VALIDATION OF PRECIPITABLE WATER ESTIMATES DERIVED BY A COST-EFFECTIVE DUAL-FREQUENCY GNSS RECEIVER SYSTEM

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ABSTRACT: The Global Navigation Satellite System (GNSS) can also be used as an all-weather sensor of accumulated water vapor, or precipitable water, by taking advantage of the fact that the speed of microwave transmission used in GNSS slows down in the tropospheric atmosphere. The estimated precipitable water information is being operationally used in numerical weather forecasting at the Japan Meteorological Agency (JMA) to enhance the prediction accuracy of severe weather events. To further enhance the capability, more denser observing network is expected by increasing the number of GNSS station. Recently, low-cost dual-frequency receivers have been released, and a cost-effective system using such a low-cost receiver can accelerate the expansion of the fixed observation network. As a first step in our investigation to confirm the potential of cost-effective systems, we have conducted two experiments with cost-effective (ZED-F9P of u-blox and QZG12fQ of Komine Musen Denki Co., LTD) and geodetic-grade (PwrPak7 and GNSS-850, both from NovAtel Inc.) observing systems. One experiment was to separate the contribution in the Zenith Tropospheric Delay (ZTD) errors from the antenna and receiver. The other experiment was to obtain simultaneous long-term data of geodetic-grade and cost-effective systems covering wide range of ZTD. From two experiments, we found that there was a little difference in performance between two receivers, since time variations of the ZTD error were almost the same when the satellites that ZED-F9P could not receive were excluded in the post-processing. We also found that the bias was larger when the QZG12fQ antenna was used. When this bias was removed, the cost-effective and geodesy-grade systems showed similar performance. Therefore, the possibility of reducing the ZTD error by applying relative antenna calibration needs to be further investigated. In addition, further experiment is necessary to actually confirm the agreement with precipitable water observation such as by radiosonde launches.

1. INTRODUCTION

In recent years, the Global Navigation Satellite System (GNSS) has become a part of people's lives. In general, GNSS is used to determine the position of a receiver, but it can also be used as an all-weather sensor of accumulated water vapor, or precipitable water, by taking advantage of the fact that the speed of microwave transmission used in GNSS slows down in the tropospheric atmosphere. In Japan, the Geospatial Information Authority of Japan (GSI) constructed and is operating the GNSS Earth Observation Network System (GEONET) that covers Japanese archipelago with over 1,300 stations at an average interval of about 20 km. Although the primary purposes of GEONET are crustal deformation monitoring and GNSS surveys, the data are also being used for estimating precipitable water. The estimated precipitable water information is being operationally used in numerical weather forecasting at the Japan Meteorological Agency (JMA) to enhance the prediction accuracy of severe weather events. To further enhance the capability, more denser observing network is expected by increasing the number of GNSS station. One of the bottlenecks in extending GNSS precipitable water measurements has been the high cost of geodetic-grade multi-frequency receivers. However, the recently introduced low-cost dual-frequency receivers are expected to solve this problem. The cost-effective system with such a low-cost receiver will accelerate the extension of the fixed observing network. Furthermore, the dynamic observing network with GNSS stations on mobile objects (e.g., enhanced car navigation equipment) is expected. In this study, we performed simultaneous measurements of GNSS signals with a cost-effective and a geodetic-grade system as an initial step to investigate the potential of the cost-effective system.

