Real-Time Tropospheric Delay Estimation Using GPS/Galileo Observations and NAVCAST Products

Mohamed Abdelazeem [1], Ahmed El-Rabbany [2]
[1]Civil Engineering Department, Aswan University, Egypt
[2]Civil Engineering Department, Ryerson University, Canada
m.abdelazeem@aswu.edu.eg

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Introduction

- Zenith tropospheric delay (ZTD) is a key parameter for precise positioning, weather forecasts and climate change applications.

- ZTD can be estimated using various techniques, including global navigation satellite systems (GNSS), radiosonde, and very long baseline interferometry (VLBI) techniques.

Introduction

- The ZTD derived from the GNSS precise point positioning (PPP) is an important, cost-effective, and precise approach for real-time atmospheric sounding applications.

- This is attributed to the recent increase in the number of GNSS satellites and the availability of real-time precise satellite orbit and clock correction services.

Introduction

- The international GNSS service (IGS) has launched its freely available real-time service (IGS-RTS), which enables reliable real-time PPP solution.

- The IGS-RTS provides real-time precise satellite orbit and clock corrections through a number of analysis centers.

- Recently, Spaceopal GmbH has launched a newly real-time satellite orbit and clock correction service for GPS and Galileo systems, namely NAVCAST

Study objectives

- To investigate the precision of the estimated real-time zenith tropospheric delays (RT-ZTD) obtained through the GPS/Galileo real-time PPP solution using the NAVCAST satellite orbit and clock corrections.

- To compare the estimated RT-ZTD with with the center for orbit determination in Europe (CODE) rapid tropospheric product counterpart.

ZTD Estimation Using GPS/Galileo PPP

- The mathematical expression for the GPS/Galileo ionosphere-free (IF) dual-frequency PPP model can be written as follows:

$$P_{3G} = \rho_r^G + \; cdt_{r,G}^{\sim} - cdt^G + T_r^G + \varepsilon_{G,p3} \tag{1}$$

$$\Phi_{3G} = \rho_r^G + \; cdt_{r,G}^{\sim} - cdt^G + T_r^G + \tilde{N}^G + \varepsilon_{G,\Phi3} \tag{2}$$

$$P_{3E} = \rho_r^E + \; cdt_{r,G}^{\sim} - cdt^E + T_r^E + ISB + \varepsilon_{E,p3} \tag{3}$$

$$\Phi_{3E} = \rho_r^E + \; cdt_{r,G}^{\sim} - cdt^E + T_r^E + \tilde{N}^E + ISB + \varepsilon_{E,\Phi3} \tag{4}$$

ZTD Estimation Using GPS/Galileo PPP

G and E	: the GPS and Galileo satellite systems, respectively
P_3 and Φ_3	: the ionosphere-free linear combination of pseudorange and carrier phase observations, respectively
ρ_r^G and ρ_r^E	: the satellite-receiver true geometric range
c	: the speed of light in vacuum
$dt_{r,G}^{\sim}$	: the sum of the GPS receiver clock error and the GPS IF receiver differential code bias
dt^G and dt^E	: the satellite clock error, which includes the IF satellite differential code bias
T_r^G and T_r^E	: the tropospheric delay
$\widetilde{N}^G$ and $\widetilde{N}^E$	: the non-integer ambiguity term for phase observations, including the IF receiver differential code and phase biases, and the IF satellite differential code and phase biases
ISB	: the inter-system bias, which is the difference in the IF receiver differential code bias between the GPS and Galileo satellite systems
ε_{p3} and $\varepsilon_{\Phi 3}$	: the code and phase un-modeled residual errors.

ZTD Estimation Using GPS/Galileo PPP

- The tropospheric delay can be broken down mathematically into two components, the wet and the dry, as follows:

$$T_r^G = Z_h \times MF_h + Z_w \times MF_w \qquad (5)$$

$$T_r^E = Z_h \times MF_h + Z_w \times MF_w \qquad (6)$$

Z_h and Z_w : the zenith hydrostatic delay (ZHD) and the zenith wet delay (ZWD), respectively.

MF_h and MF_w : the hydrostatic and the wet mapping functions, respectively.

ZTD Estimation Using GPS/Galileo PPP

- The ZHD can be accounted for using the Saastamoinen model, while the ZWD is estimated as a by-product of the PPP solution.

