An Evaluation of Multi-GNSS Zenith Tropospheric Delay Products based on Real-time Satellite Products

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Abstract

Global Navigation Satellite System (GNSS) has been demonstrated to be an effective method in meteorology for weather forecasting and climate monitoring applications due to their continuity, high spatial/temporal resolution and low cost. To further satisfy the requirements of modern weather prediction systems, real-time (RT) tropospheric products, which are useful for now-casting and severe weather event monitoring applications, attracts much attention in the meteorological community. With the development of multi-GNSS, the accuracy and reliability of zenith tropospheric delay (ZTD) results are expected to improve due to the increasing number of satellites being tracked. Under this circumstance, RT multi-GNSS PPP becomes a important tool in extracting tropospheric results. In this preliminary study, we will investigate RT ZTD estimation based on GPS/GLONASS/Galileo streams together with RT satellite products from CNES. Accuracy and reliability of the tropospheric products from single/multi-GNSS observations are evaluated by the comparison with post-processing results and radiosonde observations. The impact of GPS PPP ambiguity resolution is also evaluated.

Introduction

Water vapor plays an important role in atmospheric process and accounts for 60-70% of atmospheric warming, thus attracts much attention from scientists. GNSS meteorology, which extracts the zenith tropospheric delay (ZTD) or precipitable water vapor (PWV) from GNSS observations, has been shown to be an effective method in doing so [e.g. Bevis et al., 1992]. To date, more rapid updates of ZTD products are required for real-time (RT) monitoring of severe short-term weather change and NWP now-casting. This requires the processing of data in real-time. In terms of data processing strategies, Precise Point Positioning (PPP) is popular thanks to the progress in generating RT satellite orbit and clock products by the International GNSS Service (IGS), as well as some other institutes and companies. The method is comparable to network solutions in accuracy, but more flexible since the observation data of each station is processed separately. Thus, it is more suitable for the RT data processing of huge networks.

Previous studies in RT PPP based on GPS observations and streams have already validated the effectiveness of this method [e.g. Yuan et al., 2014]. Right now, other than GPS, GLONASS modernization is in progress, and Europe and China are making progress in establishing their own Galileo and Beidou systems, respectively. Numerous analysis results concerning these systems validate their applicability in high-precision applications. It is anticipated that the accuracy of RT tropospheric products can also be improved considering that the number of satellites tracked increases. Some research results in the RT retrieval of PWV using multi-GNSS observations in a simulated mode also validated the hypothesis [e.g. Li et al., 2015]. Thus, it is meaningful to conduct the analysis in generating ZTD products based on actual RT streams of multi-GNSS observations.

In this study, we conducted a preliminary analysis in extracting tropospheric products based on RT GPS/GLONASS/Galileo observation streams. The GPS PPP ambiguity resolution method is also applied and evaluated. Eleven stations from the IGS Multi-GNSS Experiment (MGEX) are selected for the analysis. The stations distribution is plotted in Figure 1. The experiment lasted for 5 weeks (16/08/2015-19/09/2015), and the data availability is shown in Figure 2.

