PWV Retrieval over the Ocean Using Shipborne GNSS Receivers with MADOCA Real-Time Orbits

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Abstract

We conducted observations using four shipborne global navigation satellite system (GNSS) receivers on three research vessels and one passenger ferry to assess the real-time practicality of measuring GNSS-derived precipitable water vapor (PWV) over the ocean. A kinematic precise point positioning strategy was used for the GNSS analysis with a real-time GNSS satellite ephemerides (orbit and clock information). The analyzed time series of PWV was contaminated with unrealistic sharp variations that occasionally occurred. Periodic occurrence of a spiky variation with a cycle of one sidereal day, along with post-fit phase residuals averaged at each elevation and azimuth, indicated that one of the causes of the unrealistically large time variation was interference of reflected signals (multi-path). A simple quality control (QC) procedure based on the amount of PWV time variation was proposed. After the QC was applied, the retrieved PWVs had 3.4−5.4 mm root mean square (RMS) differences against radiosonde observations, and 2.3−3.7 mm RMS against those retrieved at nearby ground GNSS stations. The proposed QC procedure rejected more than 60 percent of retrieved PWV on research vessels and 6−11 percent on a passenger ferry. The results demonstrate the great potential of the real-time ephemerides and the necessity for careful consideration of the observation environment.

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1. Introduction

Humid air approaching from over the ocean often causes hazardous torrential rainfall on the Japanese archipelago. Several studies have pointed out the significance of water vapor observations to the windward of torrential rainfall. Several studies have shown the great potential of PWV retrieval using shipborne GNSS receivers. Rocken et al. (2005) conducted two one-week experiments and achieved good agreement of PWVs between GPS and radiosonde with an RMS difference of less than 3 mm using two GPS antennas mounted near the front mast of a 138,000-ton ship. Fujita et al. (2008) compared more than 300 pairs of PWVs derived from GPS and radiosonde observed on the 8678-ton research vessel Mirai in the equatorial Indian Ocean and acquired an RMS of 2.27 mm and a mean difference of less than 1 mm at night. Since the middle of the 1990s, U.S. GPS had been the only GNSS available for civil use. Currently, multiple GNSSs (e.g., the Russian GLONASS and Japanese Quasi-Zenith Satellite System (QZSS)) can be used. Fujita et al. (2014) installed a multi-GNSS receiver on the 3991-ton research vessel Hakuko Maru and compared the PWV GPS with radiosonde observations in more than 100 profiles acquired along the east coast of Japan and the Pacific Ocean. Compared to using only GPS satellite, they acquired much better results by using GPS, GLONASS, and QZSS together for their PWV analysis.

These previous studies used final precise ephemerides, which are only available for post processing. In recent years, real-time GNSS application has been advancing at a remarkable pace. The International GNSS Service (IGS) officially started offering real-time orbit and clock corrections on 1 April 2013. The Japan Aerospace Exploration Agency (JAXA) has also developed a Multi-GNSS orbit and clock estimator called MADOCA (Multi-GNSS Advanced Demonstration tool for Orbit and Clock Analysis) (Takasu et al. 2013) and started providing real-time ephemerides via the Internet (https://ssl.tksj.jaxa.jp/madoca/public/public_index_en.html) in September 2015.

The purpose of this study is to assess the real-time availability of ocean platform GNSS PWV, especially in areas surrounding Japan. Observation and analysis procedures are described in Section 2. The results are introduced in Section 3. We discuss and summarize this study in Section 4.

2. Observation, data processing, and outlier detection

2.1 Observation

Table 1 summarizes the vessel sizes and weights, types of GNSS receivers, and observation durations, and displays the arrangement of the GNSS instruments on each vessel. The weights of three research vessels (Ryofu Maru, Keifu Maru, and Shinsei Maru) are less than half of those in the previous studies introduced in Section 1. The passenger ferry Hamayuu is the largest vessel in this study. On all four vessels, GNSS antennas were set up on the uppermost deck. For cost effectiveness, unlike the previous studies, we used relatively low-cost non-choke ring antennas. On research vessels, potential installation locations are restricted due to space limitations and to avoid affecting existing instruments. As seen in the pictures in Table 1, on research vessels, there were other observation and communication facilities near the GNSS antenna. Compared with these research vessels, the GNSS antenna on the Hamayuu was set on a spacious deck. The GNSS antennas

