Dual-layer tropospheric correction model optimally exploiting GNSS and NWM data

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IGS Workshop

July 3-7, 2017, Paris, France

Outline

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- Comparison of NWM and GNSS ZTDs
- Assessment of case studies
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    3. NWM grid densification – interpolations
    4. GNSS ZTD densification – pseudo-ZTDs
- Conclusion

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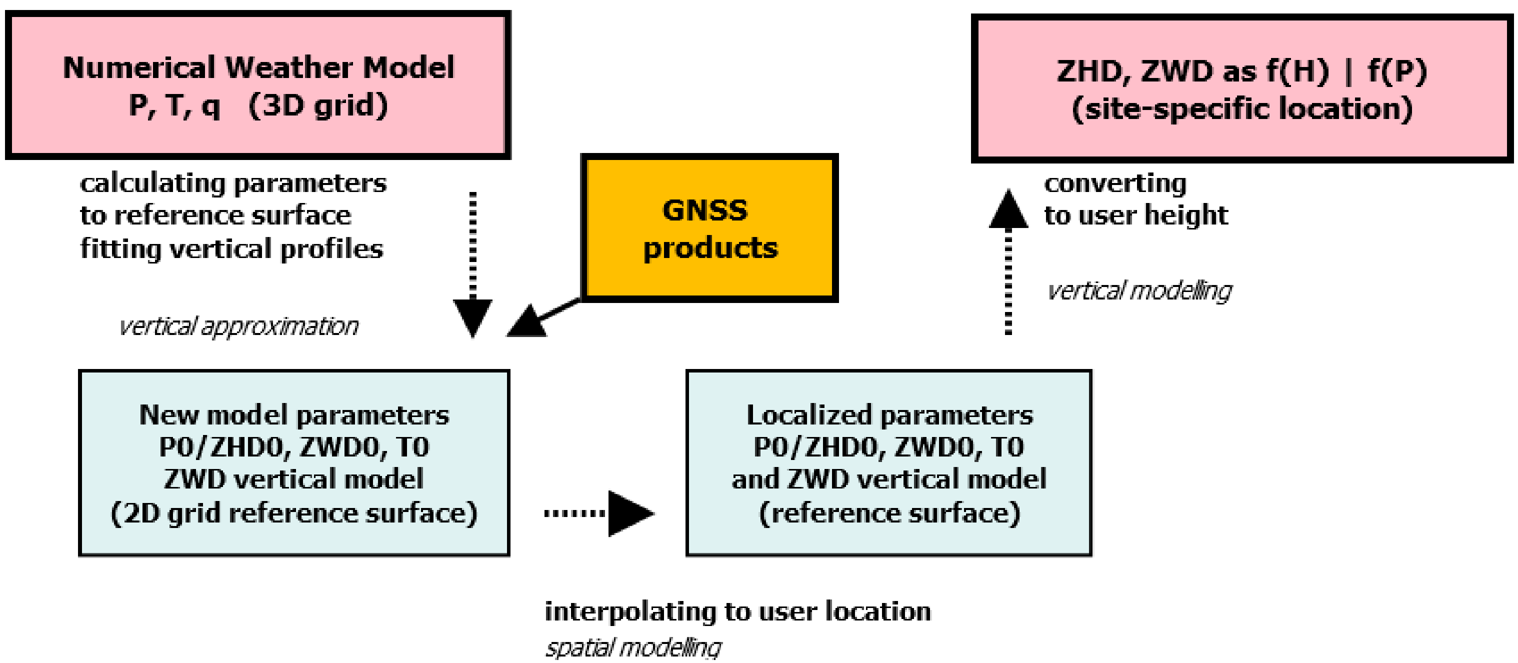
Motivation

Goal: High accurate and stable augmentation tropospheric corrections (ZHD + ZWD) for **real-time GNSS applications**

Impact studies: e.g. Lu et al, AMT, 2016, Václavovic et al. GPS Sol, 2017

Challenge: modelling ZWD (at the earth surface and above)

Basic concept:



Basic idea

Dual-layer augmentation tropospheric correction model

combining data of

1. numerical weather model (NWM) forecast
2. precise Zenith Total Delays (ZTD) from permanent GNSS network

Principles:

- The idea similar to the assimilation of GNSS ZWD (or ZTD) to NWM
- Simplified approach is used for optimal ZWD modelling for GNSS users

The goal of the combination:

- **First layer:** background GOP augmentation model (driven by NWM forecast) provides accurate corrections for dry part of the troposphere, wet correction (background) and auxiliary parameters for vertical scaling
- **Optional layer:** Improved wet part of the background model using data from a high resolution GNSS ZTD product (whenever available).

Data set and products

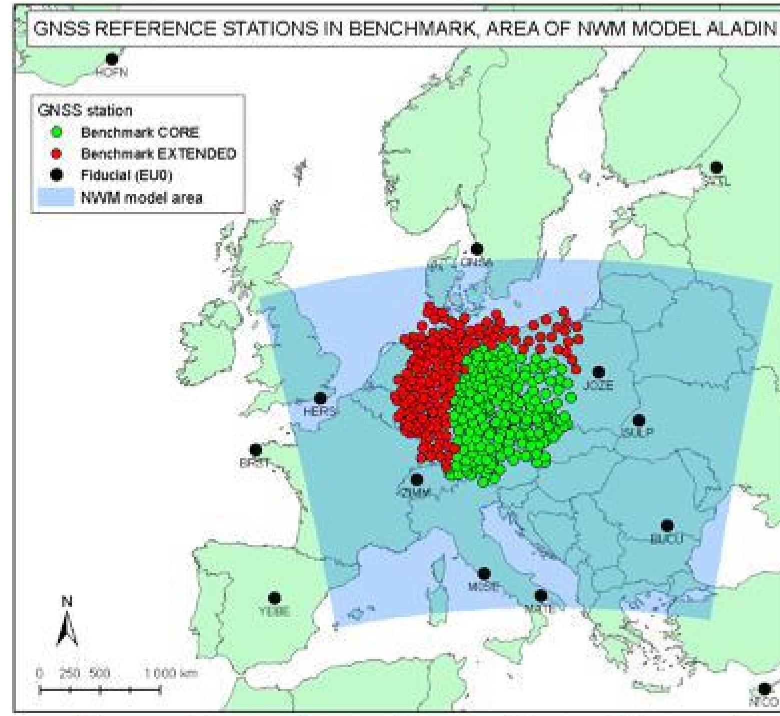
GNSS ZTD product (TRO_SINEX)

