KASINET

To illustrate ZTD trend of KASINET, time-series of the ZTD monthly mean are plotted in Fig. 7. There are two distinct stations having lower ZTD value than the others, i.e., SBAO and BHAO because they are located about 1,300 m and 1,100 m above sea level, respectively. The ZTD values of MLYN (black line) around 2007 shows jump in the trend because MLYN had operational trouble due to electric problems at that periods. The analysis of ZTD trend for climate research is not aimed in this study because a long-term trend should

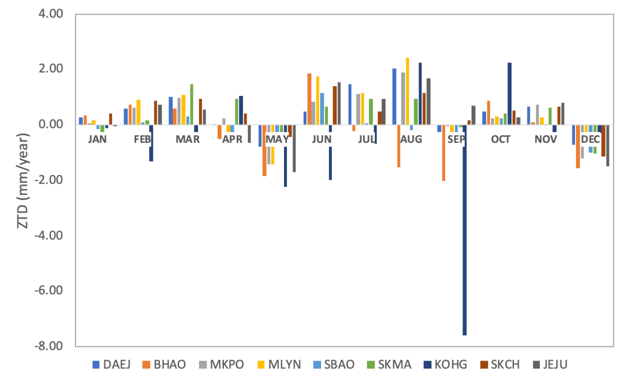

Fig. 8. Annual ZTD trend by month (2001-2014).

Table 4. Annual trend of the KASINET stations.

Site	Annual trend (mm/yr)
DAEJ	0.53
BHAO	0.76
MKPO	0.30
MLYN	1.34
SBAO	0.86
SKMA	-0.53
KOHG	-2.04
SKCH	0.33
JEJU	0.20
ALL	0.19

be defined using a reference solution achieved through combination a set of solutions from different strategies as well as evaluation with other measurement instruments. However, it is worth to see the trend of the solution since we can have an insight how to filter outliers when we make a combined reference product. In Table 4, the annual trend of the KASINET stations are summarized. They show quite large ranges from -2.04 mm/yr of KOHG to 1.34 mm/yr of MLYN. However, these two cases might be thought outlier because the data quality of MLYN is not in good (see the column (σ_{ZTD}) in Table 2) and KOHG have smallest data span (2008-2014). Average trend of all KASINET stations roughly agree with the value presented the previous study by Sohn & Cho (2010) for KASINET. More interesting feature of the trend calculated in this work is annual trends by month as drawn in Fig. 8. Namely, most of months show the increasing trend, while negative trends are clear in May, September, and December. Taking into account high correlation between PWV and temperature, this phenomenon also roughly agrees with typical trend of the Korean Peninsula's climate. For example, summer is getting longer, and temperature of December becomes lower (Kim et al. 2018). Based on these analyses, it can be concluded that this reprocessing result have enough quality for one of solutions needed for a reference product for the Korean Peninsula.

4. CONCLUSION

In this study, the reprocessed tropospheric products of KASINET are achieved through PPP strategy and using the GPS orbit and clock products from the CODE's 2nd reprocessing campaign. For keeping consistency with reprocessing activities of other networks like EPN, the VMF1 mapping function and non-tidal loading effect due to atmospheric pressure are applied in the process. This reprocessing is conducted for the GPS data from 9 of KASINET in the Korean Peninsula including 1 IGS reference station (DAEJ) and 3 additional stations from IGS network for comparison purpose. The time span covers from 2001 to 2014.

The reprocessing results are investigated through various ways. We compare the ZTD values with the CODE's 2nd reprocessing products for the common stations and check repeatability to see the quality of the processing itself. We removed outliers with large formal errors, i.e., σ_{ZTD} and the specific value set to $3\times\sigma(\sigma_{ZTD})$ of KOHG which has median value. After filtering, every processed station has similar variation of σ_{ZTD} about 2 mm. Comparison results with the CODE's 2nd reprocessing products show that the overall mean difference is found to be -0.28±5.54 mm which is similar level of the previous studies. Coordinate repeatability for 9 KASINET stations during 2014 is also calculated as 1.48, 2.78, and 4.40 mm for north, east, and up component, respectively. Climate research based on GPS tropospheric products should be done with a reference product calculated through combination of several solutions with difference processing strategies. Taking into account this limitation, the averaged ZTD trend of the Korean Peninsula is achieved as 0.19 mm/yr. The largest negative trend is shown in May as -1.26 mm/yr, while August has the largest positive value, 1.18 mm/yr. In summary, the reprocessed tropospheric product and applied strategy of this study has enough quality as one of reliable solution for a reference product for the Korean Peninsula.

AUTHOR CONTRIBUTIONS

Methodology, K-M. Roh, and H-E. Park; software, K-M. Roh; formal analysis and investigation, K-M. Roh, H-E. Park and B-K. Choi; visualization, K-M. Roh and H-E. Park.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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