heavy rainfall event on July 28, 2008. Their result demonstrated the importance of water vapor observations to the windward of torrential rainfall.
The PPP method requires precise orbit and clock information. In this study, we tested with real-time and final products of MADOCA. JAXA conducts real-time PPP experiments using the L-band experiment (LEX) signal from Michibiki (QZS-1). To do this, JAXA has developed a Multi-GNSS orbit and clock estimator called MADOCA. The goal for MADOCA real-time orbit and clock accuracy is 6 cm, 0.1 ns for GPS and 9 cm, 0.25 ns for GLONASS and QZSS. As Shoji (2009) noted, satellite clock accuracy is crucial for precise water vapor estimation by GNSS. Given that the nominal GPS satellite clock accuracy of ultra-rapid orbit (predicted half) provided by the IGS is about 3ns in RMS (http://igs.org/products), the use of MADOCA real-time products is worth examining. In 2015, MADOCA provided orbit and clock information for GPS, GLONASS, and QZSS every second. The second cut-off angles were set to zero degrees.

We also used 30s-sampling GEONET observed data which were downloaded from GSI’s Ftp server for comparison.

2.2 Data processing

In this study, we processed GNSS analyses for shipborne observations, and for several GEONET stations located within 20km of each vessel (see Fig. 4) using RNX2RTKP, a command-line application for post-GNSS processing of RTKLIB ver. 2.4.2 (patch 11 applied) (Takasu 2013). RTKLIB is an open-source program package for standard and precise positioning with GNSS and consists of a portable program library and several application programs (APs).

We adopted the kinematic precise point positioning (PPP) method (Zumberge et al. 1997) for shipborne observations to analyze the coordinates and zenith total delays (ZTDs) every 1s and every 30s and applied the static PPP method for the GEONET stations and analyzed 1-day averaged coordinates and ZTDs every 30s. Here, the analysis intervals of ZTD for the GEONET stations were set to coincide with the observation sampling interval. Site displacement due to ocean tidal loading (OTL) was considered only for the GEONET stations. The following options were set for both shipborne and GEONET analyses: (1) the cut-off elevation angle was set to five-degrees, (2) the global mapping function (Boehm et al. 2006) was used, and (3) ZTD was regarded as a random-walk variable with process noise of 0.1 mm/s^1/2 (RTKLIB’s default value).

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Table 1. Weights and sizes of the vessels, types of GNSS antennas and receivers, and observation periods.

| Name (Abbreviation) | Ryofu Maru (JMAR) | Kefu Maru (JMAK) | Shinsei Maru (SSMR) | Hamayuu (HMYU) |
|---------------------|------------------|------------------|---------------------|----------------|
| Affiliation         | Japan Meteorological Agency | Univ. of Tokyo, JAMSTEC | Kampa Ferry Co. Ltd |
| Gross Tonnage (t)   | 1,380            | 1,483            | 1,629               | 16,187         |
| Length (m)          | 82.0             | 81.39            | 66.0                | 162.0          |
| Breadth (m)         | 13.0             | 13.4             | 13.0                | 23.6           |
| GNSS Antenna        | GrAnt-G3T (JAVAD) | Zephyr 2 (Trimble) |
| GNSS Receiver       | START-GS (GNSS Technologies Inc.) | NetR9 (Trimble) |
| Pressure, Temperature| Onboard meteorological sensor | Interpolation of surface met. obs. |
| Observation Period (Year 2015) | 1 Jan. – 15 Sep. 23 Oct. – 20 Dec. | 1 Jan. – 24 Aug. | 29 May – 30 Nov. | 20 Aug. - 15 Dec. |
| GNSS antennas (marked by the circles) | | | | |
| GNSS receivers | | | | |
| Note | Radio sonde observation |
estimation interval (i.e. 1 s or 30 s), PWVs of both GEONET and shipborne GNSS receivers were estimated every minute according to the sampling interval for temperature and pressure.