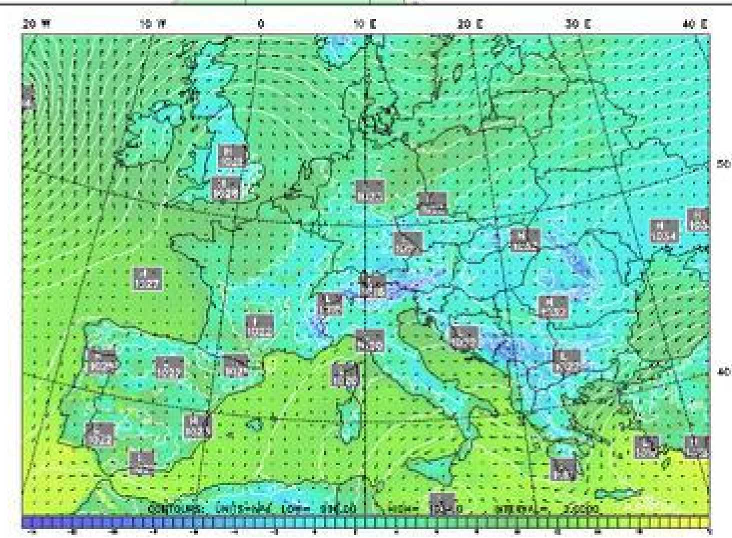
GOP reference solution from the GNSS4SWEC Benchmark campaign *(Douša et al. 2016)*

Numerical Weather Model data sets:

1. ECMWF ERA-Interim (Dee et al. 2009)
   → *global grid (1°×1°), low-resolution*
   → *long-term homegeneous reanalysis*

2. European mesoscale model WRF by Institute of Computer Science, Academy of Sciences, Czech Republic
   → *regional grid (9×9km), high-resolution*
   → *operational forecast for real-time*





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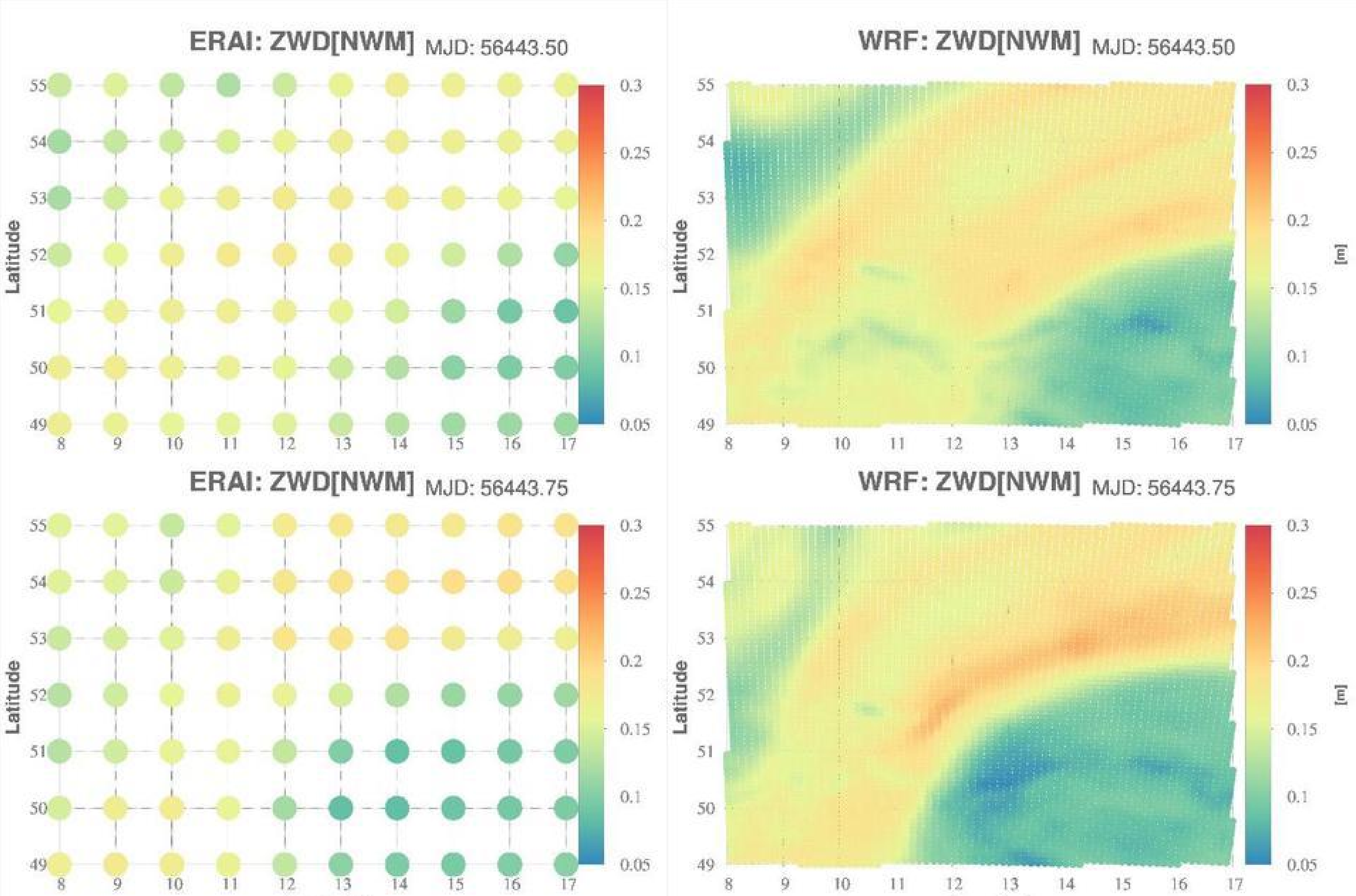
ZWD maps – ERA x WRF



Procedure of the combination

Preparing GNSS data (ZHD subtraction, auxiliary parameters)

GOP background tropo model parameters interpolated to GNSS stations

Synchronization of NWM and GNSS data sets (temporal interpolation)

Optimal ZWD given as a product of ZHD[NWM] and ZTD[GNSS]

Vertical scaling of GNSS ZWDs to a reference surface

Mean seal level used as a reference surface; Douša and Eliaš, GRL, 2014

Spatial interpolation of GNSS ZWDs at reference surface

Simple kriging, sill and range estimated from the theoretical variogram, spherical variogram estimated within the kriging process

Vertical scaling of interpolated ZWDs to NWM orography

Douša and Eliaš, GRL, 2014

Combination of NWM ZWDs with interpolated GNSS ZWDs.