2. METHOD

2.1 Experimental setup

In this subsection, we describe the experimental setup including the receivers and antennas used in our experiments. In this study, we setup two GNSS receiving systems, cost-effective and geodetic-grade systems, on the rooftop of the department building in Tokiwa Campus, Yamaguchi University. The cost-effective system consists of ZED-F9P of u-blox (Figure 1a) and QZG12fQ of Komine Musen Denki Co., LTD. (Figure 1c). ZED-F9P is a recently released low-cost dual-frequency receiver. This receiver covers dual-frequency signals of GPS, GLONASS, Galileo, BeiDou, and QZSS, with missing GPS L2P/Y. QZG12fQ is a cost-effective dual-frequency antenna compatible with GPS, GLONASS, Galileo, BeiDou, and QZSS. The geodetic-grade system consists of PwrPak7 with dual-frequency option (Figure 1b) and GNSS-850 (Figure 1d), both from NovAtel Inc. PwrPak7 can receive most GNSS dual-frequency signals. GNSS-850 supports all GNSS constellations and frequencies except QZSS L6. The receivers were installed in a waterproof case nearby the antennas (Figure 1f). Data logging of ZED-F9P was performed using RTKRCV function of RTKLIB (Takasu, 2021) program package (version 2.4.3 b34) installed on Raspberry Pi 3. PwrPak7 has its own function to store log files on internal memory. The reception interval of the receiver was set to 30 seconds for both receivers. The data were transferred manually to another computer and further post-processed. As a standard reference, we also used the data from the nearby GEONET station (Station name: Ube, Station number: 950413), which is located about 2.5 km distance and 5 m height difference from the experiment station. The station uses a TOPCON NETG5 receiver and TRM59800.80 GSI, which can receive most GNSS signals.

In the current study, we conducted two experiments. One experiment was to separate the contribution in the Zenith Tropospheric Delay (ZTD) errors from the antenna and receiver (antenna/receiver comparison experiment). The output of the geodetic-grade antenna was divided by a signal splitter and was fed to both geodetic-grade and cost-effective receivers simultaneously. After that, we replaced the antenna with cost-effective one and iterated the same measurement. In this experiment, the antenna was always powered by geodetic-grade receiver. The observation period of this experiment is shown in Table 1. The other experiment was to obtain simultaneous long-term data of geodetic-grade and cost-effective systems covering wide range of ZTD. Two antennas were powered by the respective receivers. Table 2 shows the observation periods of this experiment. In both experiments, the center positions of two antennas were separated by about 400 mm. By that distance both antennas were mutually in the far-field areas.

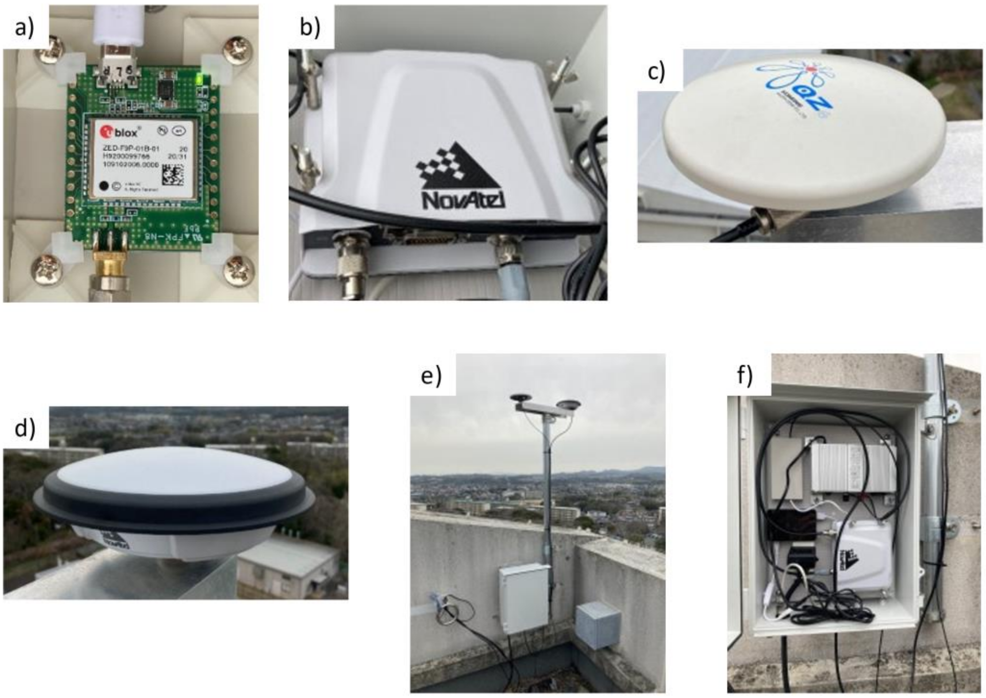


Figure 1. Experiment setup. (a) ZED-F9P, (b) PwrPak7, (c) QZG12fQ, (d) GNSS-850, (e) overall view of experiment setup, and (f) inside view of waterproof case.

