TECHNISCHE UNIVERSITÄT WIEN
Vienna | Austria

Tropospheric delay parameters derived from GNSS-tracking data of a fast moving fleet of trains

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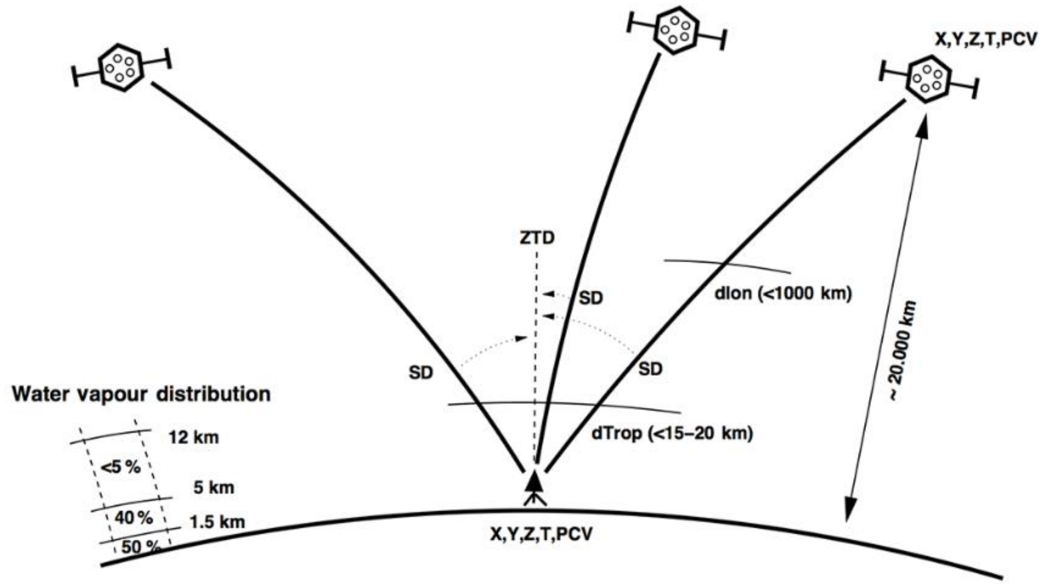
GNSS Meteorology

Troposphere:

- Introduces **delay** on GNSS signals
- Dependent on pressure, temperature and **water vapour**
- Error source for positioning but **valuable signal for meteorology**

Zenith Total Delay (ZTD)

- Common parameter in GNSS processing
- Represents signal delay in zenith direction
- Can be split up for hydrostatic (ZHD) and wet part (ZWD)
- Proportional to water vapor content
- Beneficial observation for Numerical Weather Prediction (NWP)



Guerova et. al, 2016

Processing strategy:

- Common: Double-difference approach, Estimation from (reference) stations providing high-quality observations in GNSS analysis (together with e.g. station coordinates)
- PPP processing: more and more studies, lower computational power, but also lower accuracy

Thesis contribution

- Main goal:

  Derive (reasonable) tropospheric parameters from (low-cost/single-frequency) GNSS data of a fleet of fast moving trains

- Main idea:

  Use trains as meteorological sensors ----> huge number travelling all over Austria ------> very good horizontal/temporal resolution

- Questions:
  - Reliable estimation of tropospheric delays possible?
  - Which data processing scheme(s)?
  - Which temporal and spatial resolution can be achieved/used when processing a larger fleet of trains?
  - What is the quality of the derived data and is it sufficient to be incorporated into an NWP data assimilation system?
  - Can the estimation and assimilation be carried out in a (near) real-time (NRT) operational mode?