Study of different weighting approach applied

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Assessment procedure

NWM assessment

- **R1:** 100% control points

→ comparison of NWM and GNSS ZWDs

Closed-loop test for the method performance

- **R0:** 100% input points, 100% control points

→ Impact of the involved spatial and temporal interpolation methods

Reduction of input points → control points

- **R3:** 66% input points, 33% control points (every 3rd control)
- **R2:** 50% input points, 50% control points (every 2nd control)

→ Assessment of the method using independent GNSS data

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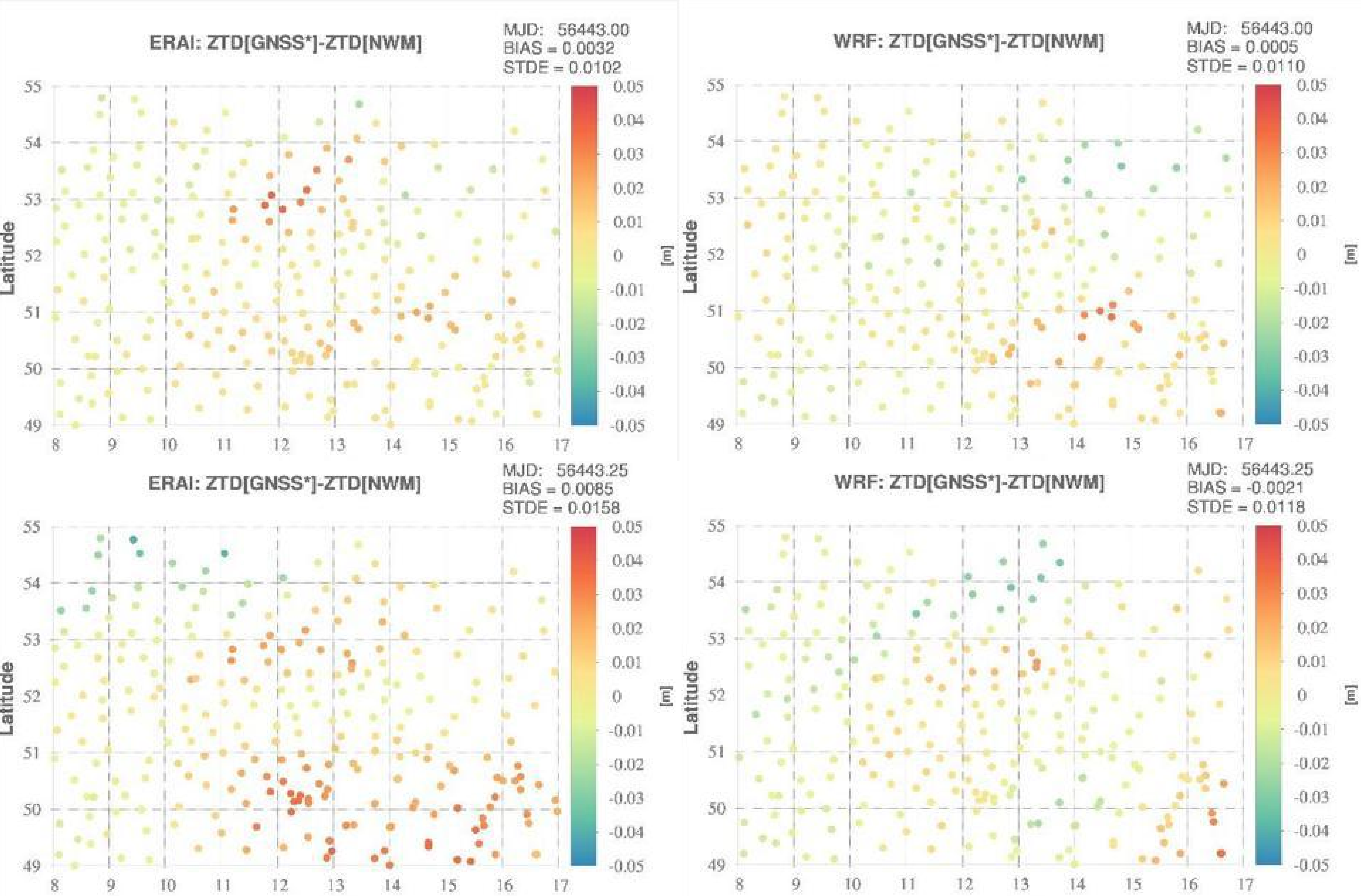
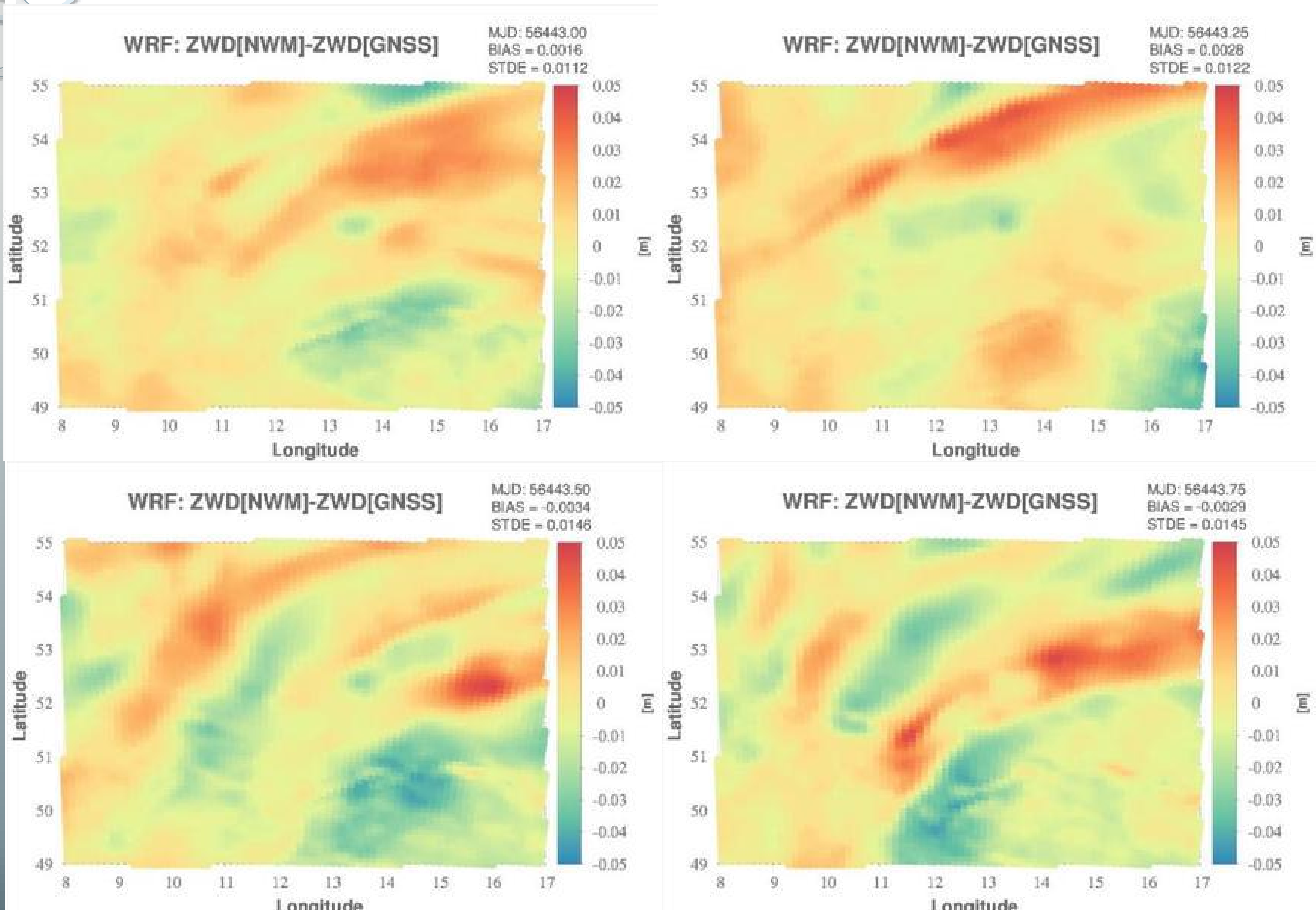
Differences of ZTDs at GNSS sites