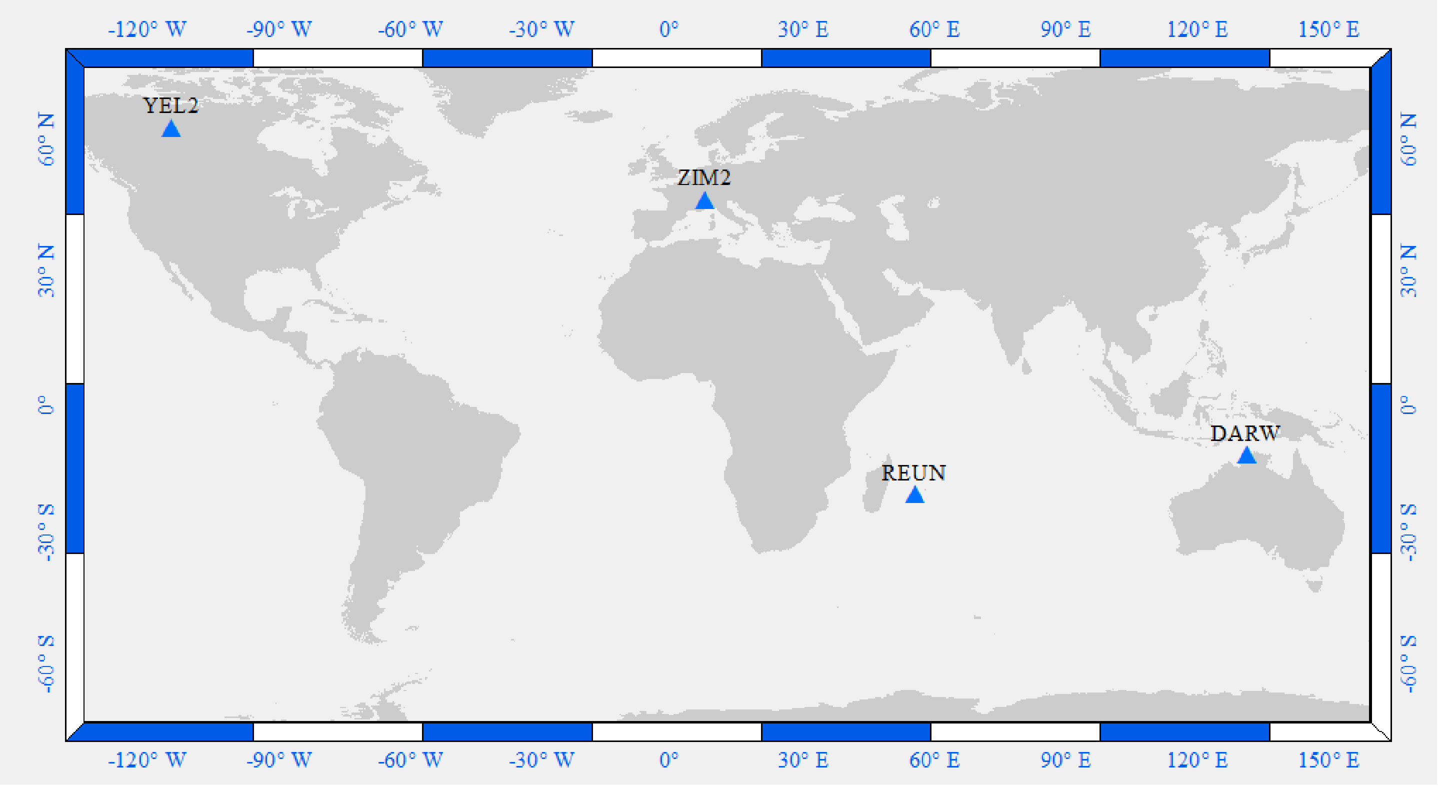
- For parameter estimation, the state vector (**X**) of the unknown parameters can be expressed as:

$$\mathbf{X} = \left(\Delta x \ \ \Delta y \ \ \Delta z \ \ cd\tilde{t}_{r,G} \ \ Z_w \ \ ISB \ \ \tilde{N}\right)^T \qquad (7)$$

$\Delta x, \Delta y$ and Δz : the corrections to the approximate initial receiver coordinates.

GPS/Galileo Real-Time Data Sets

- GPS/Galileo observations from four globally distributed reference stations have been used.



GPS/Galileo Real-Time Data Sets

- The stations have been selected to represent different latitudes and heights in order to reflect the different tropospheric characteristics.

Station	Latitude	Longitude	Height (m)
YEL2	-114.481°	62.481°	181.0
ZIM2	7.090°	46.155°	956.50
REUN	55.099°	-21.042°	1558.4
DARW	131.036°	-12.149°	125.2

GPS/Galileo Real-Time Data Sets

- GPS/Galileo observations over three consecutive days (i.e., day of year (DOY) 20, 21 and 22 in 2020) have been downloaded.

- The CLKA0_DEU stream available from the NAVCAST service has been used, which includes orbit and clock corrections.

- The real-time corrections has been obtained through the networked transport of RTCM via internet protocol (NTRIP) using the BKG NTRIP client (BNC) software.