Data: GNSS

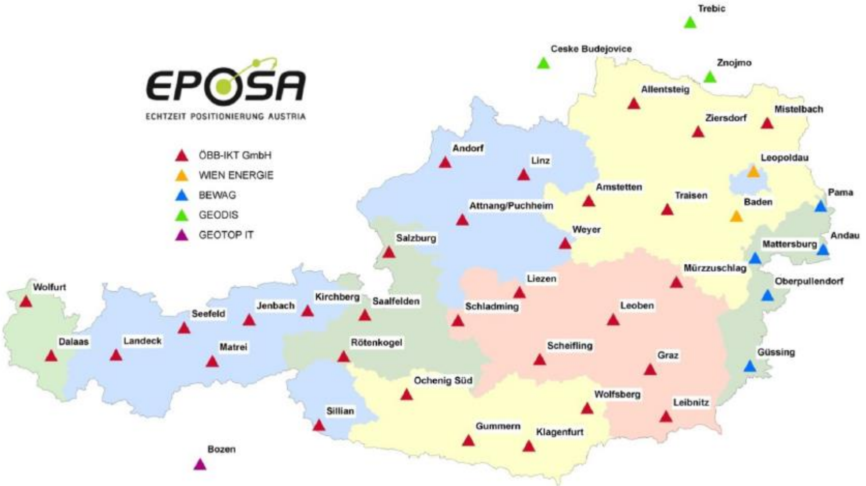
Data from **ÖBB Greenlight** project

- ublox dual-system
    - Currently GPS + GLONASS
    - in future GPS + Galileo
- Single-frequency (SF) observations
- 1 Hz update rate
- Thankfully provided by ÖBB!

Data from **EPOSA reference station network**:

- Dual-frequency (DF) data
- Use for SEID algorithm (ionospheric mitigation, Deng et al, 2009)

Copyright: DI (FH) Manfred Stättner, ÖBB Infra



Copyright: EPOSA , www.eposa.at

Data: Equipped trains

Status shown here: May 2019, till today ~ 1400 trains equipped

ÖBB-Produktion GmbH

Baureihe 1016/1116

Ausgerüstet: 23 u. 40 Stück

Baureihe 1144

Ausgerüstet: 54 Stück

Baureihe 1116 - RailJet

Ausgerüstet: 10 Stück

Baureihe 1063/1163

Ausgerüstet: 2 u. 1 Stück

Baureihe 1216

Ausgerüstet: 4 Stück

Baureihe 1064

Prototyp Einbau in Arbeit

ÖBB-Personenverkehr AG

Baureihe 2016

Ausgerüstet: 1 Stück

Baureihe 4744/4746

Ausgerüstet: 8 u. 65 Stück

Baureihe 5022

Ausgerüstet: 1 Stück

Baureihe 2070

Ausgerüstet: 1 Stück

Baureihe 4023/4024/4124

Ausgerüstet: 1 u. 15 u. 10 Stück

Baureihe 4020

Ausgerüstet: 1 Stück

Baureihe 5047

Ausgerüstet: 2 Stück

ÖBB-Infrastruktur AG

Baureihe 1064

Ausgerüstet: 4 Stück

Methodology: GNSS processing

- **Kinematic PPP approach**
- Software available:
  - CSRS –PPP online service
  - GAMP (GFZ, only DF) -----> use SEID approach for DF generation
  - PPP-Wizard (CNES)
- Ionosphere mitigation:
  - SF-PPP: GIM maps or EGNOS corrections
  - DF-PPP: DF generation using Satellite-specific Epoch-differenced Ionospheric Delay (SEID) algorithm
- Pre-processing:
  - Cycle slip detection (DF: MW-LC, SF: Time-differencing)
  - Multipath analysis
- Smoothing of time series:
  - Moving-average filtered solutions

