Extending Global and Regional Near Real-Time GNSS ZTD Solutions Using BSW5.4 at the University of Luxembourg: Contributions to E-GVAP

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Abstract

The University of Luxembourg (UL), in collaboration with the United Kingdom Met Office, continues to advance the provision of global and regional near real-time (NRT) Zenith Total Delays (ZTDs) from GNSS ground networks to support operational meteorological products within the EUMETNET EIG GNSS Water Vapour Programme (E-GVAP). E-GVAP facilitates coordination and uptake of NRT GNSS-based atmospheric monitoring, which is indispensable for assimilation in Numerical Weather Prediction (NWP) models across Europe, including at the Met Office, where high-temporal-resolution data enhance mesoscale weather forecasting. This study highlights the collaborative efforts of the Met Office and UL in delivering accurate, timely meteorological data from GNSS. The partnership has resulted in the development and enhancement of NRT processing systems using the state-of-the-art Bernese GNSS software version 5.4 (BSW5.4), generating ZTD products at both UL and the Met Office at 1-hour intervals globally and regionally, and at sub-hourly intervals regionally. Over the past year, UL has focused on developing hourly NRT ZTD solutions for global and regional networks, and more recently extending them to sub-hourly intervals (down to 15 minutes) for regional coverage, thereby refining the temporal resolution for E-GVAP users. In particular, we are now prepared to provide NRT products in the form of a global hourly product (ULGH), a regional hourly product (ULRH), and a regional sub-hourly product (ULRS) to E-GVAP. As part of the system's development, we validate our latest global, regional, and sub-hourly ZTD solutions against established NRT outputs from E-GVAP and benchmark post-processed Double-Difference Network (DDN) products, while also verifying Integrated Water Vapour (IWV) estimates against ECMWF Reanalysis v5 (ERA5). Finally, we highlight how higher-frequency updates can positively influence NWP assimilation in rapidly evolving weather situations, detailing data flow and latency management that ensure reliable NRT ZTD delivery to E-GVAP participants and the Met Office. By extending temporal coverage from hourly to sub-hourly in regional networks and continuing our global solutions, we advance the utility of GNSS-based atmospheric sensing for short-term weather forecasting, providing consistent, high-quality NRT GNSS products for meteorological operations in Europe and beyond.

Introduction

Water vapor is a key greenhouse gas that significantly influences both weather patterns and climate change. Signals from Global Navigation Satellite Systems (GNSS) are delayed during propagation, largely due to the amount of water vapor in the lower atmosphere, making it possible to estimate Zenith Total Delays (ZTD) with millimeter-level precision. By combining GNSS-derived atmospheric delays with surface observations, one can retrieve near real-time (NRT) water vapor information across various spatial and temporal scales. This capacity forms the basis of "GNSS Meteorology," where GNSS-derived atmospheric products are integrated into Numerical Weather Prediction (NWP) models to refine forecasts and, over the long term, contribute to climate research. The EUMETNET EIG GNSS Water Vapour Programme (E-GVAP) has coordinated and distributed NRT GNSS-based atmospheric data for operational meteorology since 2005, enabling analysis centers throughout Europe to supply Zenith Total Delay and Integrated Water Vapor (IWV) estimates for model assimilation and research. At the international scale, the International GNSS Service (IGS) provides high-precision tropospheric products, including its Final Troposphere product (IGFT). Building on these foundations, the University of Luxembourg (UL), in collaboration with the United Kingdom Met Office, has significantly advanced the generation of NRT ZTD products using Bernese GNSS software version 5.4 (BSW5.4). In particular, newly developed processing streams now supply global and regional ZTD estimates at hourly intervals (ULGH and ULRH), as well as sub-hourly (15-minute) updates (ULRS) in regional networks. These higher-frequency products are designed to enhance NWP assimilation, especially in rapidly evolving weather situations, and underscore the expanding role of GNSS Meteorology for short-term weather forecasting and mesoscale model improvement in Europe and beyond.

Data and Methods

SYSTEM	Update cycle	Output sampling	Processing Engine
ULGH/ULRH	Hourly	15 minutes	BSW54 (DD)
IGFT	Post processed	5 minutes	PPP -AR
CODE	Post processed	5 minutes	BSW5 (DD)

Table 1: General characteristics of GNSS processing systems at IGFT, and CODE.