GPS/Galileo Real-Time Data Sets

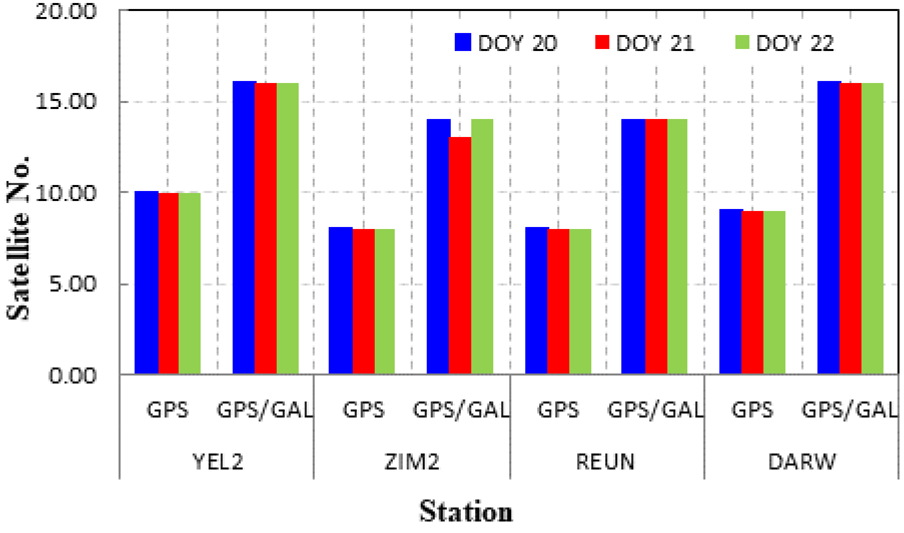
- To estimate the RT-ZTD, the pre-saved NAVCAST orbit and clock corrections, the broadcast ephemerides (i.e., BRDM) available from MGEX website, and the observation files have been used in the BNC software in order to obtain the PPP solution.

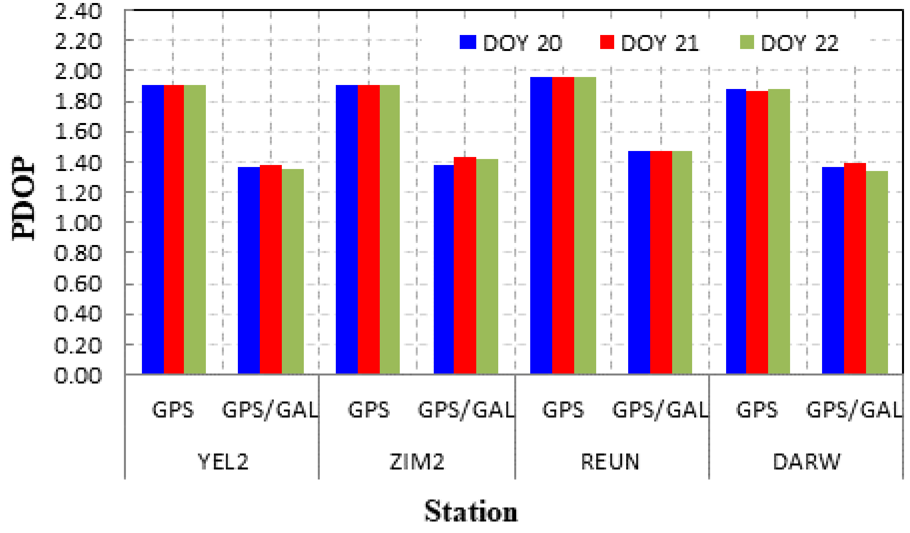
- Each observation file has a 24-hour time window and 30-second time interval. The elevation angle has been selected to be 10°

- The RT-ZTD values have been estimated every 5 minutes.

GPS/Galileo Real-Time Data Sets

- The average of the number of tracked satellites and the position dilution of precision (PDOP) values at the examined stations are given below.





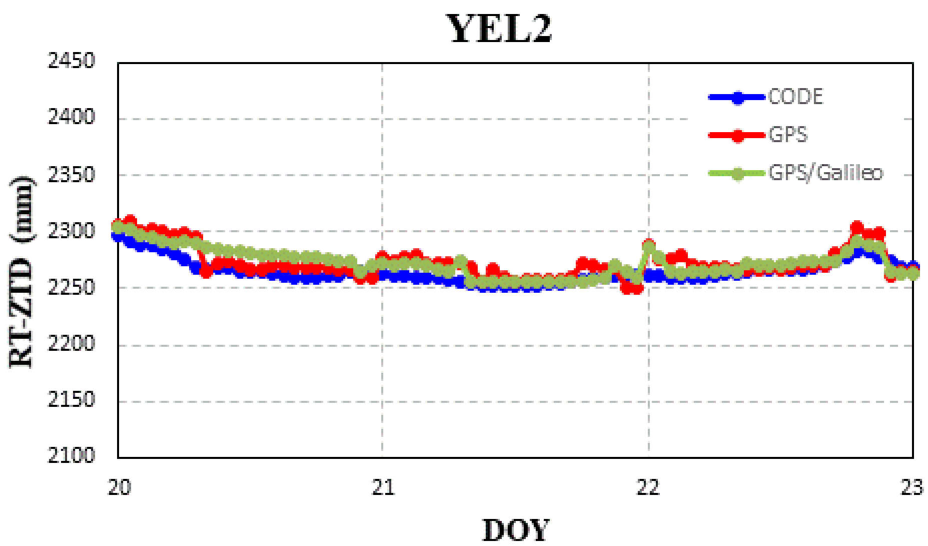
- It is noticed that the addition of Galileo constellation increases the number of the visible satellites and enhances the PDOP values.