### 2.3 Outlier detection and rejection

Compared to post processing PWV retrieval using a fixed GEONET station, there are several additional error sources in real-time PWV retrieval using a shipborne GNSS receiver, such as larger error in real-time satellite ephemerides (orbit and clock), interference from reflected signals (multipath), and an increase in unknown parameters (antenna position). In this experiment, an unrealistically large time variation of PWV often occurred in retrieved PWV based on shipborne GNSS measurements. Fig. 1a presents the time series of the PWV retrieved at the Ryofu Maru and at nearby GEONET station 3023 (Chiba Ichikawa) (Fig. 4c) from May 29 to June 2. In this figure, we use JXF for 3023 and MDC2 for the Ryofu Maru. During that period, the Ryofu Maru was located at its homeport (Daiba, Minato-Ward, Tokyo). The PWV at the Ryofu Maru roughly agrees with that of 3023; however, short-term fluctuations (a sharp increase followed by a sharp decrease) are conspicuous. Figure 1b presents a time series of their differences overlapped according to the time of day. Large differences, exceeding 10 mm, occurred at approximately 0200 and 0700 UTC. In addition, differences of approximately −10 mm occurred after 0600 UTC. Multi-path, depending on the constellation of satellites, could periodically affect the PWV analysis at the Ryofu Maru. As Shoji et al. (2004) reported, the ZTD error caused by multi-path repeats with a cycle of one sidereal day, the repeating period of the GNSS satellite constellation. Iwabuchi et al. (2004) simulated the ZTD biases caused by multi-path effects and found that the variability in the ZTD biases increases when the time interval of the ZTD estimation is shorter, especially at sites with poor observation conditions. The periodic variations in the PWV difference at the Ryofu Maru against 3023 shows the typical characteristics of error caused by multi-path. In Fig. 1b, we also recognize non-periodic spiky time variations, for example around 0100 and 1200 UTC on 29 May, 0500 UTC on 31 May, and 2100 UTC on 2 June. These non-periodic rapid and large variations could be attributed to error in the satellite ephemerides and/or deterioration of the observation conditions due to tilt and/or rotation of the ship body caused by sea waves. At present we have no method to identify the cause of these non-periodic errors. No matter what the cause is, once such a big difference occurs, approximately one to two hours seems to be needed for the PWV to return to normal values.

In order to assess the possibility of multi-path related error on each vessel, we checked the observation conditions on each vessel by averaging one-way post-fit phase residuals over time at each azimuth and elevation angle of the GNSS satellite when these vessels were anchored at their homeports. The panels in Fig. 2 are sky maps of the averaged post-fit phase residuals. Sky maps of post-fit phase residuals have been used to assess and eliminate the error caused by reflected signals (multi-path) (e.g., Iwabuchi et al. 2004; Shoji et al. 2004). Large residuals are sporadically distributed in the sky maps of the three research vessels, indicating a large influence from reflected signals (multi-path). The Ryofu Maru’s sky map has the largest variability even at high elevation angles. Compared with these research vessels, the Hamayuu’s sky map has much smaller variations.

According to Ferrier et al. (1996), the budgets of the condensed water and water vapor associated with cumulus convection are given by the following equation:

\[
FV = SV + (C - E),
\]

where \(FV\) is the total horizontal flux convergence of water vapor, \(SV\) is the local change in PWV, \(C\) is the total condensation, and \(E\) is the evaporation. Because we are discussing short-term PWV variations, we ignore evaporation from the ground in this equation. Misumi and Murayama (2008) discussed precipitation efficiency and the effect of low-level convergence on convective precipitation using high-resolution numerical simulations. Their results suggest that under the strong mesoscale convergence during the Japanese Baiu season, \(SV\) relates to \(FV\) as follows:

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**Fig. 1.** (a) GNSS PWV retrieved from (red) the Ryofu Maru and (blue) GEONET station 3023 (Chiba Ichikawa) for the five days from 29 May to 2 June. (b) The retrieved GNSS PWV difference for the Ryofu Maru versus 3023 overlapped by time of day. The comparison was conducted with a 1-min interval.