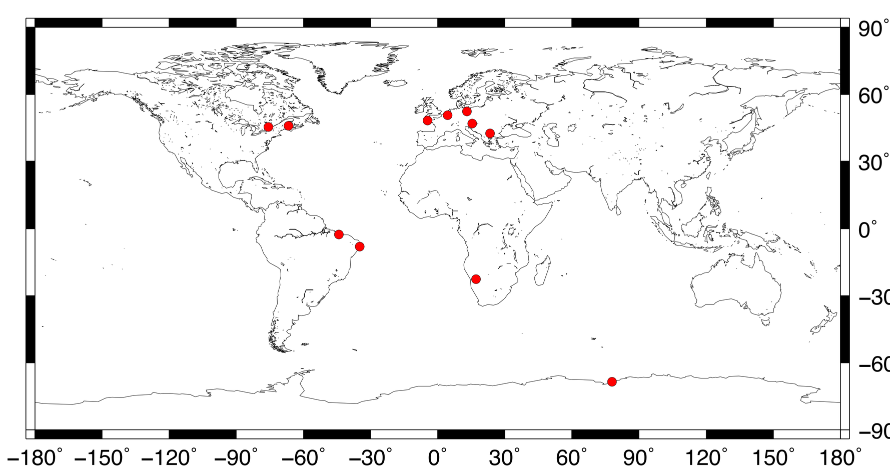

Figure 1 Distribution of multi-GNSS stations in real-time troposphere analysis

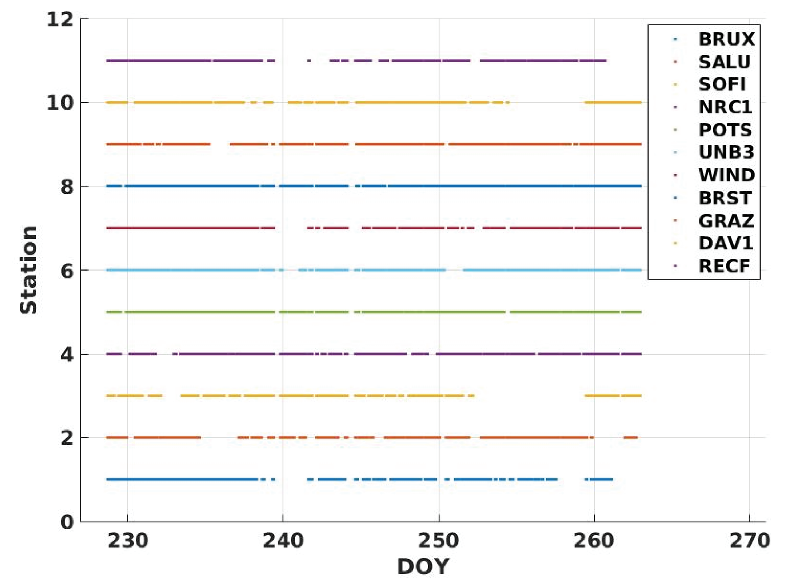

Figure 2 Data availability during the experiment

Methodology

In this study, a modified version of PPP-Wizard, which is developed by CNES for RT "integer PPP" demonstrator (http://www.ppp-wizard.net/index.html) and provided to public users, is applied for the analysis. The basic data processing alogirhtm of PPP-Wizard is shown in Figure 3. A Kalman filter is applied in parameter estimation. For meteorological applications, the station coordinates are fixed to the latest weekly solution. Since PPP-Wizard is mainly developed for real-time kinematic positioning, the observation model is not accurate enough to fulfill the accuracy requirements of meteorological applications [e.g. Ahmed et al., 2014]. Following modifications have been applied to the source code: (1) the receiver antenna phase center offset (PCO) and phase center variation (PCV) corrections from igs08.atx are applied to GPS/GLONASS observations, the same values as GPS are applied to Galileo observations, and the PCV corrections for GPS/GLONASS satellites are also applied based on igs08.atx; (2) ocean tide loading corrections based on FES2004 model are applied; (3) The tropospheric delay is modeled into two parts, in which the Global Pressure and Temperature (GPT) model is applied to calculate the temprature and pressure value and the Global Mapping function (GMF) is applied in troposphere modeling; (4) Elevation dependent weighting strategy (Q = 1/cos(zen)**2).

RT satellite orbit/clock products from the CNES caster (CLK93 mountpoint) are applied in the analysis. It also provides GPS phase biases information, which enables PPP ambiguity resolution for GPS. The basic structure in generating the products is shown in Figure 4.