Table 1. Observation period of antenna/receiver comparison experiment.

Start	End	Antenna
2021/07/01	2021/07/20	GNSS-850
2021/07/23	2021/08/05	QZG12fQ

Table 2. Observation period of long-term experiment.

Start	End	Receiver	Antenna
2021/02/18	2021/06/06	PwrPak7	GNSS-850
		ZED-F9P	QZG12fQ

2.2 Post-processing and ZTD evaluation

In this subsection we describe the procedures of post-processing and ZTD evaluation. The RNX2RTKP function of RTKLIB was used to estimate the ZTD values. We only used GPS data in this study and processed by the precise point positioning (PPP) mode. For the phase center variation (PCV) correction, we used ANTEX file (igs14.atx) provided by the National Geodetic Survey (NGS) for our receiving stations, Ube station and satellites. The precise orbit and clock solutions were provided by the International GNSS Service (IGS). We used 2-days data for one processing cycle and used only the result of second day to stabilize the ZTD solution in the Kalman filter processing. The configuration of RTKLIB setting is summarized in Table 3.

Table 3. Settings of RTKLIB post-processing

Positioning method	PPP-static
Observations	GPS-only
Elevation cutoff	10 degrees
Clock & orbits	IGS Rapid
Analysis interval	30 seconds
Antenna PCV correction	Receivers & Satellites

3. RESULTS AND DISCUSSION

3.1 Antenna/receiver comparison experiment

Figure 2 shows the time series variation of the estimated ZTD from ZED-F9P receiver and the GEONET station in the antenna comparison experiments. Since the variability of ZTD differs for two periods, rigorous comparison of values between two antennas may be somewhat difficult.

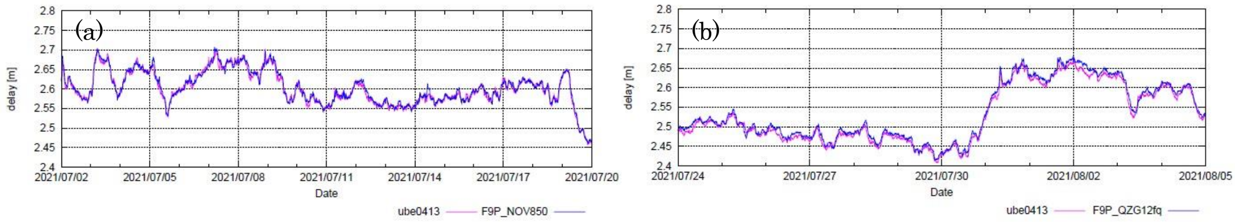
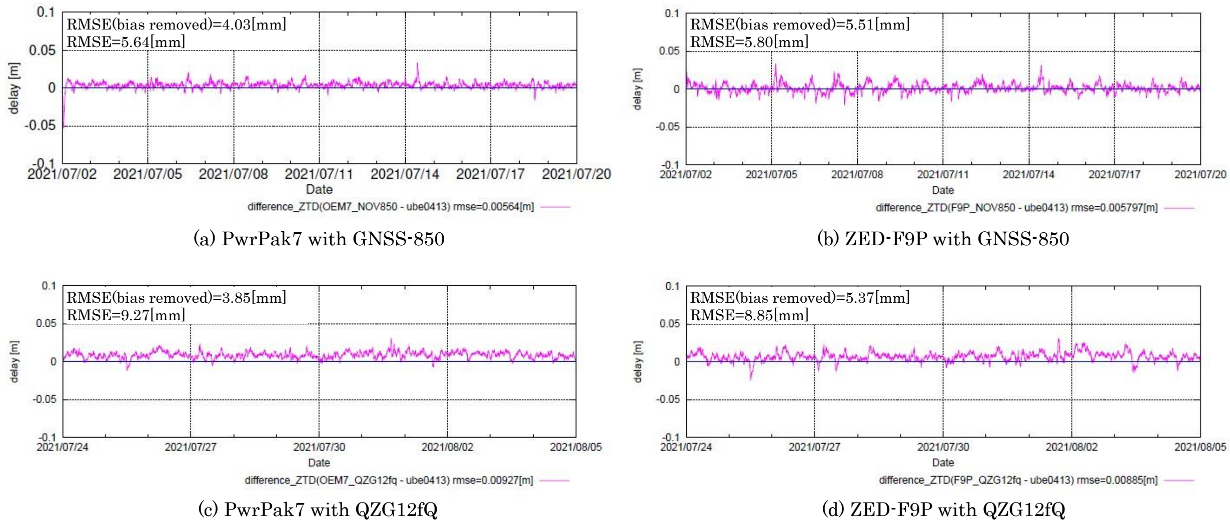