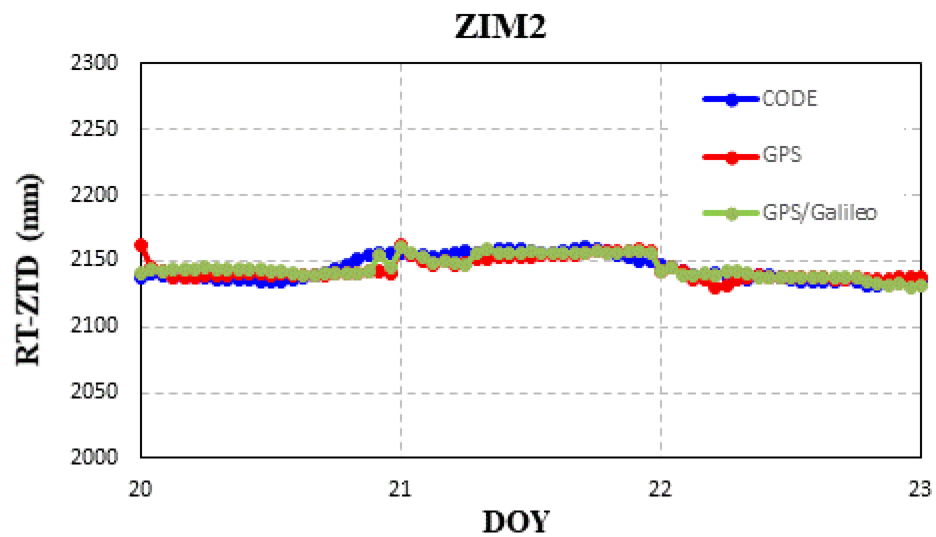
Results and analysis

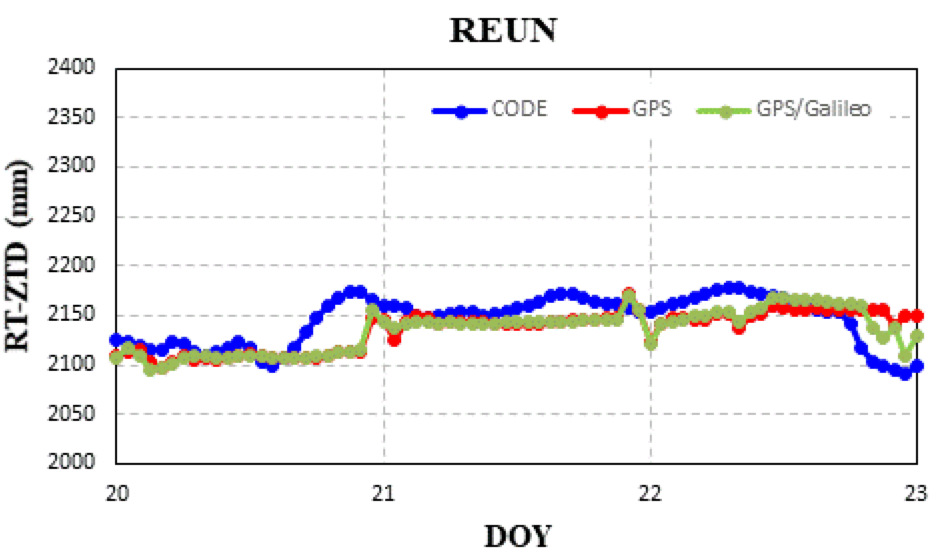
- The RT-ZTD time series for the examined stations over three days are given below.

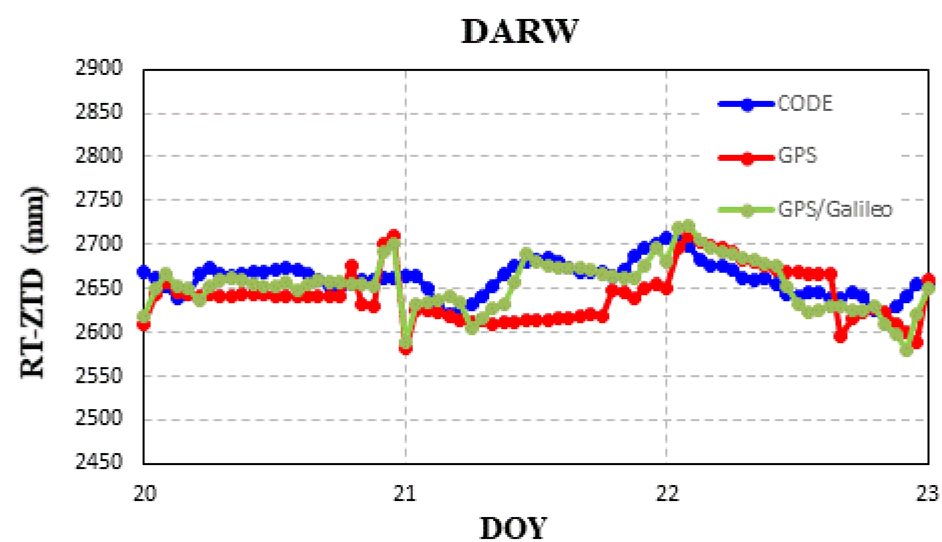
- It can be seen that the estimated RT-ZTD values from both of the GPS-only and GPS/Galileo solutions closely match those of the CODE counterparts.