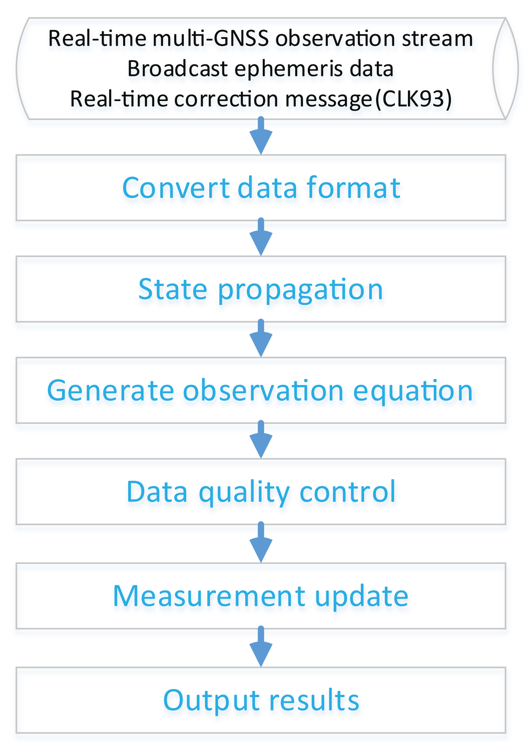

Figure 3 Flow chart of data processing in PPP-Wizard

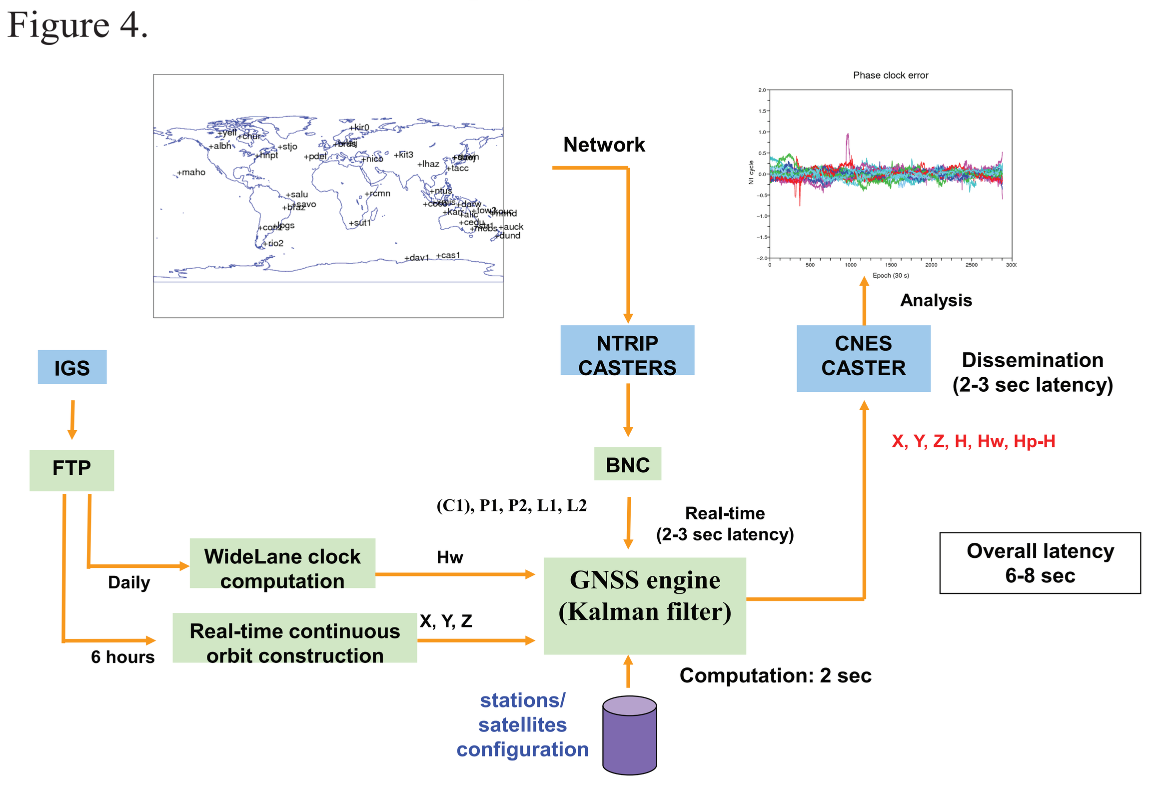

Figure 4 Basic structure for generating the RT products at CNES (Laurichesse, 2011)

Acknowledgements

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Internal Comparison

Figure 5 plots the number of satellites tracked by different systems for POTS during one day. At least 6 GPS and 5 GLONASS satellites can be tracked, but for most of the time more satellites are visible. In addition, more than 2 Galileo satellites can be tracked for over 6 hours. On average a total of 17 satellites are visible.