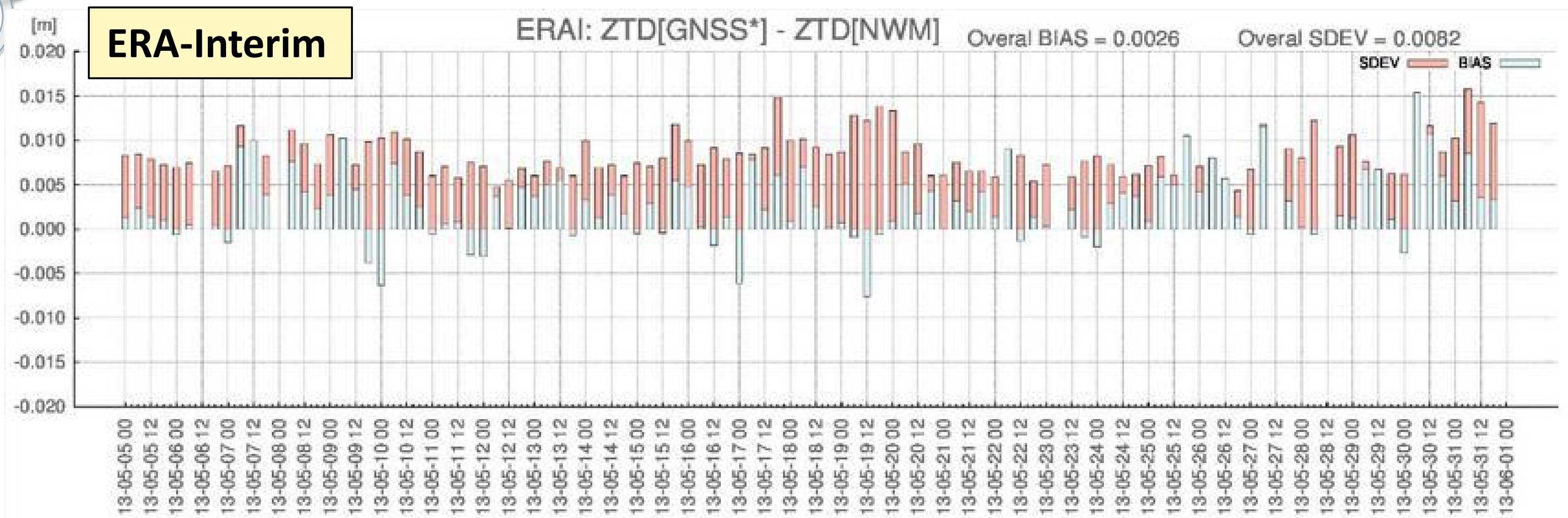


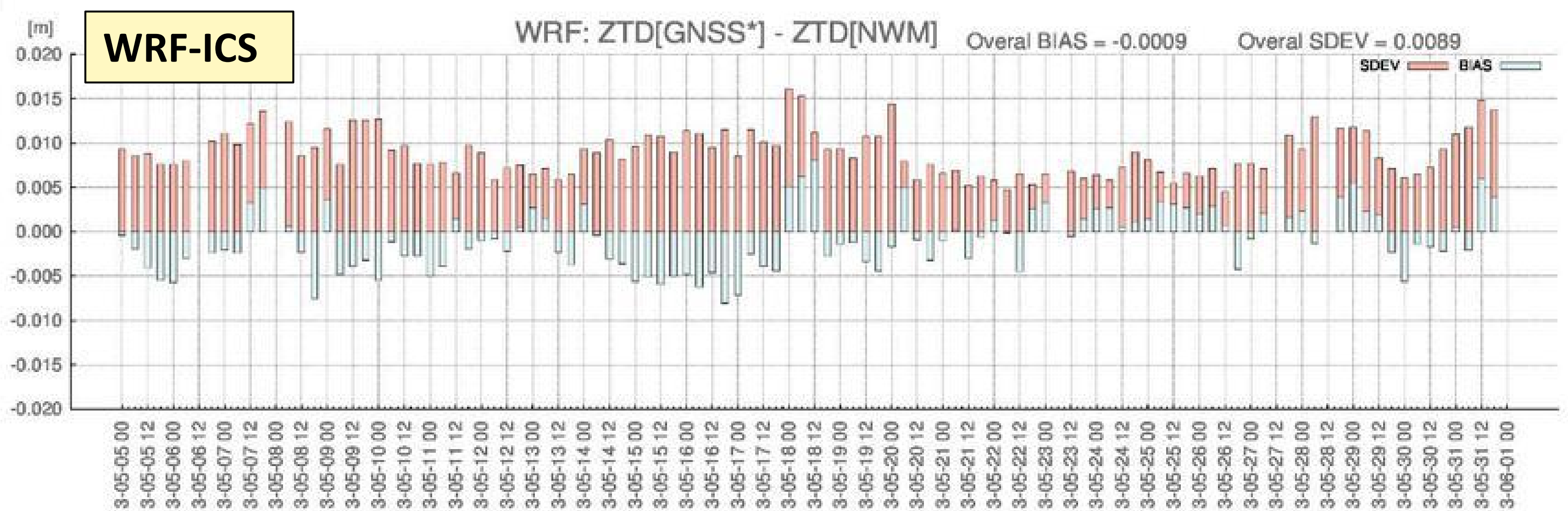
Differences of ZTD/ZWD at NWM grid



Initial GNSS and NWM comparison

Day-to-day statistics for the ERA-Interim and WRF-ICS w.r.t. GNSS





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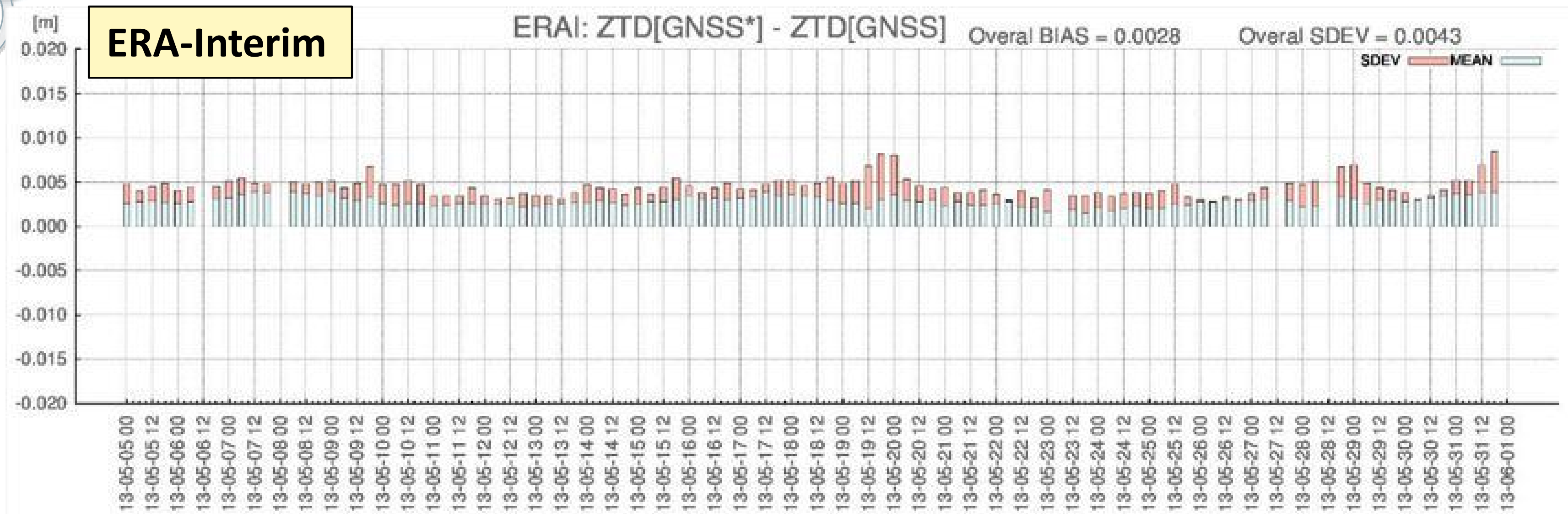
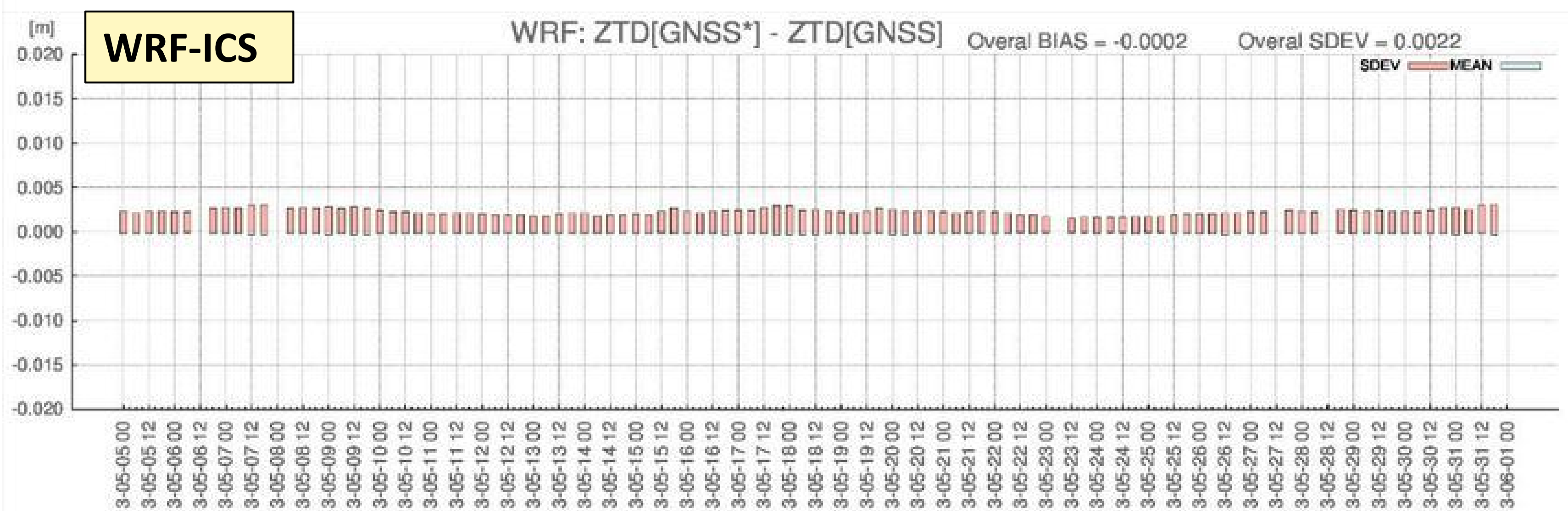
Case study 1: Procedure testing

Day-to-day statistics for the ERA-Interim and WRF-ICS w.r.t. GNSS





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Case study 2: optimal weighting

Presented study variants – A, B, C, D, E

A. $\delta_{GNSS} = 5mm$ $\delta_{NWM} = \infty$ *ZWD replaced by GNSS*

B. $\delta_{GNSS} = 5mm$ $\delta_{NWM} = 10mm$

C. $\delta_{GNSS} = krig$ $\delta_{NWM} = 10mm$

D. $\delta_{GNSS} = 10mm$ $\delta_{NWM} = 10mm$

E. $\delta_{GNSS} = \infty$ $\delta_{NWM} = 10mm$ *Original NWM model*

ZWD combination given as