PPP processing schemes

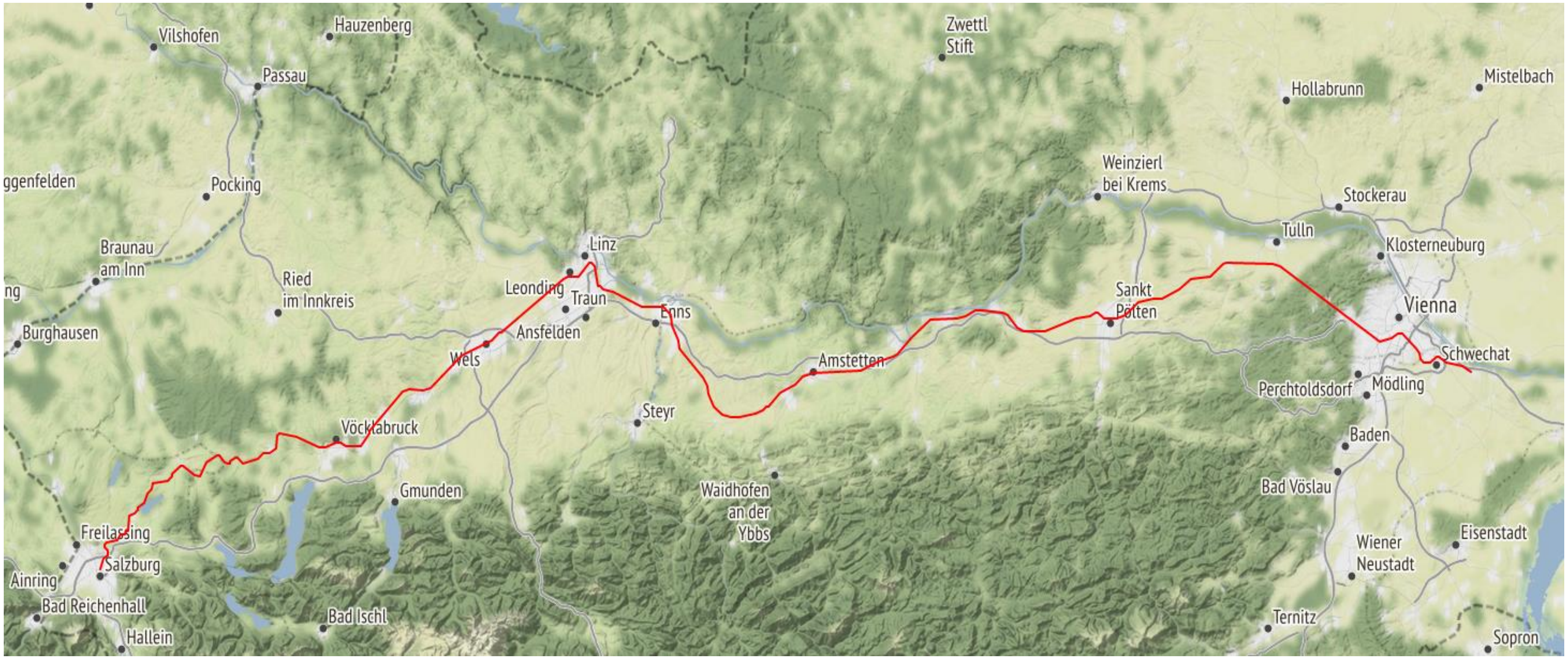
Processing schemes:

- **CSRS-PPP (CSRS-PPP):** online PPP service, SF/DF data, Seq. least squares estimation
- **GAMP (SGAMP):** GFZ, DF data, use with SEID model, Kalman Filter
- **PPP-Wizard (PPPW):** CNES**,** SF/DF data, Kalman Filter
- **PPP-Wizard with height constraint (PPPW-HC):**
  - Use database of Austrian railway tracks (thankfully provided by ÖBB)
  - Constrain height coordinate using heights from database
  - Search nearest point to 2D GNSS position in database and take height from there
  - These are heights from pylons (not antenna heights!) ----> correction needed!
  - Problem: correction unknown ---> use median of height differences between pylons and GNSS antenna (dH, ~4 m)
  - Criterion for application:

$$|H_{GNSS} - (H_{RDB} + dH)| > 0.1m$$

Case studies: Overview and PPP settings

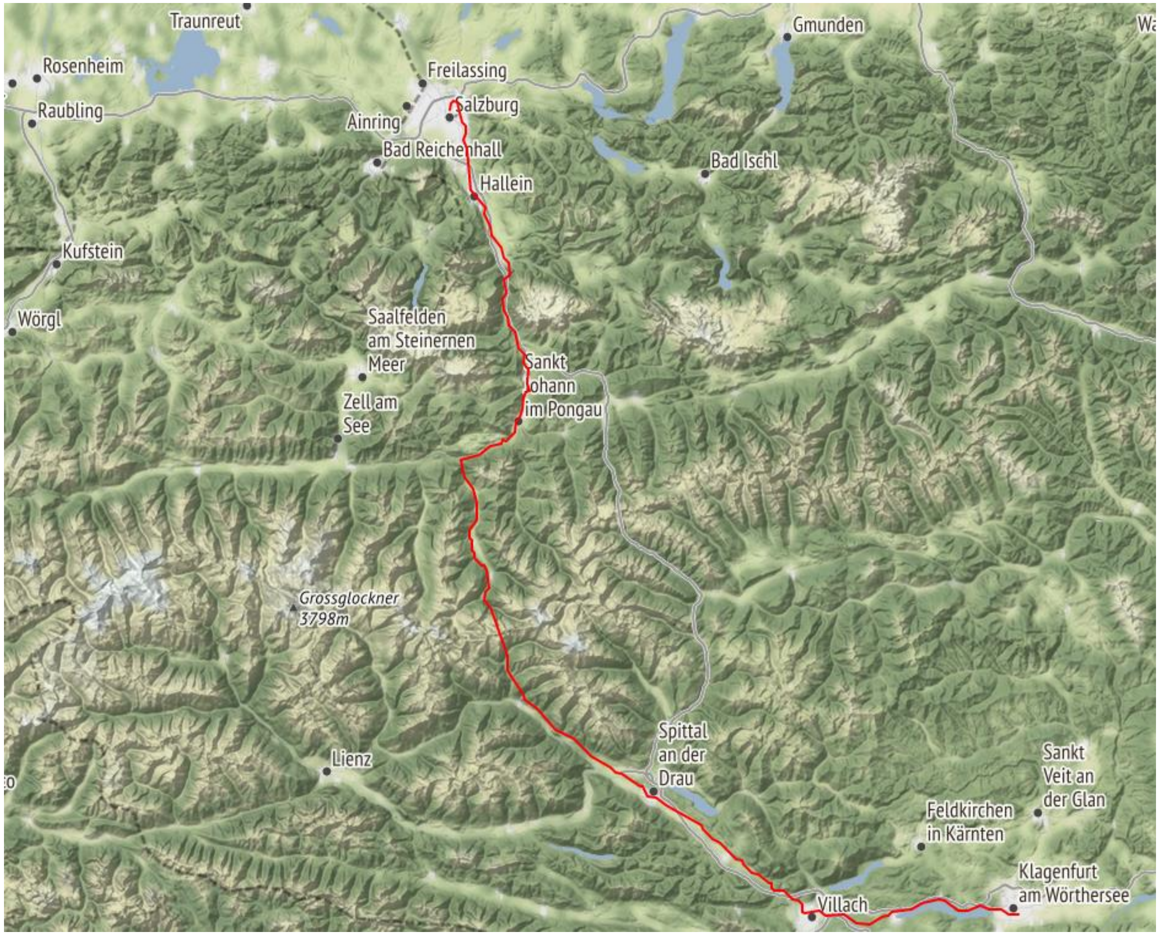
Test case	Date	Route	Processing
CS1	11.05.2017	Salzburg - Vienna airport	CSRS-PPP/PPP-Wizard
CS2	28.09.2017	Salzburg - Klagenfurt	CSRS-PPP/PPP-Wizard/SGAMP
CS3	29.11.2019	Innsbruck - Wörgl - Schwarzach/St.Veit - Liezen	CSRS-PPP/PPP-Wizard
CS 4	01.12.2019	Innsbruck - Wörgl - Schwarzach/St.Veit - Liezen - Graz	CSRS-PPP/PPP-Wizard