Results and analysis









Results and analysis

- To validate the estimated RT-ZTD with respect to the CODE counterparts, the standard deviations (STD) for the differences are computed for the examined days and given bellow.

Station	**Solution**	**STD (mm)**		
		DOY 20	**DOY 21**	**DOY 22**
YEL2	GPS	7.8	8.0	9.1
	GPS/GAL	5.3	5.0	6.5
ZIM2	GPS	9.3	6.0	3.4
	GPS/GAL	10.3	4.5	2.6
REUN	GPS	20.1	10.9	28.5
	GPS/GAL	20.6	9.4	23.4
DARW	GPS	23.7	34.8	27.7
	GPS/GAL	18.4	20.1	25.6

Results and analysis

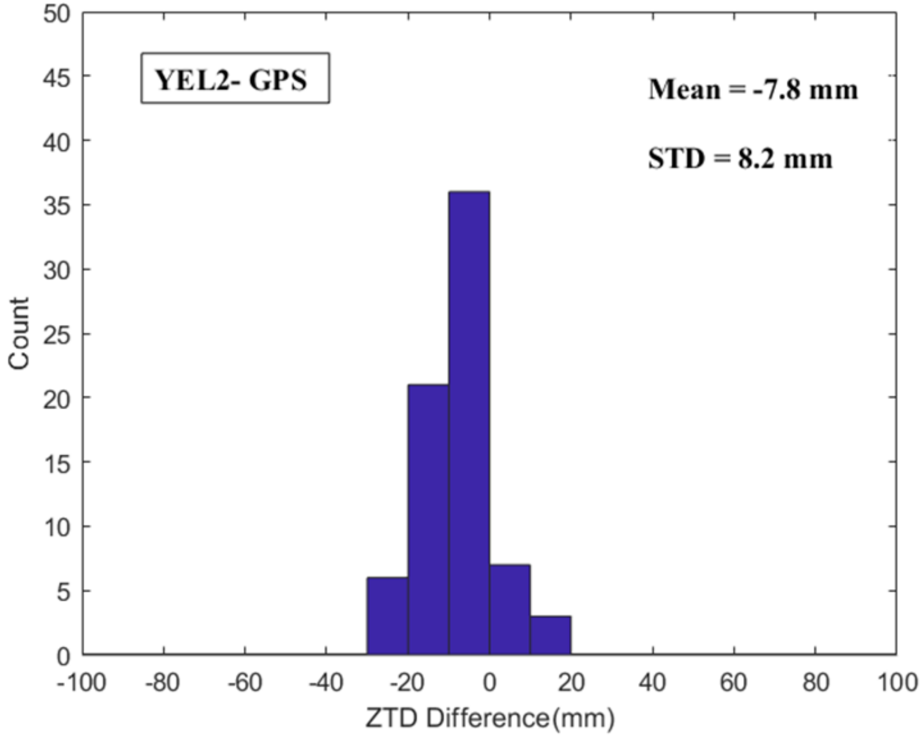
- It can be seen that the estimated RT-ZTD values agree at the mm-cm level with the CODE counterparts.

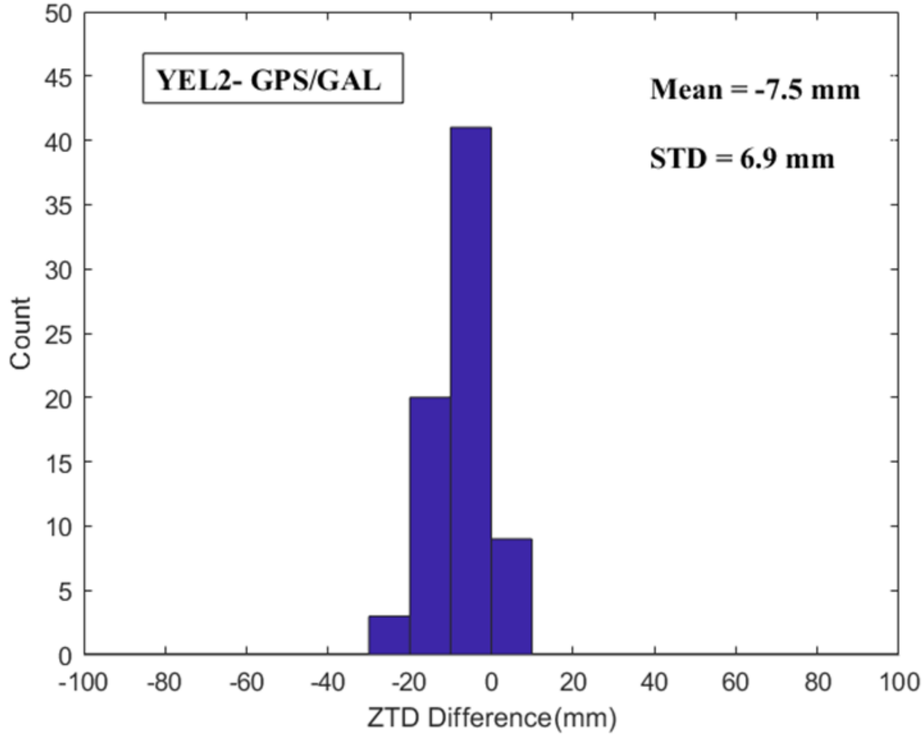
- An exception is for station DARW, which is located at a low latitude. This might be attributed to a relatively lower model performance at low latitudes.