To evaluate the impact of multi-GNSS observations on the accuracy of RT ZTD products, five solutions are generated separately: 1) GLONASS-only solution (RFLT), 2) GPS-only solution (GFLT), 3) GPS-only solution with ambiguity resolution (GFIX), 4) GPS/GLONASS solution (MFLT), 5) GPS/GLO/Galileo solution with ambiguity resolution (MFIX). Figure 6 plots the ZTD error with respect to the post-processing products from USNO. The ZTD error using GLONASS-only observations is biggest, which may be correlated with the accuracy of observation model and RT products. The results in the last solution is most accurate and stable, especially when few satellites are tracked.

Station	RFLT/mm		GFLT/mm		GFIX/mm		MFLT/mm	
	Bias	RMS	Bias	RMS	Bias	RMS	Bias	RMS
BRUX	3.3	10.1	2.1	6.2	-0.7	4.5	3.5	4.3
SALU	0.4	5.4	-1.2	8.8	-0.4	8.2	3.0	3.0
SOFI	2.3	7.7	0.5	4.1	-0.6	4.1	2.2	2.4
NRC1	2.4	9.3	-1.2	4.5	-1.5	3.7	2.2	2.2
POTS	2.3	8.0	2.6	5.4	-0.2	3.2	3.0	3.8
UNB3	4.2	9.9	-0.8	5.2	-1.2	4.0	3.7	3.9
WIND	4.3	9.7	-2.4	6.8	-0.9	5.9	5.7	5.8
BRST	3.2	9.6	1.5	5.2	-1.0	3.6	4.4	4.7
GRAZ	2.6	6.4	-0.5	3.8	-0.5	2.8	1.9	1.9
DAV1	3.1	5.2	-1.9	3.9	-1.6	3.0	1.6	1.6
RECF	2.1	7.1	-1.1	4.7	-1.1	3.8	2.6	2.6
Mean	2.7	8.0	-0.2	5.3	-0.9	4.3	3.1	3.3