$$ZWD[CMB] = \frac{ZWD_{GNSS} \cdot w_{GNSS} + ZWD_{NWM} \cdot w_{NWM}}{w_{GNSS} + w_{NWM}}$$

where

$$w_{NWM} = \frac{1}{\sigma^2_{NWM}} \; ; \; w_{GNSS} = \frac{1}{\sigma^2_{GNSS}}$$

Case study 2: optimal weighting

Variant ID	Data weighting [mm] / Data reduction:	R0 or R1 bias / sdev [mm]	R3 (33%) bias / sdev [mm]	R2 (50%) bias / sdev [mm]	Improvement R3 × NWM (sdev)
A	$\sigma_{GNSS} = 10.0\ ;\ \sigma_{NWM} = \infty$	**2.8 / 4.3**	**2.4 / 4.7**	**2.7 / 5.2**	**43.4 %**
B	$\sigma_{GNSS} = 5.0\ ;\ \sigma_{NWM} = 10.0$	2.8 / 4.7	2.5 / 5.0	2.7 / 5.3	39.8 %
C	$\sigma_{GNSS} = \sigma_{Kriging}\ ;\ \sigma_{NWM} = 10.0$	2.8 / 5.0	2.4 / 5.6	2.7 / 5.6	33.5 %
D	$\sigma_{GNSS} = 10.0\ ;\ \sigma_{NWM} = 10.0$	2.7 / 5.9	2.5 / 6.0	2.7 / 6.0	27.7 %
E	$\sigma_{GNSS} = \infty\ ;\ \sigma_{NWM} = 10.0$	2.6 / 8.2	2.5 / 8.3	2.7 / 8.1	-

ZTD statistics of **GNSS** and **ERA-Interim** weighting scenarios for ZWD combination and improvement of E3 reduction with respect to background NWM model (last line).