- The STD value at station REUN are slightly larger than those of YEL2 and ZIM2 counterparts, which might be attributed to the much higher altitude of station REUN.

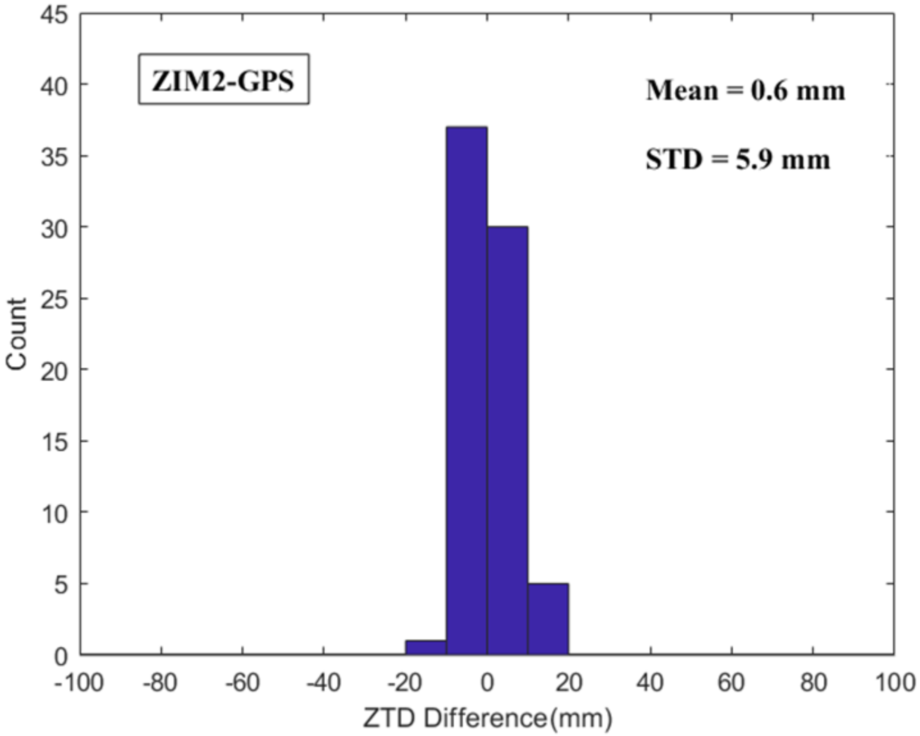
Results and analysis

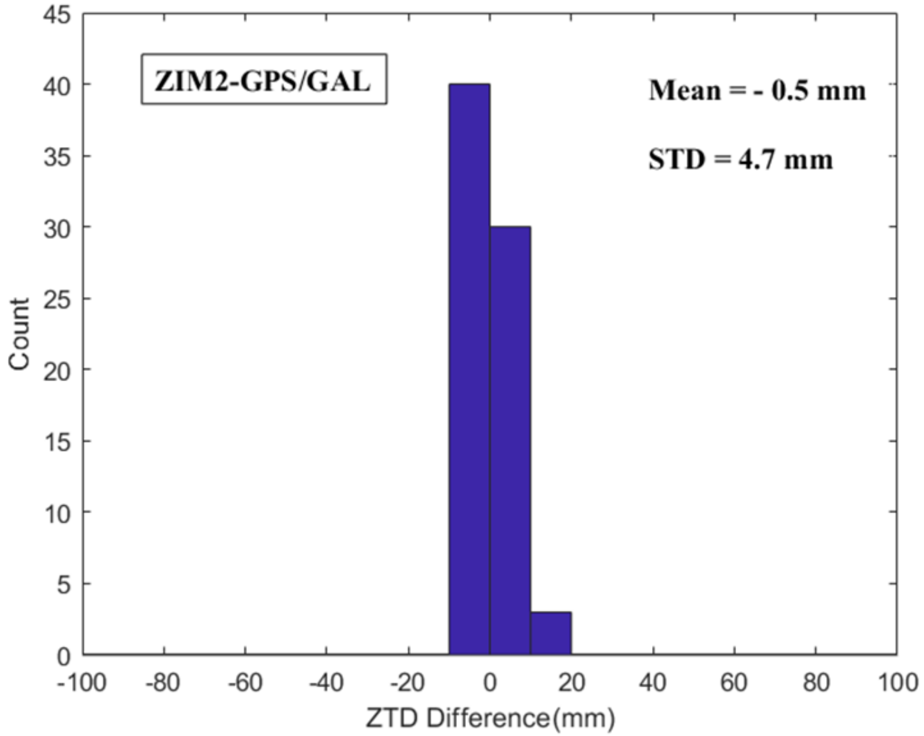
- To further verify the precision of the estimated RT-ZTD with respect to the CODE counterpart, the distribution of the RT-ZTD-CODE differences is determined and given as follows:



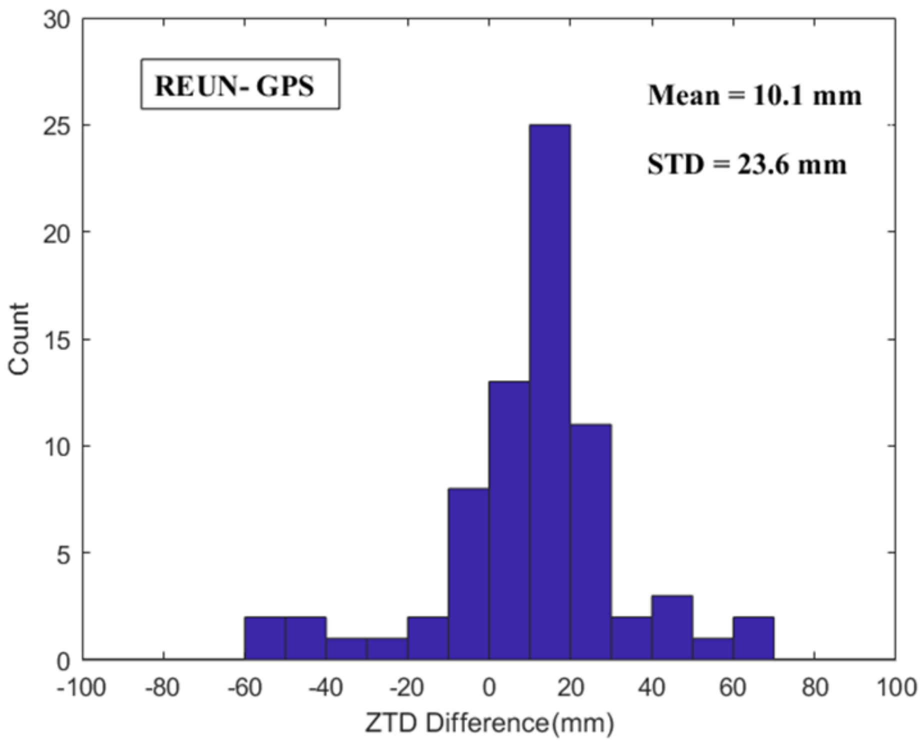


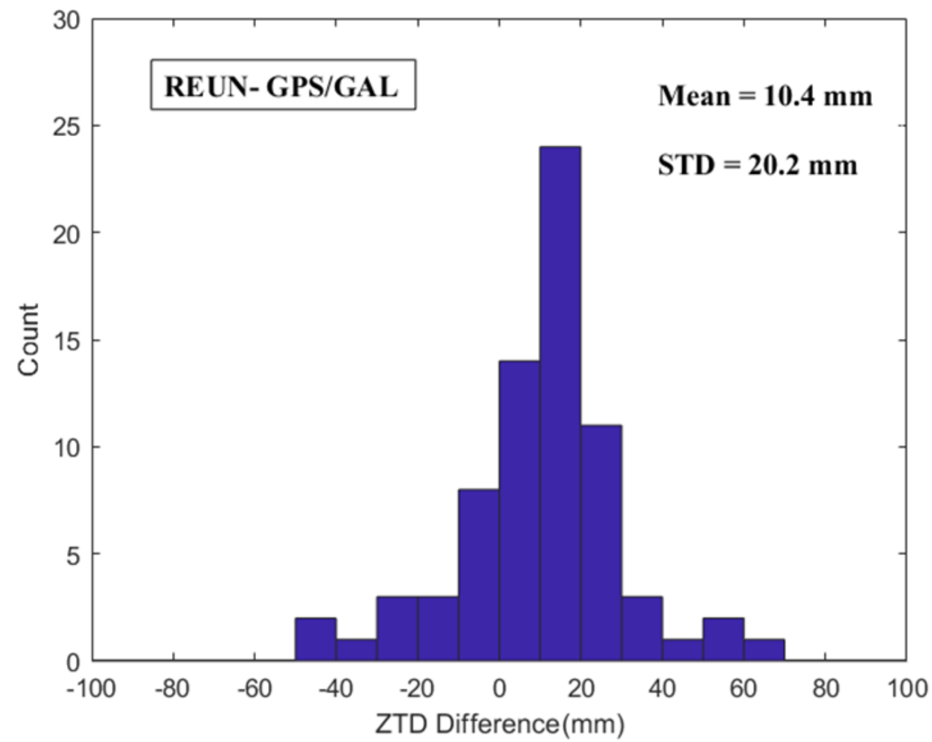
Results and analysis



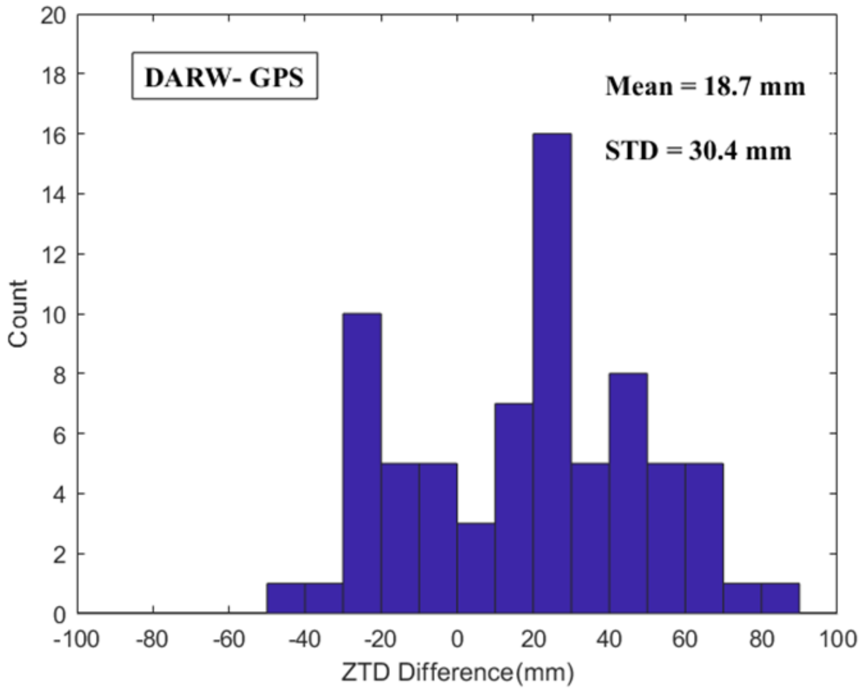


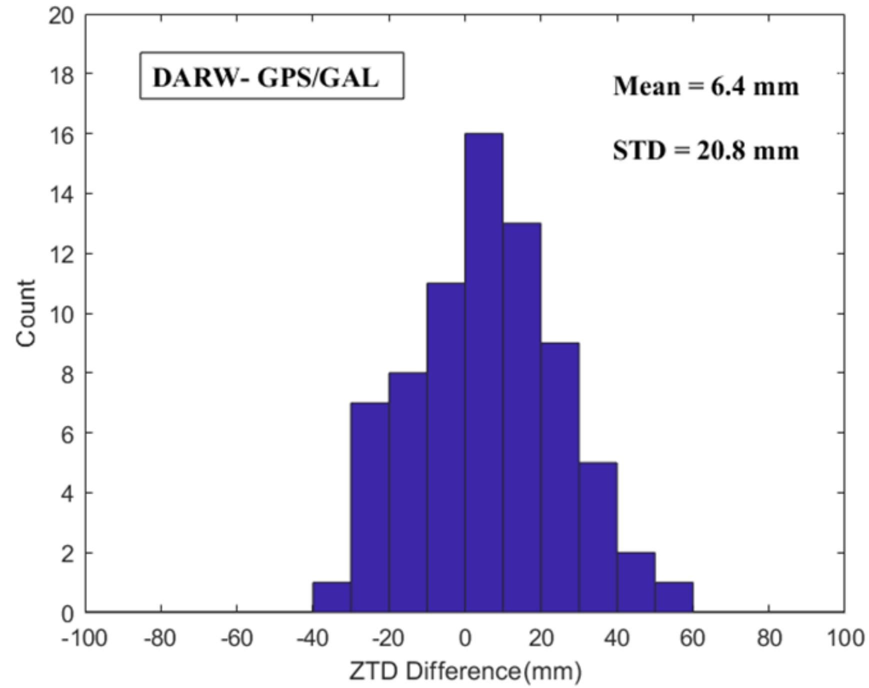
Results and analysis





Results and analysis





Results and analysis

- It is shown that the precision of the estimated RT-ZTD from the GPS/Galileo solution is better than the one obtained from the GPS-only solution.

- This is expected, as the satellite geometry is improved through the addition of Galileo constellation.

Results and analysis

- The statistical parameters including the mean, minimum, maximum and STD values are computed and summarized below.

Parameter (mm)	**GPS-only**	**GPS/Galileo**
Mean	5.4	2.2
Min.	81.6	75.5
Max.	-58.8	-43.1
STD	22.2	16.5

Conclusion

- The estimated RT-ZTD values agree with the CODE counterparts with a maximum standard deviation of 22.2 mm.

- The precision of the RT-ZTD obtained through the GPS/Galileo PPP solution is improved by about 25% in comparison with the GPS-only counterpart.

- The obtained RT-ZTD can be used in real-time atmospheric sounding applications, including nowcasting and forecasting weather applications.


Thank You