**Fig. 2.** Sky plots of the time averaged post-fit phase residual of the L3 ionosphere free linear combination.
\[ SV = 0.25 FV - 0.24. \]  

(2)

If we assume that, in the Baidu season, 10^{-3} \, s^{-1} is a representative wind convergence, 15 \, kg^{-1} is the mixing ratio, and most of the water vapor convergence occurs below 700 hPa, then \( FV \) is

\[ FV \approx \frac{1}{g} \int_{p_{\text{sea}}}^{p_{\text{atm}}} \rho q \Delta V \, dp \approx 10^{-2} \cdot 1.5 \cdot 10^{-1} \cdot 10^{-3} \cdot 3 \cdot 10^4 \approx 45 \, \text{mm} \cdot \text{s}^{-1}. \]  

(3)

Therefore, \( SV \) becomes 0.435 mm per minute.

We calculated the frequency of the PWV variation during one minute for all four vessels and for ground GNSS station 3023 (see Supplement 1). More than 99.5% of the one-minute PWV variations were less than 1 mm for 3023 and the Hamayuu, and around 97% were less than 1 mm/min for other vessels. After seeing the results of Fig. 1, the above theoretical speculation, and the analysis of a frequency of one-minute GNSS PWV variations, as a simple quality control, we rejected the estimated PWV as erroneous if the estimated PWV value met one of the following conditions:

1) Any of the PWV time variations exceeded 1 mm min^{-1} within the previous one hour,
2) The PWV value was less than or equal to 0 mm, or
3) The PWV value was greater than or equal to 90 mm.

By adopting these quality control conditions, the data rejection rate (the number of rejected data divided by the total number of pairs) indicates the quality of the GNSS PWV. As shown in the comparison of PWV derived from ground GNSS stations against radiosonde observation in Supplement 2, rejection rates are ranged from 0.8~7.7% when JXF was used, while those became 6.8~15.0% when MDC2 was used. The comparison results clearly show excellent performance as erroneous if the estimated PWV value met one of the following conditions:

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3 Results

3.1 Comparison with radiosonde

The Ryofu Maru is equipped with a radiosonde launching facility and conducts upper-air observation (VAISALA RS92-SGP) over the ocean. Figure 3 compares results of GNSS PWV with radiosonde observation after the quality control described in Subsection 2.3 was applied. In general, it takes about half an hour for the radiosonde to travel up through the lower troposphere where most of the water vapor exists. Therefore, GNSS PWVs were time-averaged over 30 minutes beginning at each radiosonde launch time. The interval of the satellite clock information is 30 s in JXF and 1 s in MDC2. In order to distinguish the effect of the analysis sampling interval, we tested two analysis intervals for MDC2, 30 s and 1 s (hereafter referred to as MDC2 30 s and MDC2 01 s). There were 163 radiosonde observations. Therefore, the rejection rates of JXF 30 s, MDC2 30 s, and MDC2 01 s were 21%, 33%, and 52% respectively. Biases (averaged GNSS PWV minus averaged radiosonde PWV) ranged from −0.42~0.03 for the daytime comparison (0000 UTC) and −3.57~2.52 mm for the nighttime comparison (1200 UTC). RMS ranged from 3.39~4.28 in the daytime and 4.23~5.40 mm in the nighttime.

3.2 Comparison with nearby ground GNSS stations

The estimated PWVs when the vessels were sailing were compared with the retrieved PWVs at several GEONET stations located within 20 km of each vessel. Figure 4 indicates the trajectory of the vessels and the GEONET stations used for the comparison. The altitude difference of shipborne GNSS antennas against compared GEPNET stations ranged from −21 to 8 m. The locations of manned and unmanned meteorological stations are plotted in Fig. 4e. As indicated in Fig. 4, except for GEONET station 0456 (Kamitsushima), all of the GEONET stations used for comparison were located near the ports of call of the vessels. The Hamayuu sailed off the coast of 0456 at a velocity of approximately 30 km h^{-1}. This speed was the fastest for all the pairs of vessels and GEONET stations.