Figure 2. Time series variation of estimated ZTD from ZED-F9P and GEONET UBE station during antenna/receiver comparison experiment. Antennas used were (a) GNSS-850 and (b) QZG12fQ.

Figure 3 shows the time series of ZTD differences between our measurements and the GEONET station during the antenna/receiver comparison experiment. For both antennas, ZTD values estimated from ZED-F9P receiver show larger variation. In case of using QZG12fG as an antenna, larger offsets can be seen in both receivers compared to that with GNSS-850. As explained in subsection 2.1, ZED-F9P is not able to receive the GPS L2P/Y signal. Due to this limitation, the number of available satellites for PPP is generally less in ZED-F9P observations. To keep identical conditions for the comparison, we excluded the Block IIR satellites which do not send the L2C signal. Figure 4 shows the same time series as in Figure 3 but with Block IIR satellites were excluded in the post-processing. In Figure 4, we can observe almost similar time variations between two receivers with identical conditions. Figure 5 shows scatter plots between observations by the GEONET station and our systems.

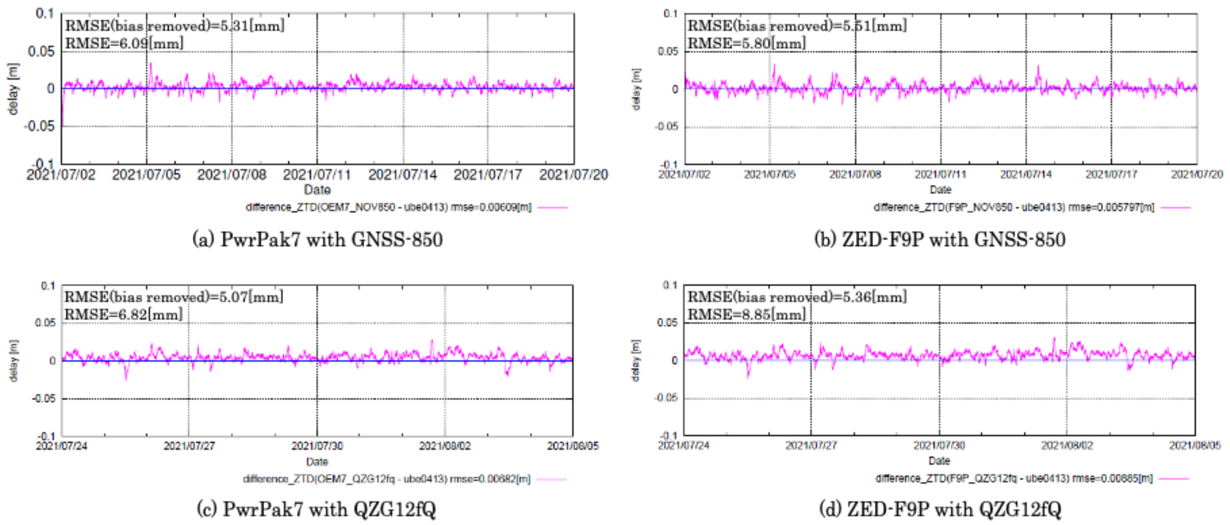
Table 4 summarizes the ZTD errors against the GEONET station. The root mean square error (RMSE) was computed for ZTD differences between our systems and the GEONET station. The bias and the RMSE (bias-removed) are also shown. We can see that the values of RMSE (bias-removed) are almost the same for all the antenna-receiver combinations. This indicates that the ZTD errors are almost identical in terms of time variation. However, there are some biases depending on the combinations, particularly significant with QZG12fQ antenna was used. Therefore, it is necessary to further investigate the possibility to reduce the ZTD error by applying the relative antenna calibration (e.g., Krietemeyer et al., 2020).



