UNIVERSITY OF WARMIA AND MAZURY IN OLSZTYN

WYDZIAŁ GEOINŻYNIERII

Validation of low-cost receiver derived tropospheric products against ERA5 reanalysis

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MOTIVATION AND GOAL OF THE STUDY

- A factor that may particularly stimulate innovations and, in turn, open the door to novel applications low-cost GNSS receivers is their ubiquity. One of the applications that may especially benefit from an omnipresence of such receivers is **troposphere sensing**, for which the spatial resolution of soundings is of high importance.

- This study address a scientific question on the quality of the tropospheric estimates derived from low-cost receiver data processing and thus the potential usability of such receivers for climate and weather applications.
  - We aim to verify whether low-cost receivers may provide information on the parameters that describe the state of the troposphere with accuracy and reliability close to that of high-grade receivers.

- We investigate zenith tropospheric delays (ZTD) and horizontal gradients obtained from GNSS data of **mass-market receivers** and **compare to those from high-grade receiver**.
- **ZTD accuracy is compared to ERA5**, which is the fifth generation reanalysis for the global climate and weather, considered as the most accurate and comprehensive global atmospheric data. ERA5 does not assimilate GNSS observations; thus, it is an excellent independent validation data set.

DATA AND INSTRUMENTS

- Three collocated stations equipped with low-cost DF u-blox ZED F9P receivers and one station with a high-grade Trimble Alloy receiver were installed.
- Receivers were connected to the Leica AR10 surveying-grade antenna and the patch ANN-MB antenna through an antenna splitter forming zero-baseline set-ups.
- Two campaigns that ensure diverse tropospheric conditions were carried out:
    1. in late autumn/early winter on November 17–19, 2020,
    2. in summer on June 16–18, 2021.

Fig. 1 GNSS antennas employed in the study.

Table 1: Summary of the receivers and antennas forming two collocated zero-baselines.

Receiver type	Antenna type	Acronym of the receiver+antenna set	# of baseline
Trimble Alloy	Leica AR10	**TRMB+LEIAR10**	Zero-baseline #1
u-blox ZED F9P		**ZED F9P+LEIAR10**	
u-blox ZED F9P	u-blox ANN-MB	**ZED F9P+ANN-MB #1**	Zero-baseline #2
u-blox ZED F9P		**ZED F9P+ANN-MB #2**	

METHODS

Table 2: Selected GNSS data processing parameters in **Bernese GNSS Software v.5.2.**

Constellations	GPS, GLONASS
Processing model	Ionosphere-free Precise Point Positioning (**IF PPP**)
Mode	Static
Sessions	24 h with the 30 s sampling rate
Elevation cut-off angle	3°
Orbits, clocks and Earth orientation parameters	CODE MGEX final products
Differential code biases for satellites and receivers	CODE monthly solution
Antenna phase center variations and offsets	Absolute IGS
Ocean tidal loading model	FES2004
Global ionosphere model	CODE final
Conventional models	IERS Conventions 2010
A priori tropospheric model	Global Pressure and Temperature (**GPT**) with Global Mapping Function (**GMF**)
ZTD parameter spacing	**15 minutes**
Relative constraints of ZTD	1 mm
Tropospheric gradient model	**Chen&Herring**
Gradient spacing	**1 hour**
Relative constraints of gradients	0.1 mm

RESULTS OF DATA PROCESSING

(1) Insight into the tropospheric parameters

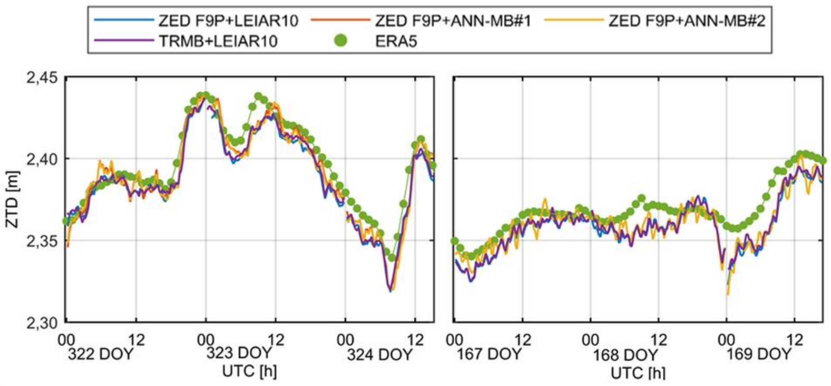

Fig. 2 **ZTD time series** during the winter and summer campaigns, in the left and right panels, respectively.