CS1 : Track plot from CSRS-PPP processing

CS2: 28.09.2017

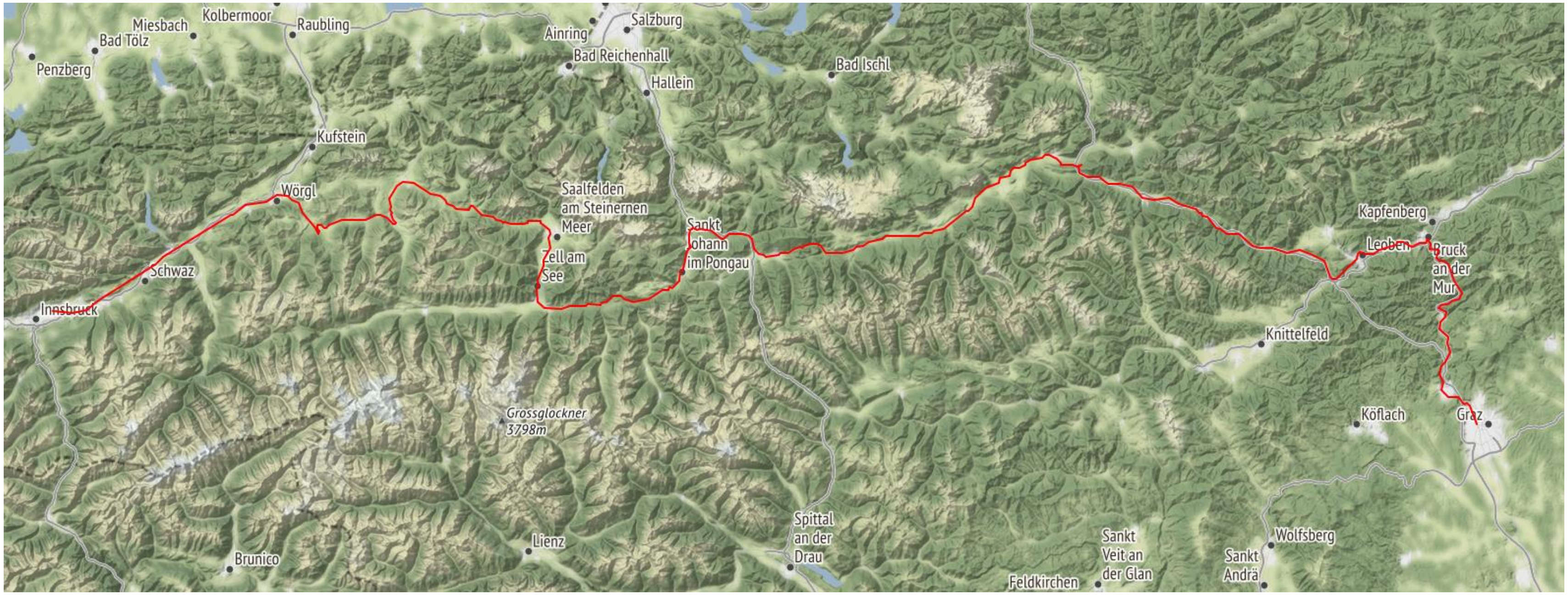
CS2: Salzburg – Villach - Klagenfurt



Track plot from CSRS-PPP processing