Results-1

Table 2 shows EGVAP regional and global Anaysis Centers (ACs) information.

EGVAP ACs	Update cycle	Output sampling	Processing Engine
ASIC	Hourly	15 minutes	GIPSY
ASI_	Hourly	15 minutes	GIPSY
BKG_	Hourly	15 minutes	BSW52
GOPG	Hourly	15 minutes	BSWV5
GF1G	Hourly	15 minutes	EPOS_P8
LPT_	Hourly	15 minutes	BSW5_5
MTGH	Hourly	15 minutes	BSW52
MTRH	Hourly	15 minutes	BSW52
NGA1	Hourly	15 minutes	BSW54
ROBG	Hourly	15 minutes	BSW52
ROBH	Hourly	15 minutes	BSW52
SGN_	Hourly	15 minutes	BSW52
ULGH	Hourly	15 minutes	BSW54
ULGR	Hourly	15 minutes	BSW54
WUHM	Hourly	15 minutes	PANDA

Table 2: Hourly regional and global EGVAP ACs used in this study.The shaded region are global ones.

Maps of Egvap NRT solutions: Regional and Global

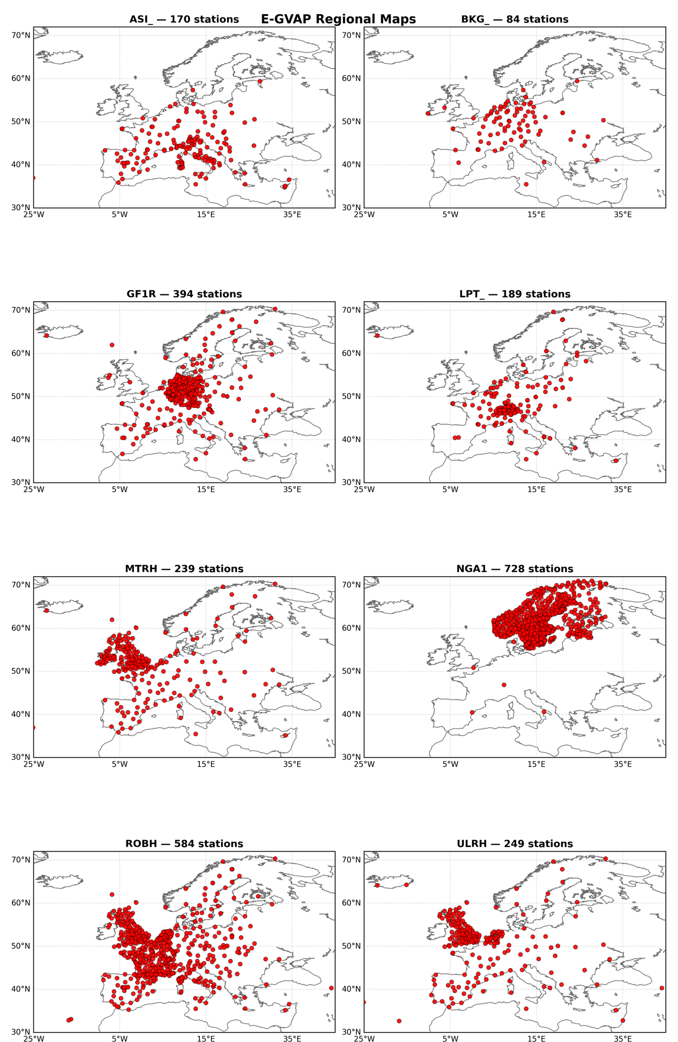

Figure 1a E-GVAP regional maps for each of the ACs used in this study

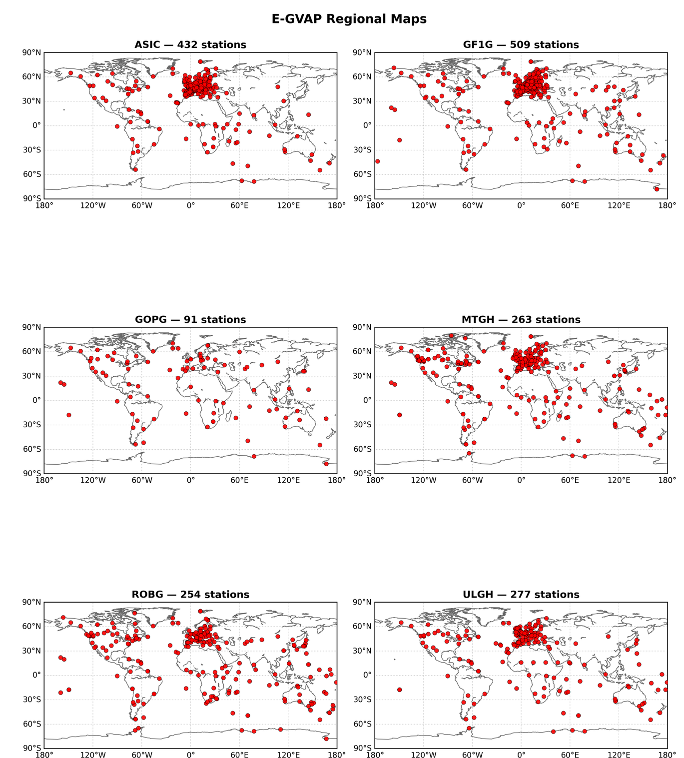