Table 3: Standard deviations and mean of ZTD and gradient time series.

Source of the tropospheric parameters	ZTD		GN		GE	
	STD [m]	Mean [m]	STD [mm]	Mean [mm]	STD [mm]	Mean [mm]
Winter 2020 campaign						
TRMB+LEIAR10	0.0261	2.3892	0.53	-0.29	0.52	-0.21
ZED F9P+LEIAR10	0.0255	2.3879	0.50	-0.33	0.49	-0.14
ZED F9P+ANN-MB#1	0.0269	2.3908	0.62	-0.04	0.64	0.39
ZED F9P+ANN-MB#2	0.0270	2.3904	0.64	0.00	0.60	0.32
ERA5	0.0313	2.3897	n/a	n/a	n/a	n/a
Summer 2021 campaign						
TRMB+LEIAR10	0.0166	2.3612	0.50	-0.18	0.56	0.33
ZED F9P+LEIAR10	0.0154	2.3576	0.47	-0.17	0.49	0.26
ZED F9P+ANN-MB#2	0.0149	2.3595	0.58	-0.40	0.68	0.20
ERA5	0.0161	2.3701	n/a	n/a	n/a	n/a

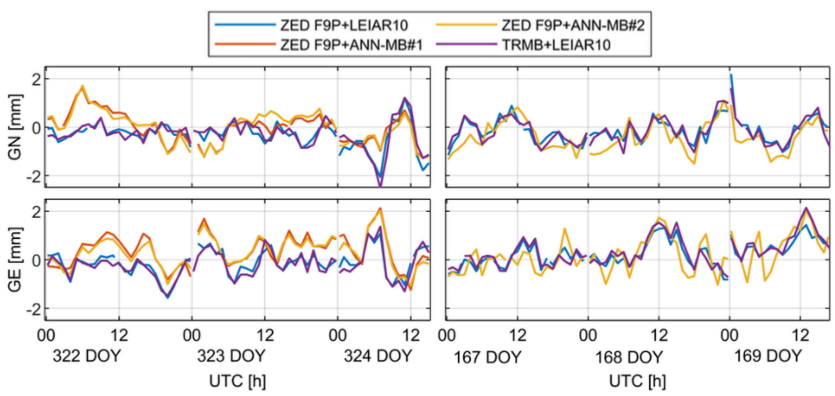

Fig. 3 **North and East tropospheric gradients** during the winter and summer campaigns, in the left and right panels, respectively.

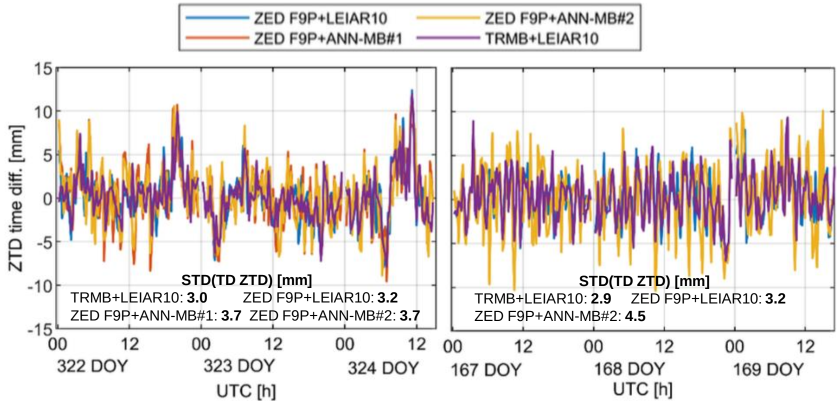

Fig. 4 **Time differences of ZTD** during the winter and the summer campaigns, in the left and right panels, respectively.

RESULTS OF DATA PROCESSING

(2) VALIDATION OF THE LOW-COST RECEIVER AGAINST THE HIGH-GRADE RECEIVER

Table 4: **Minimum, maximum, STD, and mean of ZTD and gradient differences between Trimble and low-cost receiver** solutions.