Variant ID	Data weighting [mm] / Data reduction:	R0 or R1 bias / sdev [mm]	R3 (33%) bias / sdev [mm]	R2 (50%) bias / sdev [mm]	Improvement R3 × NWM (sdev)
A	$\sigma_{GNSS} = 10.0\ ;\ \sigma_{NWM} = \infty$	**-0.2 / 2.2**	**-0.5 / 4.4**	**-0.2 / 4.7**	**49.4 %**
B	$\sigma_{GNSS} = 5.0\ ;\ \sigma_{NWM} = 10.0$	-0.3 / 2.7	-0.5 / 4.4	-0.3 / 4.6	49.4 %
C	$\sigma_{GNSS} = \sigma_{Kriging}\ ;\ \sigma_{NWM} = 10.0$	-0.3 / 2.7	-0.8 / 5.3	-0.7 / 5.7	39.0 %
D	$\sigma_{GNSS} = 10.0\ ;\ \sigma_{NWM} = 10.0$	-0.6 / 4.7	-0.6 / 5.4	-0.5 / 5.6	37.9 %
E	$\sigma_{GNSS} = \infty\ ;\ \sigma_{NWM} = 10.0$	-0.9 / 8.9	-0.8 / 8.7	-0.8 / 8.8	-

ZTD statistics of **GNSS** and **WRF-ICS** weighting scenarios for ZWD combination and improvement of E3 reduction with respect to the background NWM model (last line).

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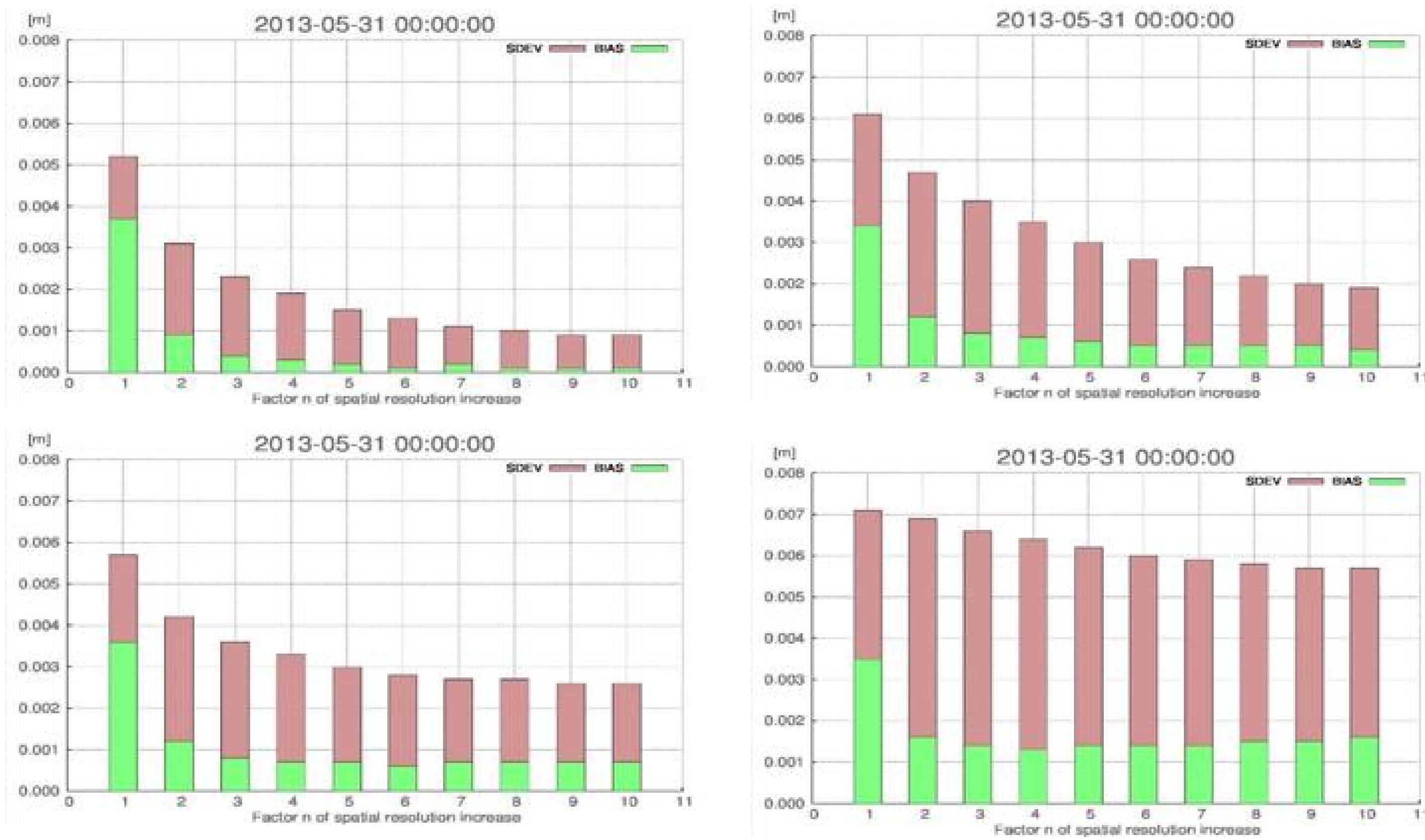
Case study 3: NWM densification

Impact of the grid resolution on the contribution from GNSS products



Statistics of differences between ZTD[NWM] and ZWD[GNSS] and using four weighing scenarios in testing an impact of increased horizontal resolution of ERA-Interim model. The ZWD weighting scenarios A, B, C and D (from the top-left to the bottom-right) were studied in 31 May, 2013, 00UTC.