(a) PwrPak7 with GNSS-850 (b) ZED-F9P with GNSS-850

(c) PwrPak7 with QZG12fQ (d) ZED-F9P with QZG12fQ

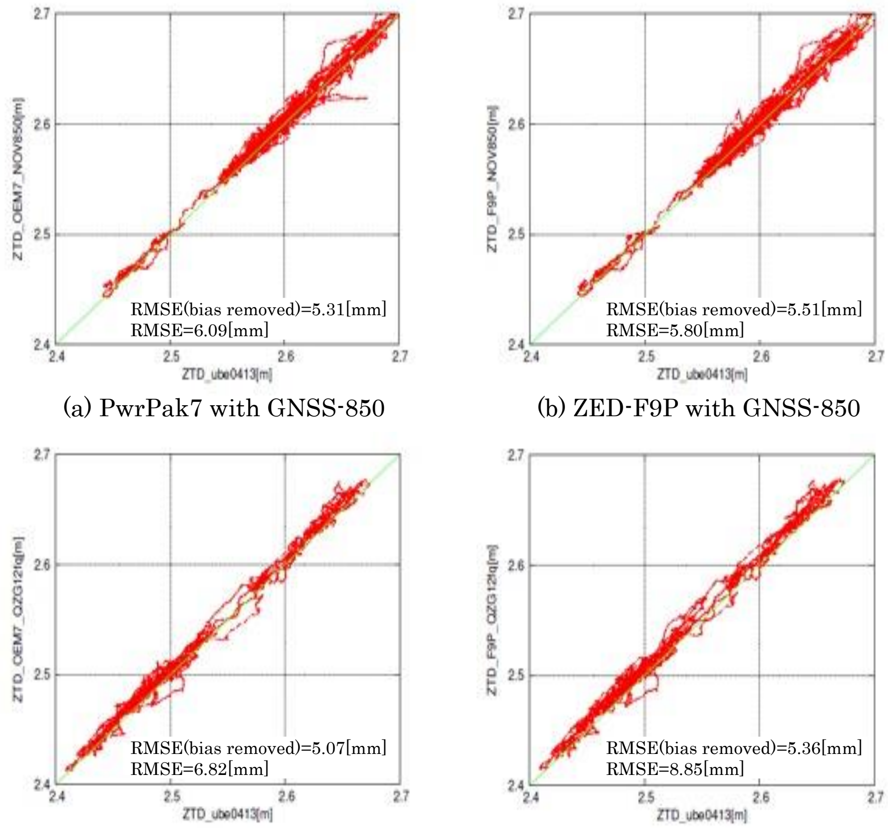
Figure 3. Time series of ZTD differences between our systems and GEONET station during antenna/receiver comparison experiment. Different combinations of antenna and receiver are shown from (a) to (d).



(a) PwrPak7 with GNSS-850 (b) ZED-F9P with GNSS-850

(c) PwrPak7 with QZG12fQ (d) ZED-F9P with QZG12fQ

Figure 4. Same as in Figure 3, but with Block IIR satellites were excluded.



(a) PwrPak7 with GNSS-850 (b) ZED-F9P with GNSS-850

(c) PwrPak7 with QZG12fQ (d) ZED-F9P with QZG12fQ

Figure 5. Scatter plots between observations by GEONET station (horizontal axis) and our systems (vertical axis) during antenna/receiver comparison experiment. Different combinations of antenna and receiver are shown from (a) to (d).