Statistics [mm]	TRMB+LEIAR10 vs. ZED F9P+LEIAR10		TRMB+LEIAR10 vs. ZED F9P+ANN-MB#1		TRMB+LEIAR10 vs. ZED F9P+ANN-MB#2	
	Winter	**Summer**	**Winter**	**Summer**	**Winter**	**Summer**
ZTD differences						
Min	-3.8	-3.0	-15.8	n/a	-15.9	-15.4
Max	7.0	9.7	19.9	n/a	17.6	16.1
STD	1.8	1.7	4.7	n/a	4.9	5.3
Mean	0.7	1.1	-2.2	n/a	-1.7	-0.8
GN differences						
Min	-0.7	-0.7	-1.6	n/a	-1.7	-0.7
Max	0.8	0.4	1.0	n/a	1.0	1.1
STD	0.2	0.2	0.6	n/a	0.7	0.4
Mean	0.0	0.0	-0.3	n/a	-0.3	0.2
GE differences						
Min	-0.5	-0.6	-1.6	n/a	-1.6	-1.3
Max	0.4	0.8	0.8	n/a	0.8	1.6
STD	0.2	0.2	0.5	n/a	0.5	0.5
Mean	-0.1	0.1	-0.6	n/a	-0.5	0.1

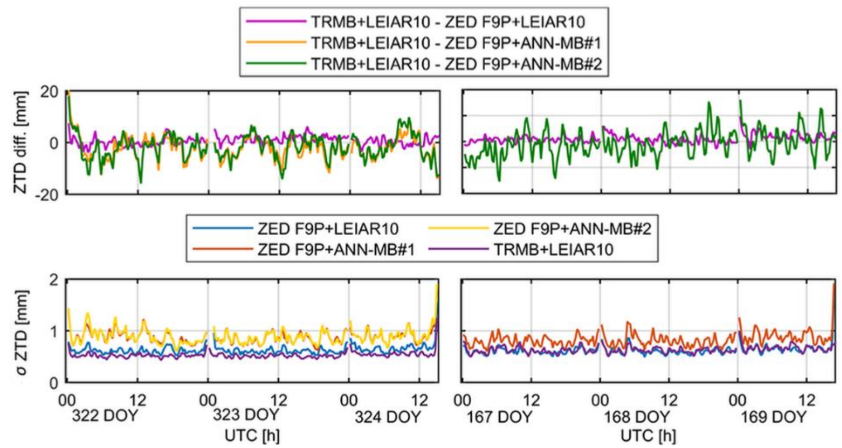

Fig. 5 **ZTD differences between Trimble and low-cost receivers** in the top panels. **The formal errors of ZTD** in the bottom panels.

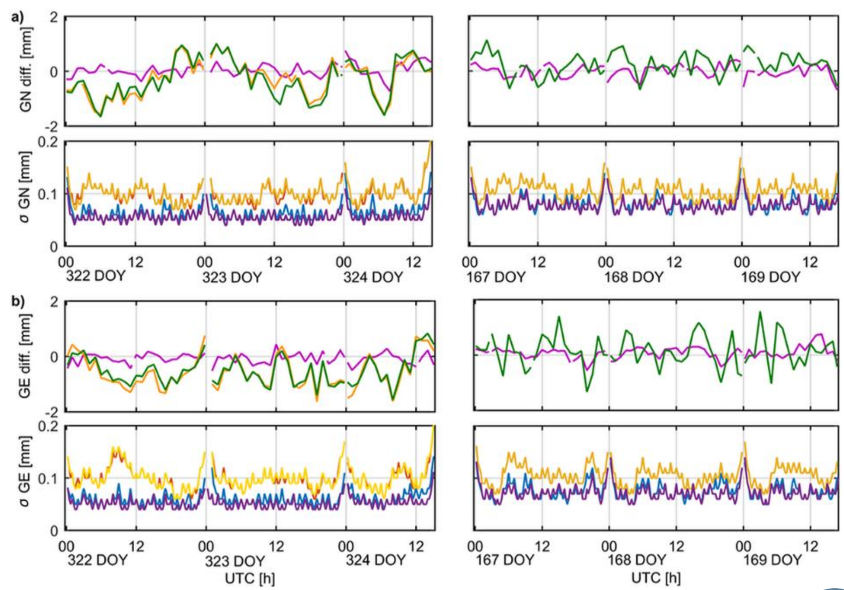

Fig. 6 **North** (a) and **East** (b) **gradient differences between Trimble and low-cost receivers** (top), formal error of gradients (bottom).