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Case study 3: NWM densification

Study of increasing ERA-Interim spatial resolution before combining ZWDs:

ERA-Interim	**Factor for increasing spatial resolution**	**F=1.0 (none)**	**F=2.0 (twofold)**	**F=3.0 (threefold)**	**F=4.0 (fourfold)**	**WRF: E0 (none)**
Variant ID	**Data weighting [mm]**	**bias / sdev [mm]**	**bias / sdev [mm]**	**bias / sdev [mm]**	**bias / sdev [mm]**	**bias / sdev [mm]**
A	$\sigma_{GNSS} = 10.0\ ;\ \sigma_{NWM} = \infty$	2.8 / 4.3	0.6 / 2.7	0.3 / 2.0	**0.2 / 1.6**	-0.2 / 2.2
B	$\sigma_{GNSS} = 5.0\ ;\ \sigma_{NWM} = 10.0$	2.8 / 4.7	0.9 / 3.7	0.7 / 3.2	**0.6 / 2.9**	-0.3 / 2.7
C	$\sigma_{GNSS} = \sigma_{Kriging}\ ;\ \sigma_{NWM} = 10.0$	2.8 / 5.0	1.0 / 4.2	0.8 / 3.6	**0.6 / 3.1**	-0.3 / 2.7
D	$\sigma_{GNSS} = 10.0\ ;\ \sigma_{NWM} = 10.0$	2.7 / 5.9	1.4 / 6.2	1.3 / 6.0	**1.2 / 5.7**	-0.6 / 4.7
E	$\sigma_{GNSS} = \infty\ ;\ \sigma_{NWM} = 10.0$	2.6 / 8.2	2.2 / 10.5	2.2 /10.7	**2.2 /10.6**	-0.9 / 8.9

Densification of low-resolution NWM grid (ERA-Interim)

→ full benefit from high-resolution GNSS ZTDs

Variant A - replacement of interpolated ZWD from GNSS at NWM grid points

- Fast decrease of NWM biases (from 2.8 mm to 0.3 mm)
- Progressive improvement in standard deviation (from 4.3 mm to 1.6 mm)

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Case study 4: GNSS pseudo-ZTDs

Basic idea

- Better benefit of GNSS in high-resolution NWM
  - GNSS (50-70km), WRF-ICS (9×9km)

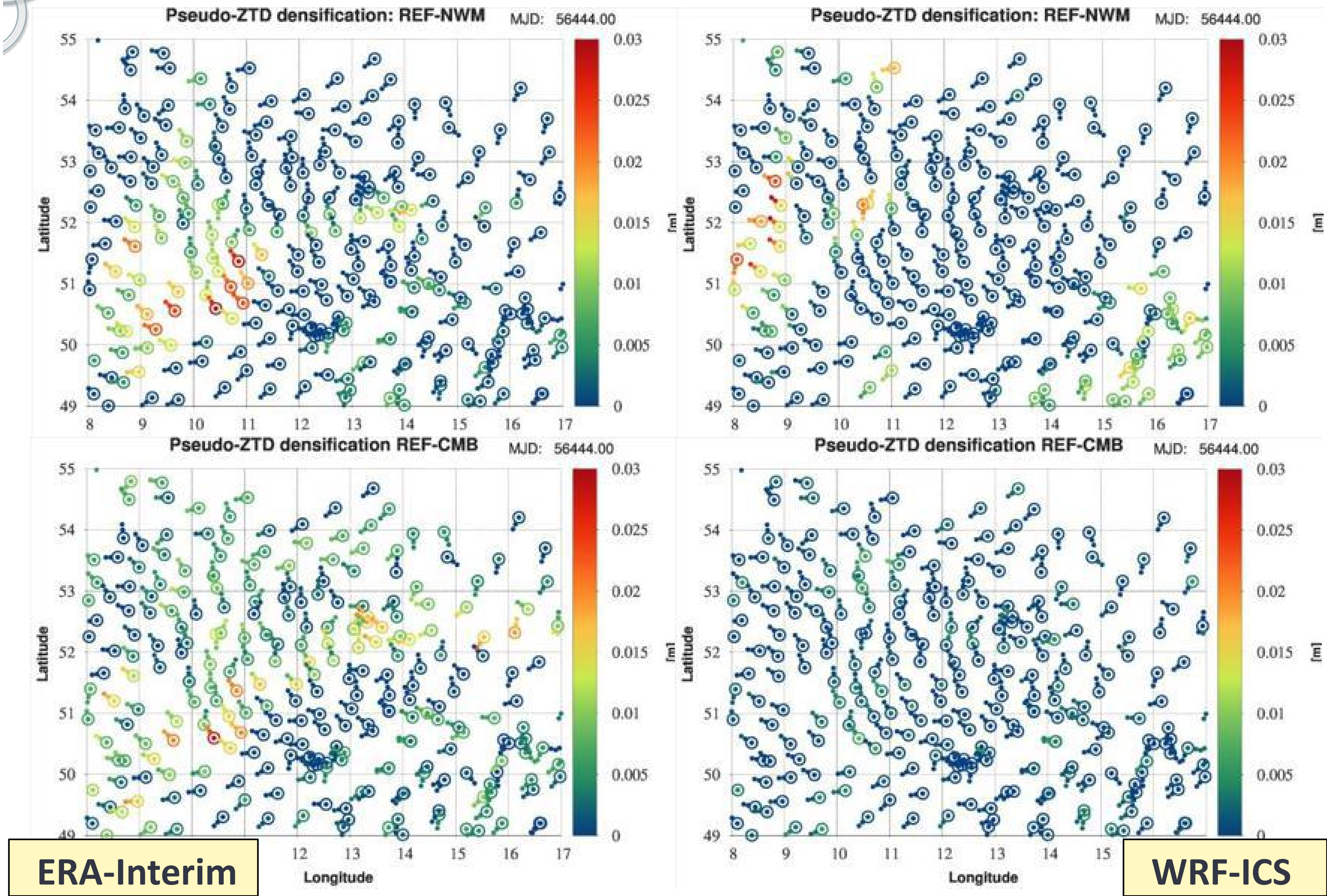
- Exploitation of GNSS horizontal gradients
  - Densification of GNSS ZTD product
  - Method to calculate pseudo-ZTD

$$\overline{ZTD} = ZTD + 1/\tan(e) \cdot \left[G_N \cos(A) + G_E \sin(A) \right]$$

  - Expression of pseudo-ZTD in the distance of 15km
  - Expression of pseudo-ZTD in the azimuth of minimum gradient