Figure 1b) Global distribution of E-GVAP ground stations by Analysis Center. Panels show locations for each solution: **ASIC** (432 sites), **GF1G** (509), **GOPG** (91), **MTGH** (263), **ROBG** (254), and **ULGH** (277). Red markers denote station positions used in this study.

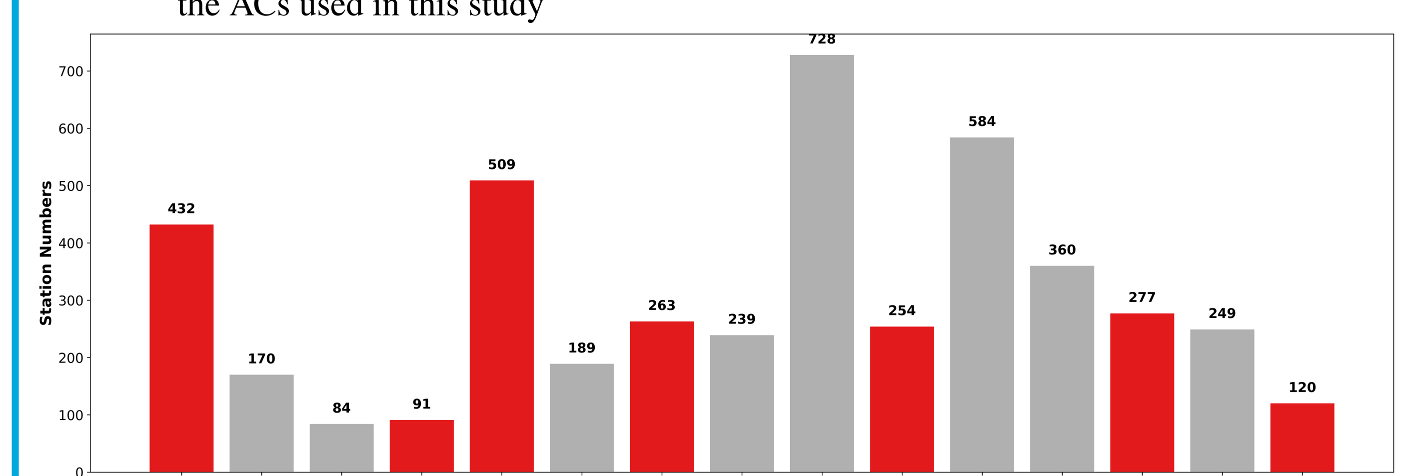

Figure 1c Number of stations processed by each E-GVAP AC at the time of writing

Results-2

Figure 2a shows per-station heatmaps of mean and standard-deviation offsets between ULGH and the IGFT/CODE solutions, revealing clear spatial patterns. Figure 2b overlays ZTD-difference histograms for the 17 stations, with biases from –0.60 mm (IGFT–CODE) to +0.38 mm (CODE–ULGH) and standard deviations of 5.09 mm –7.64 mm. Figures 2c–e present pooled Bland–Altman plots across all stations, yielding negligible biases (–0.66 mm to +0.33 mm) and 95 % limits of agreement (±8.3 mm to ±12.3 mm). After per-station outlier removal, the CODE–ULGH pair narrows to ±8.3 mm (bias –0.66 mm), demonstrating sub-centimetre consistency. Finally, Figure 2f plots the ZTD time series for one station from ULGH, IGFT, and CODE.