Table 2 summarizes the results of the comparison. The Hamayuu had the smallest rejection rates at 0.5% (JXF 30 s), 5.7% (MDC2 30 s), and 10.8% (MDC2 01 s) while the Ryofu Maru had the largest and second largest at 16.4% (JXF 30 s), 26.1% (MDC2 30 s), and MDC2 01 s have the smallest rejection rates at 0.5% (JXF 30 s), 5.7% (MDC2 30 s), and 10.8% (MDC2 01 s) respectively. Biases (averaged GNSS PWV minus averaged radiosonde PWV) ranged from −0.42~0.03 for the daytime comparison (0000 UTC) and −3.57~2.52 mm for the nighttime comparison (1200 UTC). RMS ranged from 3.39~4.28 in the daytime and 4.23~5.40 mm in the nighttime. A 3 mm difference in the day and night biases was also recognized in previous research (Fujita et al. 2008). However, Fujita et al. (2008) measured 0.2~0.27 biases at night and 2.45~3.13 biases in the daytime. Compared to their results, our result implies negative biases in GNSS PWV. These negative biases are also seen in PWVs derived from two other research vessels when compared with those retrieved at nearby GEONET stations (see Subsection 3.2 and Table 2). The larger rejection rate of MDC2 30 s than JXF 30 s can be attributed to the larger error in MDC2. The largest rejection rate, for MDC2 01 s, might reflect a higher possibility of encountering the multi-path effect. As seen in Fig. 1, once an unrealistically large time variation of PWV occurs, it takes 1~2 hours to return to normal. Taking data every 1 s may raise the potential for a multi-path interference signal.

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Fig. 4. Trajectories of the vessels (green Ryofu Maru, blue Keifu Maru, orange Shinsei Maru, red Hamayuu) used in this study. The triangles with the four-character IDs show the positions of the ground GNSS stations used to evaluate the shipborne GNSS-derived PWV. Note that 3023 and 3077 are used for both the Ryofu Maru and the Keifu Maru. In Fig. 4e, green notations indicate the locations of AMeDAS unmanned meteorological stations (four elements); the black open squares are the locations of manned stations. In this study, we interpolated temperature observations at AMeDAS stations and pressure observations at manned stations to estimate temperature and pressure at the GNSS antenna in the HAMAYUU and GEONET stations. Purple stars represent the locations of wave gauges. The time sequence of significant wave height observed at the wave gauges is plotted in Fig. 5 and Supplement 3.

Table 2. Statistical comparison of shipborne GNSS-derived PWV against data analyzed at nearby GEONET stations. In the scatter diagrams, the colored (not gray) dots were used for calculating BIAS and RMS, while the gray dots were rejected through the quality control procedure described in Subsection 2.3.
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The tendency in which the rejection rate is two or three times larger in MDC2 01 s than in MDC2 30 s is consistent with the comparison of the GNSS PWV with radiosonde PWV obtained on the Ryofu Maru (Fig. 3). Negative biases are conspicuous in the three research/observation vessels while only the Hamayuu resulted in positive biases. The Hamayuu also has the smallest RMS values at 1.82 mm (JXF 30 s), 3.25 mm (MDC2 30 s), and 2.27 mm (MDC2 01 s). Multi-path might cause not only unrealistic sharp variations in PWV but also a negative tendency in the PWV biases.

Figure 5 presents the PWV time series analyzed at ground GNSS station 0079 (Shimonoseki) (see Fig. 4e) and that analyzed when the Hamayuu sailed within 20 km of the GEONET station. The shipborne GNSS PWV expressed both seasonal and short-term variations of PWV associated with precipitation well. In Fig. 5, the time series of significant wave height (SWH) observed on a nearby wave gauge of the Japan Coast Guard (JCG) is also plotted with an orange line. During this observation campaign, SWH varies over the range of 0–3 m. The relation between the PWV error and wave height is unclear. For example, the data rejection rate was relatively high near station 0079 from 13 September to 11 October. SWHs of less than 2 m were observed during that period. Relatively frequent outlier occurrence during that period might reflect the accuracy of MDC2. The time series of PWV, precipitation, and SWH near Tsushima are given in Supplement 3.