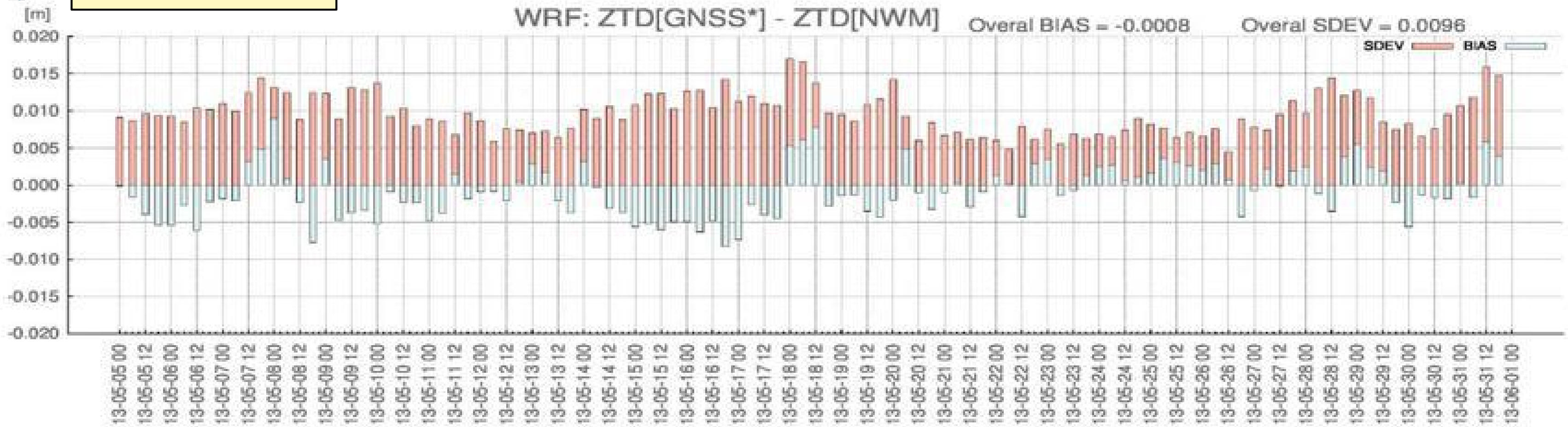
Case study 4: GNSS pseudo-ZTDs

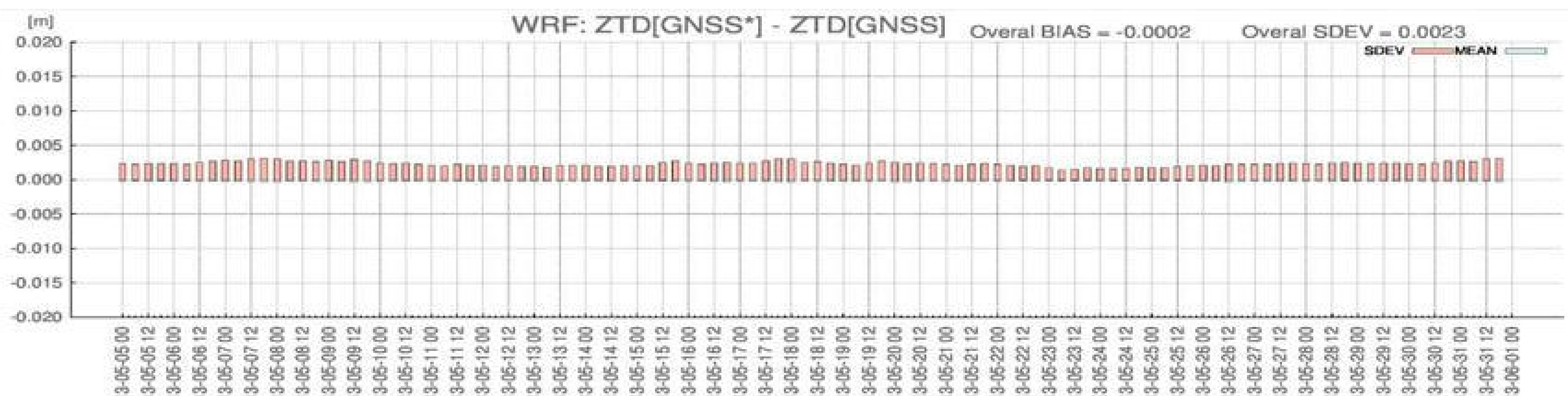
Pseudo-ZTD gradients calculated at distances 15 and 25 km from GNSS site



Case study 4: GNSS pseudo-ZTDs

WRF-ICS





daily statistics of ZTD comparisons at GNSS sites using original GNSS ZTDs as reference; top: ZTD[NWM] from the WRF-ICS model; bottom: ZTD[GNSS] from the combination.

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Case study 4: GNSS pseudo-ZTDs

ZTD statistics when using GNSS pseudo-ZTDs and the WRF-ICS model:

WRF-ICS

Variant ID	Data weighting [mm] — Data reduction:	R0 or R1 bias / sdev [mm]	R3 (33%) bias / sdev [mm]	R2 (50%) bias / sdev [mm]
A (original-ZTDs)	$\sigma_{GNSS} = 10.0$; $\sigma_{NWM} = \infty$	–0.2 / 2.2	–0.5 / 4.4	+0.2 / 4.7
A (pseudo-ZTDs)	$\sigma_{GNSS} = 10.0$; $\sigma_{NWM} = \infty$	**–0.2 / 2.4**	**–0.2 / 2.9**	**+0.0 / 3.0**
E (original-ZTDs)	$\sigma_{GNSS} = \infty$; $\sigma_{NWM} = 10.0$	–0.9 / 8.9	–0.8 / 8.7	–0.8 / 8.8
E (pseudo-ZTDs)	$\sigma_{GNSS} = \infty$; $\sigma_{NWM} = 10.0$	–0.8 / 9.6	–0.7 / 9.5	–0.8 / 9.6

Densification of GNSS ZTD product (for high-resolution NWM)

Exploitation of gradients for deriving pseudo-ZTDs at 15 km distance from stations

- Significant improvement in precision (35% in standard deviations)
- Further reduction of biases (already sub-mm)

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Conclusions

- New dual-layered concept combining NWM and GNSS data
  - Background layer – GOP-ZWD augmentation model (NWM-driven)
  - Advanced layer (optional) – GNSS ZTDs from regional networks
- Use of GNSS ZTDs in augmentation model
  - Assessment in close-loop scenario and independent control points
  - Improvement up to 40% achieved (NWM's ZWD replaced from GNSS)
    - GNSS corrected NWM for errors in both ZWD and ZHD and reduced biases in NWM
    - GNSS significantly stabilized the NWM solution in day-to-day performance
- Impact studies of two densification scenarios
  - Densification of low-resolution NWM grid (ERA-Interim)
    - Full benefit from high-resolution GNSS ZTDs
    - Fast decrease of NWM biases and progressive improvement in precision (SDEV)
  - Densification of GNSS ZTD product (for high-resolution NWM)
    - Use of gradients to calculated pseudo-ZTDs in distances of 15-25 km to stations
    - 35% improvement in precision and reduction in bias

➔ Superior method for a tropospheric augmentation service

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Thank you for your attention

Acknowledgements

ESA for funding the study of new concept (DARTMA project)

IGS for providing final and real-time GNSS products

ECMWF for providing ERA-Interim reanalysis

ICS for providing WRF forecasts

All GNSS contributors to GNSS4SWEC WG1 Benchmark dataset (Douša et al, 2016)

Disclaimer: *The work reported in this paper has been performed under a contract of the European Space Agency in the frame of the Announcement of Opportunities on GNSS Science and Innovative Technology within the European GNSS Evolutions Programme, . The views presented in the paper represent solely the opinion of the authors.*

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