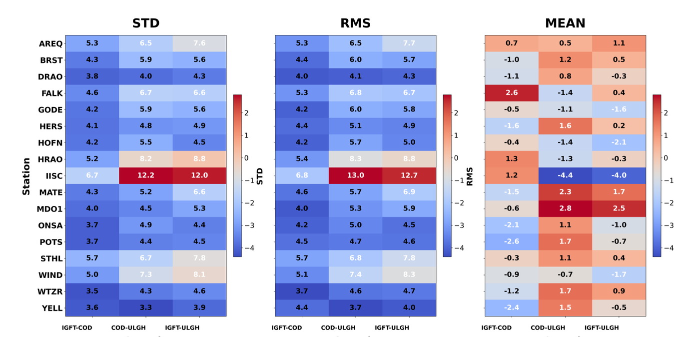

Figure 2(a) Per-station heatmaps statstics

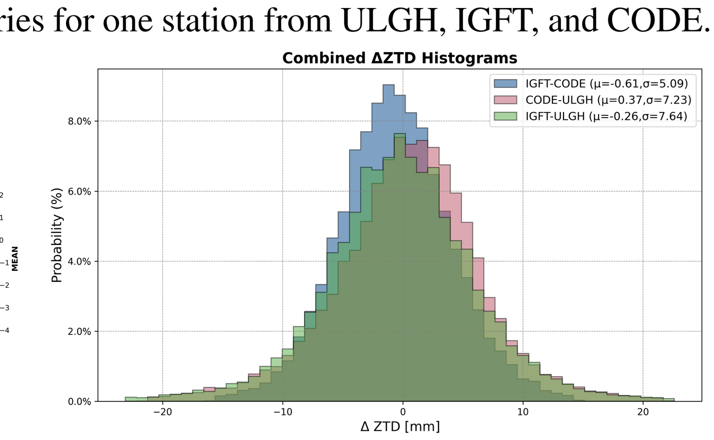

Figure 2(b) Histogram comparison between IGFT, CODE, ULGH for all the 17 stations.

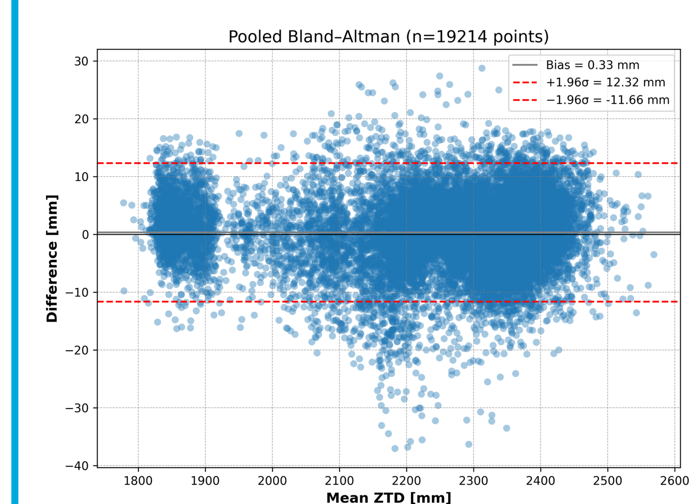

Figure 2(c) Pooled Bland–Altman diagrams comparing pairwise ZTD solutions across all 17 stations. **CODE vs. ULGH**: bias = +0.33 mm, limits of agreement $\pm 1.96\sigma = [-11.66, +12.32]$ mm.

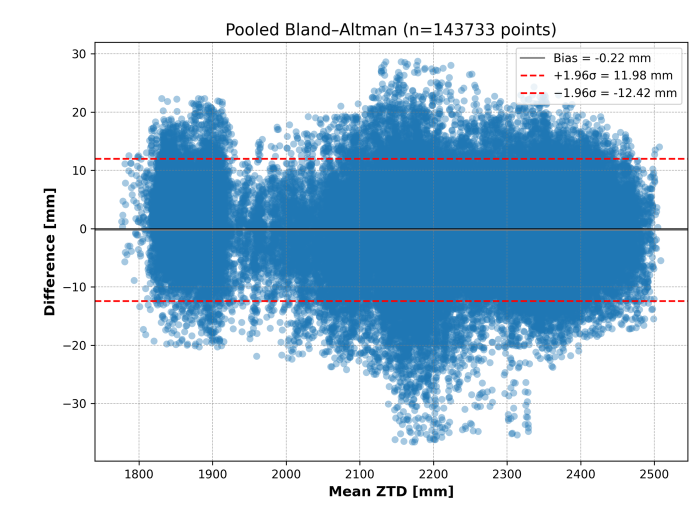

Figure 2(d) Pooled Bland–Altman diagrams comparing pairwise ZTD solutions across all 17 stations. **CODE vs. IGFT**: bias = –0.22 mm, limits of agreement $[-12.42, +11.98]$ mm.