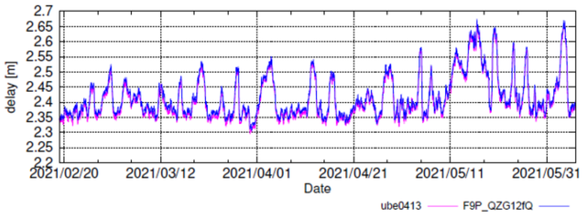
Table 4. Summary of ZTD errors against GEONET station during antenna/receiver comparison experiment.

Antenna	Receiver	RMSE [mm]	RMSE (bias-removed) [mm]	Bias [mm]
GNSS-850	PwrPak7	6.1	5.3	3.0
	ZED-F9P	5.8	5.5	1.8
QZG12fQ	PwrPak7	6.8	5.1	4.6
	ZED-F9P	8.9	5.4	7.1

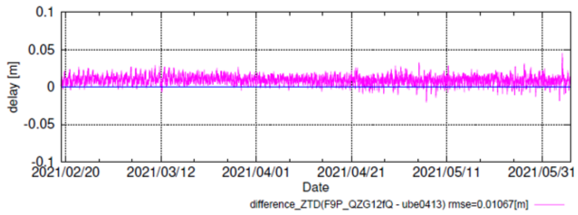
3.2 Long-term observation experiment

Figure 6 shows the time series of ZTD values and their differences during the long-term observation experiment. Although the observed period was over 3 months, the atmosphere had been in relatively dry condition during the period as indicated in Figure 6 (a). In Figure 6 (b) and (c), we can observe stable ZTD differences against GEONET without any significant dependency on ZTD values. In Figure 6 (d), we can confirm larger variations of ZTD difference with GPS block IIR satellites removed in the post-processing as seen in Figure 4. Figure 7 shows scatter plots between ZTD values by GEONET and geodetic-grade/cost-effective systems. Table 5 summarizes the ZTD errors against the GEONET station during the long-term observation experiment. From Table 5, we can see that the geodetic-grade system is more accurate in ZTD estimation than the cost-effective system. However, by considering the number of available GPS satellites, the difference is not so significant in terms of time variation. In other words, with the increase of new generation GPS satellites with L2C signal available, we can expect better performance of the cost-effective system. Also, utilizing the multi-GNSS capability may solve the issue even at the current condition. As discussed for the antenna/receiver comparison experiment, ZTD offsets are the issue to solve particularly significant for cost-effective system.

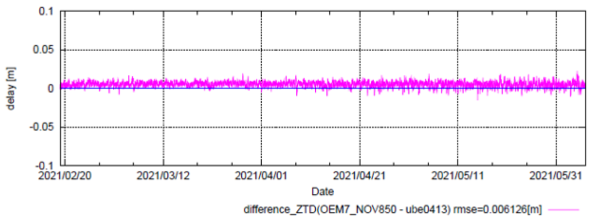
At the moment, we have only performed ZTD-basis comparison. Roughly speaking, ZTD variation of 10 mm corresponds to 1.5 mm of precipitable water changes. Therefore, bias-removed RMSE value of 4.8 mm by the cost-effective system roughly corresponds to precipitable water error of 0.7 mm. Considering that the typical RMSE value of geodetic-grade GNSS precipitable water observation against the radiosonde measurement is around 2 mm, additional 0.7 mm error is not so critical based on the propagation law of random errors. This means that the cost-effective systems can be used to fill the spatial gaps of precipitable water observations by geodetic-grade systems. Further experiment is necessary to actually confirm the agreement with precipitable water observation such as by radiosonde launches.