Table 1 Statistics of real-time ZTD with respect to MFIX solution

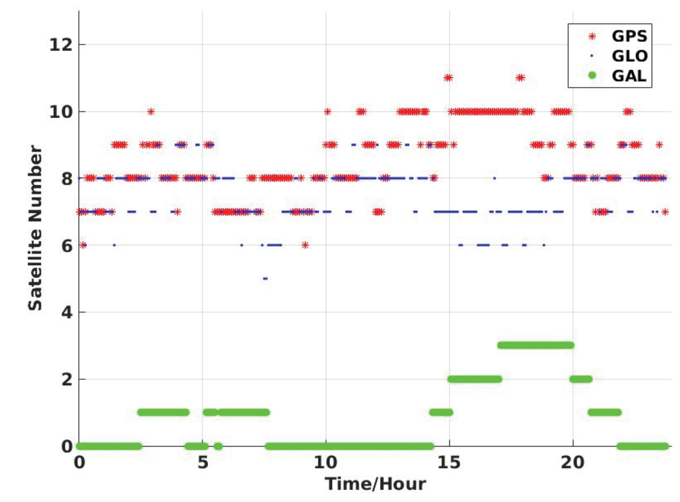

Figure 5 Number of GPS/GLO/GAL satellites tracked by POTS

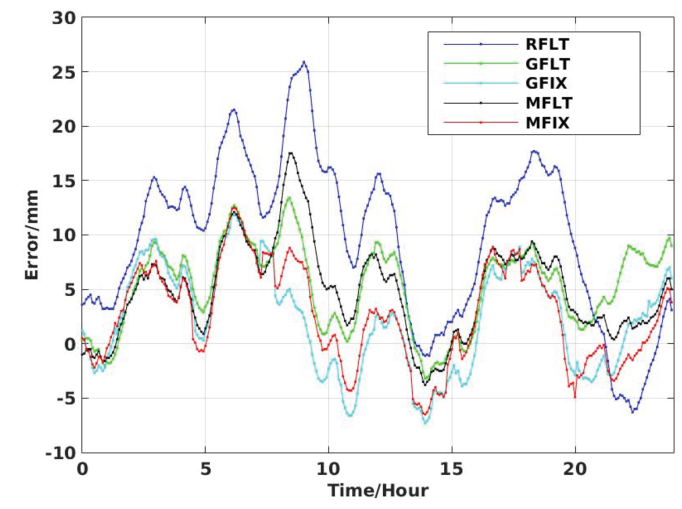

Figure 6 Real time ZTD error of POTS with respect to post-processing products by USNO

Selecting the MFIX solution as reference, we evaluate the difference of the ZTD products generated in the first 4 solutions with respect to it. Table 1 shows the mean value and RMS of the differences for all stations. We can find from the solution that the difference between RFLT and MFIX solution is largest, and an obviously large mean bias is evident between them. The accuracy of MFLT solution is the best, which reveals the effect of multi-GNSS observation in extracting RT tropospheric results.

External Comparison

We select the post-processing tropospheric products geneerated by CODE and USNO as reference to further evaluate the products. The results are shown in Figure 7, and the average value is plotted in Figure 8. The accuracy of all solutions is better than 20mm. The RFLT solution is the worst in terms of mean bias and RMS, while the MFIX solution is the best. The accuracy is improved by 1mm after applying ambiguity resolution. However, the multi-GNSS solution is worse than single GPS solution for SOFI, which means the importantance of appropriate weighting scheme between observation of different systems.

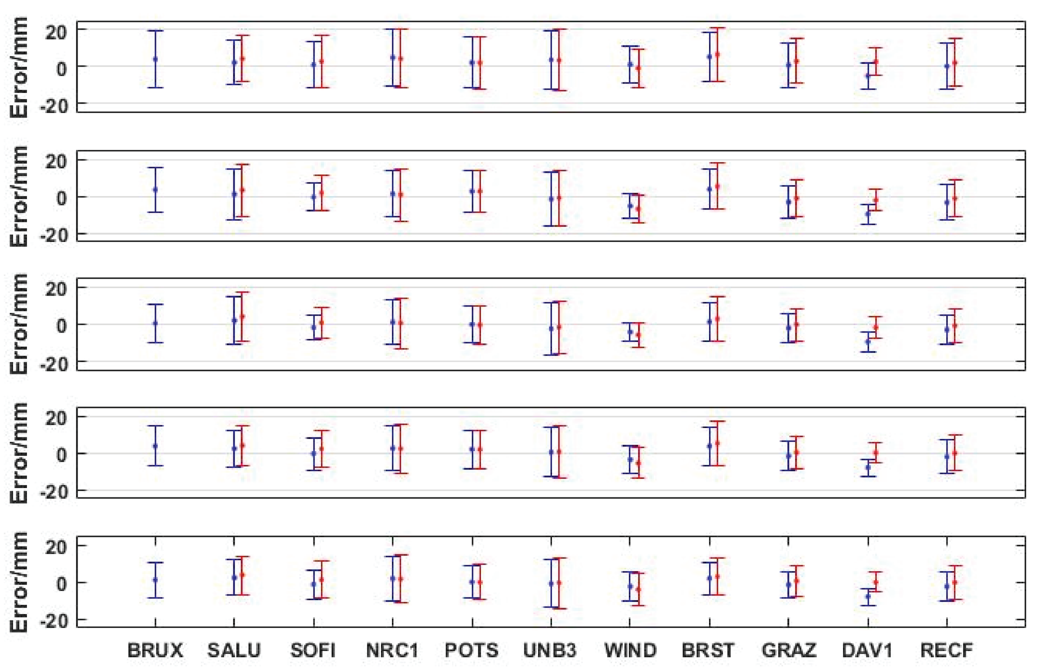

Figure 7 Accuracy of RT ZTD with respect to post-processing products from CODE (Blue) and USNO (Red)