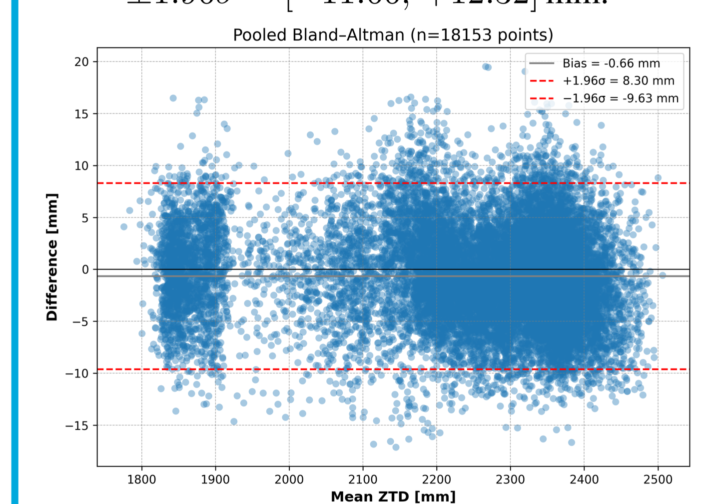

Figure 2(e) IGFT vs. ULGH: bias = –0.66 mm, limits of agreement $[-9.63, +8.30]$ mm.

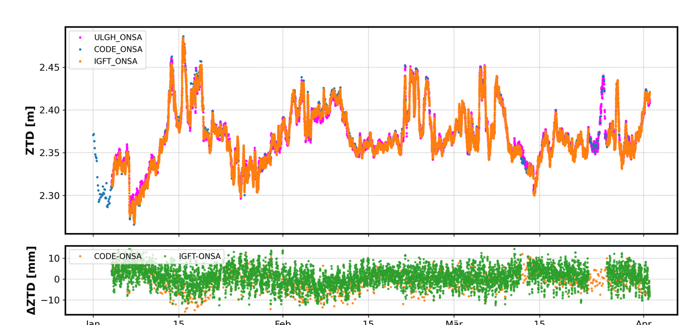

Figure 2(f) ZTD time series and their differences for station ONSA for ULGH, CODE and IGFT solutions for station ONSA.

Conclusions

The accuracy of UL's hourly near-real-time ZTD estimates was assessed against both the IGS Final Troposphere product and the CODE solutions. For the global UL NRT stream (ULGH), the mean bias relative to IGS Final Troposphere was –0.6 mm, and 0.4 mm relative to CODE and standard deviation both at around 7mm. At the regional level (ULRH), against seven E-GVAP Analysis Centers yielded station-by-station biases of only a few millimetres and standard deviations up to 6 mm. These results demonstrate that UL's NRT ZTD products agree at the few-millimetre level with other E-GVAP AC solutions, with particularly close correspondence to MTGH and MTRH.