4. Summary and conclusions

Several previous studies discussed the performance of PWV retrieval using ocean platform GNSS observations with precise ephemerides (e.g., Rocken et al. 2005; Fujita et al. 2008; Fujita et al. 2014). Our results show the potential of MADOCA real-time multi-GNSS ephemerides for practical real-time operation of GNSS PWV analysis over the ocean. At the same time, the significance of a careful consideration of error sources was also revealed. Though our proposed simple outlier rejection procedure works well, distinguishing each error source and investigating ways to avoid errors are crucial. In this preliminary study, we have mainly discussed multi-path effect. We have learned through this experiment that when planning GNSS observation on vessels, ensuring GNSS satellite visibility and test observations for several days is necessary, especially on relatively small vessels. Furthermore, the effect of pitching and rolling should be examined because it may impose limitations on the vessel’s body size and weight. We did not discuss the effect of pitching and rolling in our experiments because the multi-path effect was so large, except on the ferry Hamayuu. As the next step, we will investigate how wave conditions (e.g., height and frequency) affect water vapor estimation, as well as the effects of analysis options (e.g., elevation cut-off angle, mapping function, combination of satellites, and analysis time interval).

From the view point of practicality, one of the major issues for real-time shipborne GNSS PWV retrieval is the communication line. The file size for the MADOCA real-time ephemerides exceeds 150 MB per day. The acquisition of such a large amount of data could overload the vessel’s telecommunication facilities. The Japanese QZSS is planned to increase to four or more satellites in 2018 and to provide real-time ephemerides via its L-band Centimeter Level Augmentation Signal (L6). Following this development, precise PWV estimation on each vessel is expected to become feasible. The transmission of only the resulting PWV value and the vessel position can significantly reduce the telecommunication volume.

From the results obtained in this preliminary study, we conclude that an ocean platform GNSS has the potential to provide a practical water vapor observation system over the ocean that is available under all weather conditions, at least surrounding the Japanese archipelago. By advancing this study, we want to contribute to achieving operational dense water observation over the ocean in the future.

Fig. 5. GNSS-derived PWV time series at Shimonoseki ground GNSS station (0079) (gray dots) and on the Hamayuu (blue dots, rejected; red dots, used for the statistical comparison in Table 2) when Hamayuu sailed within 20 km of the ground GNSS station. Green bars represent 10-minute precipitation observed at the Shimonoseki AMeDAS station (81428). Brown lines represent significant wave height observed at Kanmon West Aisss (0718) of the Japan Coast Guard’s Maritime Information and Communication System (MICS).
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GEO NET observation data were acquired from the FTP server of the Geospatial Information Authority of Japan (GSI) in RINEX format. Wave gauge data from the Japan Coast Guard (JCG) were downloaded from the Maritime Information and Communication System (MICS) data server at http://www6.kaiho.mlit.go.jp/07kanku/info/kakokisyou/kakokisyou2015.html.

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Supplement

Supplement 1

Frequency distribution of 1 min PWV variation obtained from shipborne GNSS observations (Hamayuu, Keifu Maru, Ryofu Maru, and Shinsei Maru), and fixed GNSS station 3023 (Chiba Ichikawa). Lines with points represent the frequency of each bin divided by the 0.1mm interval (left axis). Lines represent the accumulated frequency (right axis).

Supplement 2

Statistical comparison of GNSS-derived PWV against radiosonde observations at five locations in Japan during 2015. In the scatter diagrams, the red dots were used for calculating BIAS and RMS, while the black dots were rejected through the quality control procedure described in Subsection 2.3.

Supplement 3

GNSS-derived PWV time series at Kami-tsushima ground GNSS station (0456) and on the Hamayuu when the Hamayuu sailed within 20km of the ground GNSS station.

Green bars represent 10-minute precipitation observed at Waniura AMeDAS station (84012).

Brown lines represent significant wave height observed at Mitsushima lighthouse (07101) of the Japan Coast Guard’s Maritime Information and Communication System (MICS).

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