Station	RFLT/mm		GFLT/mm		GFIX/mm		MFLT/mm		MFIX/mm	
	Bias	STD	Bias	STD	Bias	STD	Bias	STD	Bias	STD
SALU	8.6	25.4	5.5	24.5	4.9	24.1	6.9	24.7	6.6	24.0
SOFI	-30.3	9.7	-34.0	10.2	-32.4	12.3	-30.0	19.8	-31.8	15.7
WIND	0.5	18.7	-9.3	18.1	-6.8	18.3	-3.0	18.5	-2.4	20.8
BRST	-5.0	19.6	-10.7	21.7	-10.8	20.7	-13.4	21.3	-8.5	19.1
DAV1	-2.7	10.0	-5.8	10.4	-5.5	8.1	-4.7	7.5	-4.7	7.7
RECF	27.4	11.2	26.0	10.8	27.9	12.7	29.3	13.2	26.9	12.5

Table 2 Statistics of comparison between ZTD from RT PPP and radiosonde observations

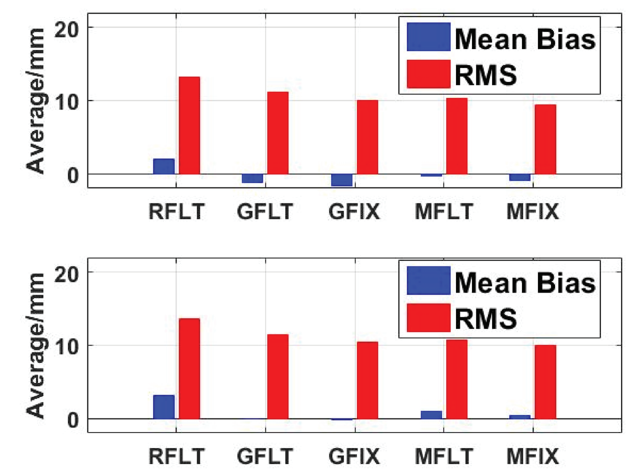

Figure 8 Average value of mean bias and RMS with respect to CODE products (top) and USNO products (bottom)

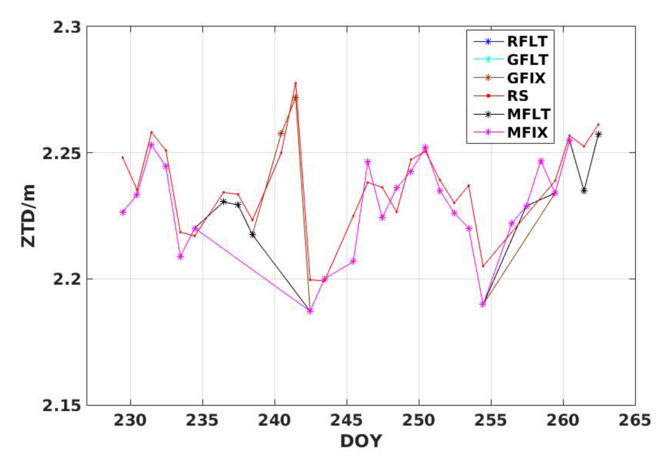

Figure 9 Time series of ZTD from five solutions and radiosonde observations

In additon, we compare with the results extracted from the nearby radiosonde observations for six stations, of which the results are shown in Table 2. We also plot the time series for station DAV1 in Figure 9. The STD is smaller than 20mm for all stations except SALU. However, we can notice the big mean bias for station SOFI and RECF, which need further investigation.

Conclusions

In this study, we analyzed the performance of extracting RT tropospheric products based on multi-GNSS observation streams. Different solutions are generated and compared with various source of products to evaluate the accuracy.

1. RT tropospheric products generated based on single/multi-GNSS observation streams can fulfill the requirements for meteorological applications.
2. The RFLT products agree the worst, while the MFIX products agree the best, which reveals that it is useful to extract tropospheric products based on multi-GNSS observations.
3. A small improvement, 1mm on average, can be noticed when applying PPP ambiguity resolution for GPS.
4. Further research in the weighting scheme of observations between systems is required.

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