Result-3

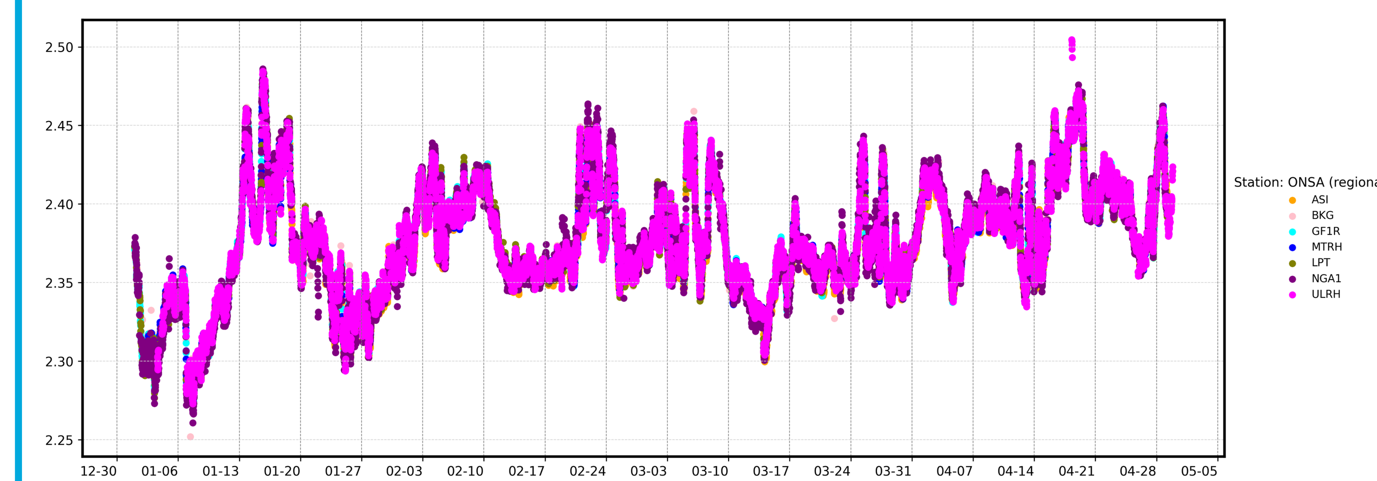

Figure 3: Comparison of E-GVAP ZTD time series for the station ONSA, spanning from January 3, 2025, 00:00 UTC to April 30, 2025, 00:00 UTC. The ULGH solution is highlighted in magenta, while the solutions from other EGVAP ACs follow a different color scheme. Measurements on the vertical axis are expressed in millimetres (mm). (http://www.egvap.dmi.dk).

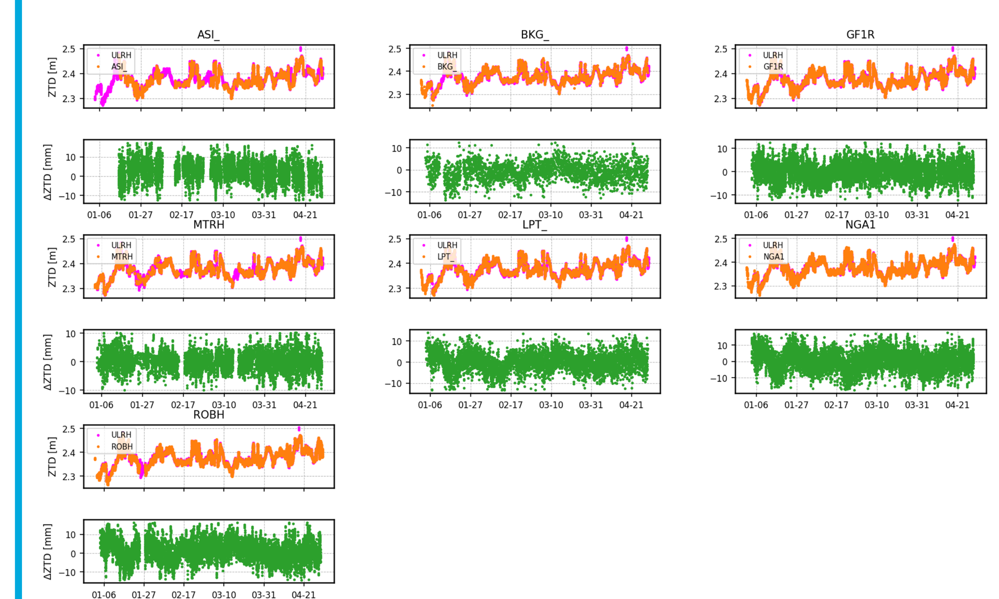

Figure 1: Comparison of reference ULRH ZTD time series (magenta) against seven other NRT solutions (orange) for stations `ASI_`, `BKG_`, `GF1R`, `MTRH`, `LPT_`, `NGA1`, and `ROBH`. Each column is one station: the *top* panel shows the raw ZTD in metres, and the *bottom* panel shows the difference (ULRH–comparison) in millimetres, clipped to $\pm 3\sigma$. X-axis ticks are weekly (Mondays) formatted as MM-DD.