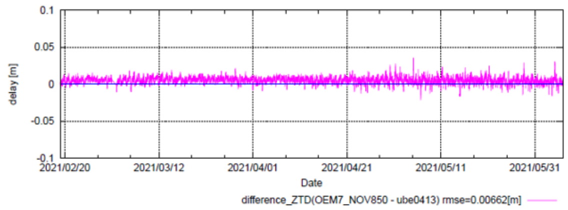
(a)Cost-effective system and GEONET



(b) Cost-effective system minus GEONET

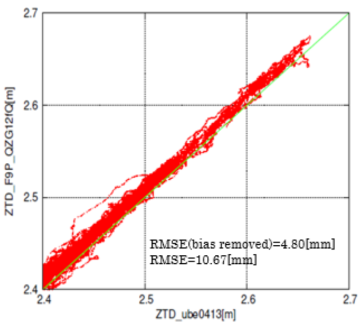


(c) Geodetic-grade system minus GEONET

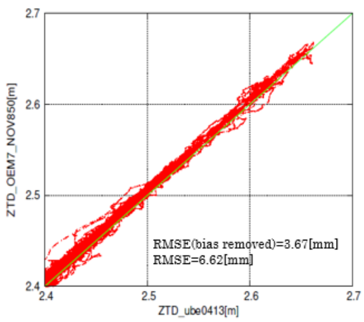


(d) Geodetic-grade system minus GEONET
(GPS block IIR removed)

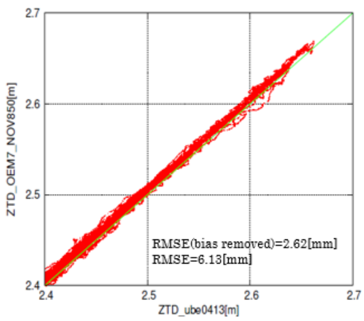
Figure 6. Time series of ZTD values and their differences. (a) ZTD values of cost-effective system and GEONET station, (b) ZTD difference between cost-effective system and GEONET station, (c) ZTD difference between geodetic-grade system and GEONET station, and (d) ZTD difference between geodetic-grade system and GEONET station (GPS block IIR removed).



(a)Cost-effective system and GEONET



(b) Geodetic-grade system and GEONET
(GPS block IIR removed)



(c) Geodetic-grade system and GEONET

Figure 7. Scatter plots between observations by GEONET station (horizontal axis) and our systems (vertical axis) during long-term observation experiment.

Table 5. Summary of ZTD errors against GEONET station during long-term observation experiment.

System	RMSE [mm]	RMSE (bias-removed) [mm]	Bias [mm]
Geodetic-grade	6.1	2.6	5.6
Geodetic-grade (GPS Block IIR removed)	6.6	3.7	5.6
Cost-effective	10.7	4.8	9.6

4. CONCLUSION

As a first step in our investigation to confirm the potential of cost-effective systems for precipitable water observation, we have conducted two experiments with cost-effective and geodetic-grade observing systems. One experiment was to separate the contribution in the ZTD errors from the antenna and receiver. The other experiment was to obtain simultaneous long-term data of geodetic-grade and cost-effective systems covering wide range of ZTD. In the antenna/receiver comparison experiment, we found that there was a little difference in performance between two receivers, since time variations of the ZTD error were almost the same when the satellites that ZED-F9P could not receive were excluded in the post-processing. We also found that the bias was larger when the QZG12fQ antenna was used. Therefore, the possibility of reducing the ZTD error by applying relative antenna calibration needs to be further investigated. In the long-term observation experiment, the geodetic-grade system was found to be more accurate in ZTD estimation than the cost-effective system. However, considering the number of available GPS satellites as in the antenna/receiver comparison experiment, the two systems have almost similar performance in terms of time variation. Therefore, with the increase of new generation GPS satellites with L2C signal available, we can expect better performance of the cost-effective system. Also, utilizing the multi-GNSS capability may solve the issue even at the current condition. In addition, as discussed for the antenna/receiver comparison experiment, ZTD offsets are the issue to solve particularly significant for cost-effective system. Assuming that ZTD variation of 10 mm corresponds to 1.5 mm of precipitable water changes, bias-removed RMSE value of 4.8 mm by the cost-effective system roughly corresponds to precipitable water error of 0.7 mm. Because this is not the critical number, the cost-effective systems can probably be used to fill the spatial gaps of precipitable water observations by geodetic-grade systems. Further experiment is necessary to actually confirm the agreement with precipitable water observation such as by radiosonde launches.

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