RESULTS OF DATA PROCESSING

(3) Validation of GNSS-derived ZTDs against ERA5 reanalysis

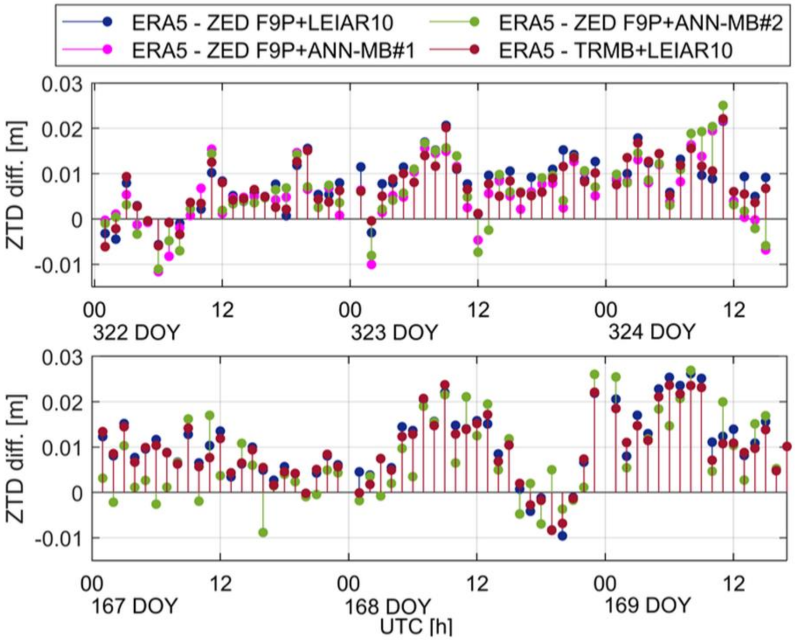

Fig. 7 **ZTD differences between ERA5 and GNSS** during the winter and summer campaigns.

Table 5: **Minimum, maximum, STD, and mean of ZTD differences** between the ERA5 and GNSS estimates.

Item	Min [mm]	Max [mm]	STD [mm]	Mean [mm]
Winter 2020 campaign				
ERA5 vs. ZED F9P+LEIAR10	-5.7	21.6	5.8	8.0
ERA5 vs. ZED F9P+ANN-MB#1	-11.6	21.8	6.8	5.6
ERA5 vs. ZED F9P+ANN-MB#2	-11.1	25.1	7.4	6.0
ERA5 vs. TRMB+LEIAR10	-6.1	22.1	5.7	7.3
Summer 2021 campaign				
ERA5 vs. ZED F9P+LEIAR10	-9.6	26.2	10.2	7.8
ERA5 vs. ZED F9P+ANN-MB#2	-8.8	26.9	7.8	8.9
ERA5 vs. TRMB+LEIAR10	-8.4	23.7	9.6	7.4

Table 6: The **correlation coefficients** between the ZTD time-series of ERA5 reanalysis and GNSS.

Item	Winter 2020	Summer 2021
ERA5 vs. ZED F9P+LEIAR10	0.974	0.906
ERA5 vs. ZED F9P+ANN-MB#1	0.968	n/a
ERA5 vs. ZED F9P+ANN-MB#2	0.963	0.885
ERA5 vs. TRMB+LEIAR10	0.976	0.920

CONCLUSIONS

- We revealed the **high accuracy of the solutions based on the low-cost receiver+antenna dataset**:
  - in the winter campaign, the mean ZTD for the low-cost set differed only by about 1.6 mm compared to that for the high-grade one treated as a benchmark.
- We proved a **significant impact of the GNSS antenna on the tropospheric estimates**:
  - applying a surveying-grade antenna instead of a patch one to a low-cost receiver can noticeably enhance the accuracy of the tropospheric estimates.
- We showed **strong correspondence between GNSS**-derived tropospheric parameters and these of the **ERA5 reanalysis**:
  - the correlation coefficients between the ZTDs of ERA5 and low-cost receivers were higher than 0.96 during the winter campaign.
- The results proved that recent multi-frequency low-cost GNSS equipment may now be considered a mature complement to the high-grade one in troposphere sensing. Such receivers may especially contribute to atmospheric studies taking advantage of their low-cost and thus ease of GNSS permanent network densification enhancing the spatial resolution of soundings.

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For more information see:

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Thank you for your attention!

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