Further Comparisons: Box-Whisker plot

Figure 5 presents box-and-whisker plots of ΔZTD at four GNSS sites (ONSA, YEBE, WTZR, MATE), comparing residuals from ASI, BKG, GF1R, MTRH, LPT_, NGA1 and ROBH against the ULRH reference. Boxes span the 25th–75th percentiles, horizontal lines denote the median, whiskers extend to ± 1.5 IQR, and filled circles mark the mean. Above each box the values of μ and σ (in mm) are annotated, highlighting sub-centimetre biases and station-dependent scatter. Overall, ULRH shows the closest agreement with the MTRH solution, exhibiting the smallest bias and variability across all four sites.

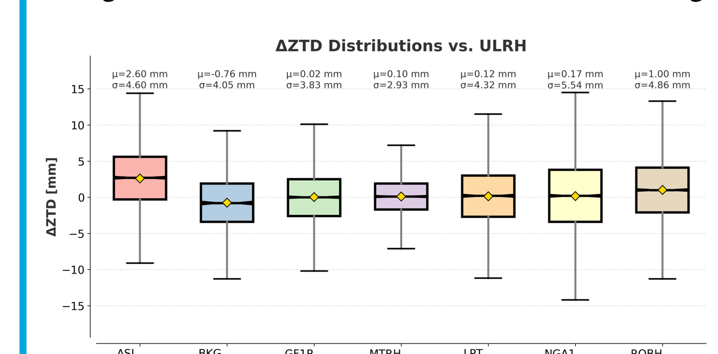

Figure 5(a) ONSA station boxplot

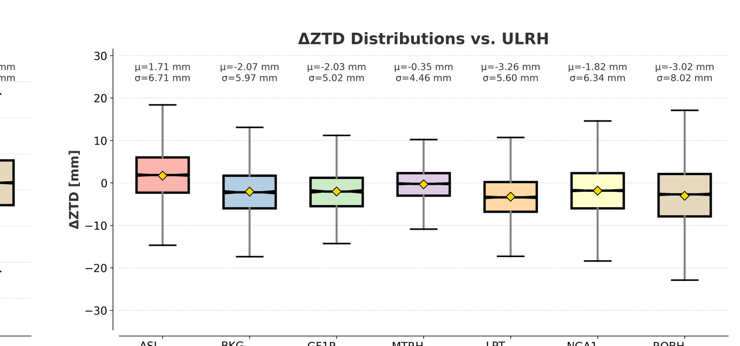

Figure 5(b) YEBE station boxplot

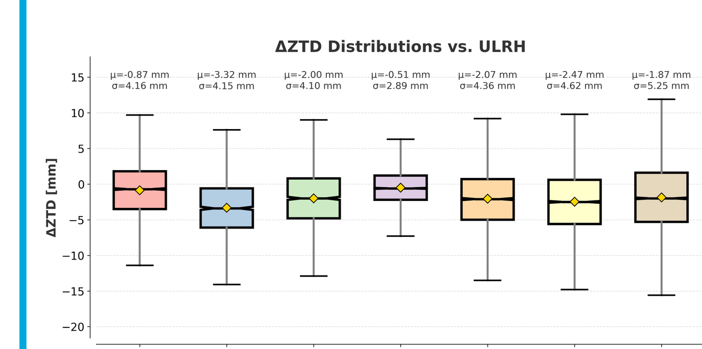

Figure 5(c) WTZR station boxplot

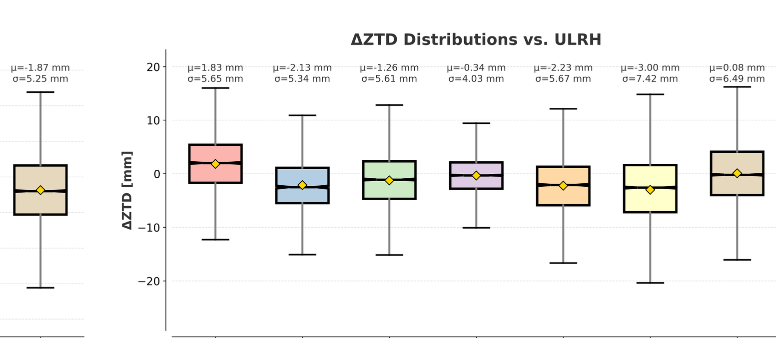

Figure 5(d) MATE station boxplot