CS3 and CS4: 29.11.2019/01.12.2019

CS3 and CS4: Innsbruck – Wörgl – Liezen - Graz



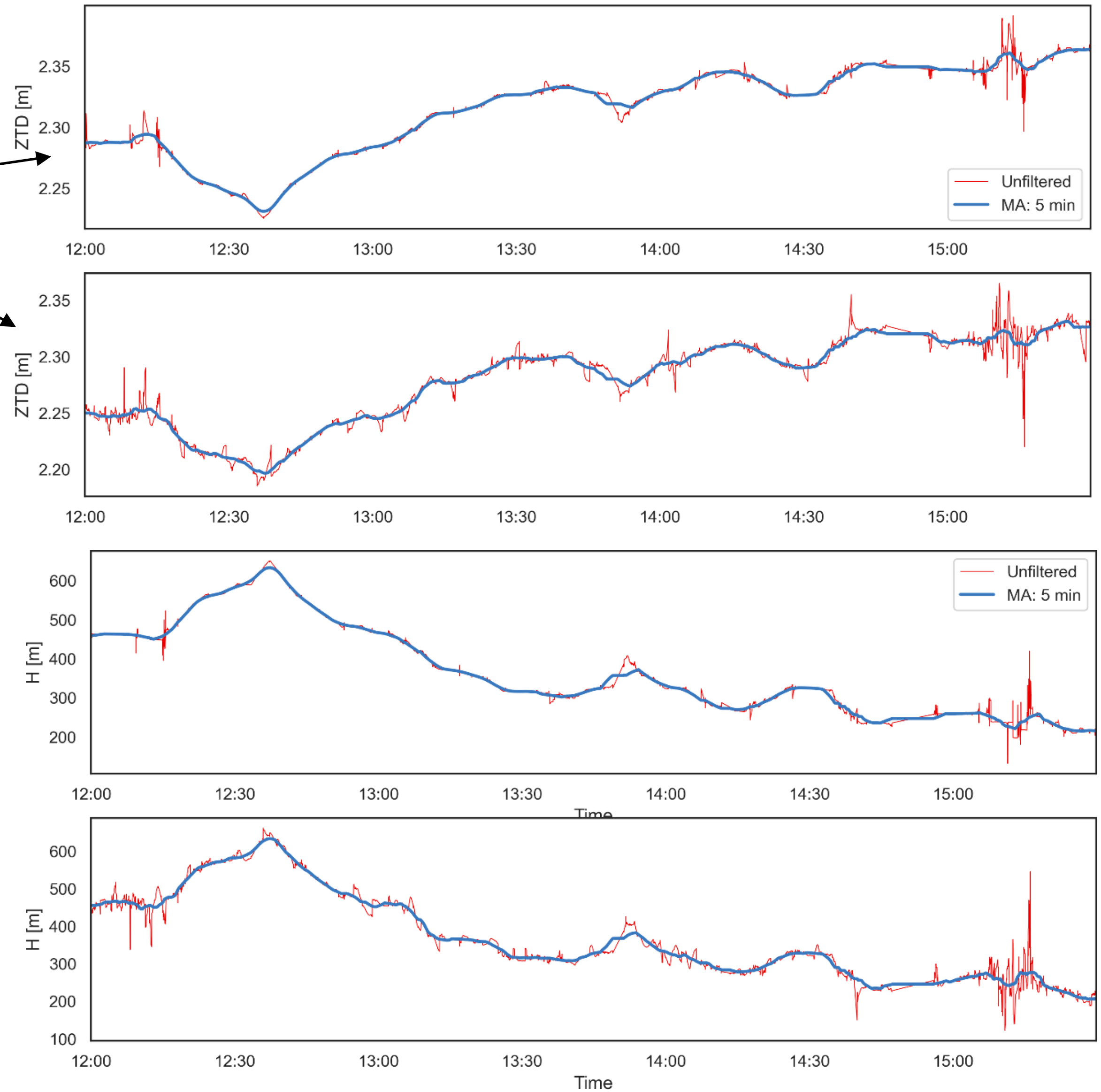
Track plot from CSRS-PPP processing

PPP processing settings

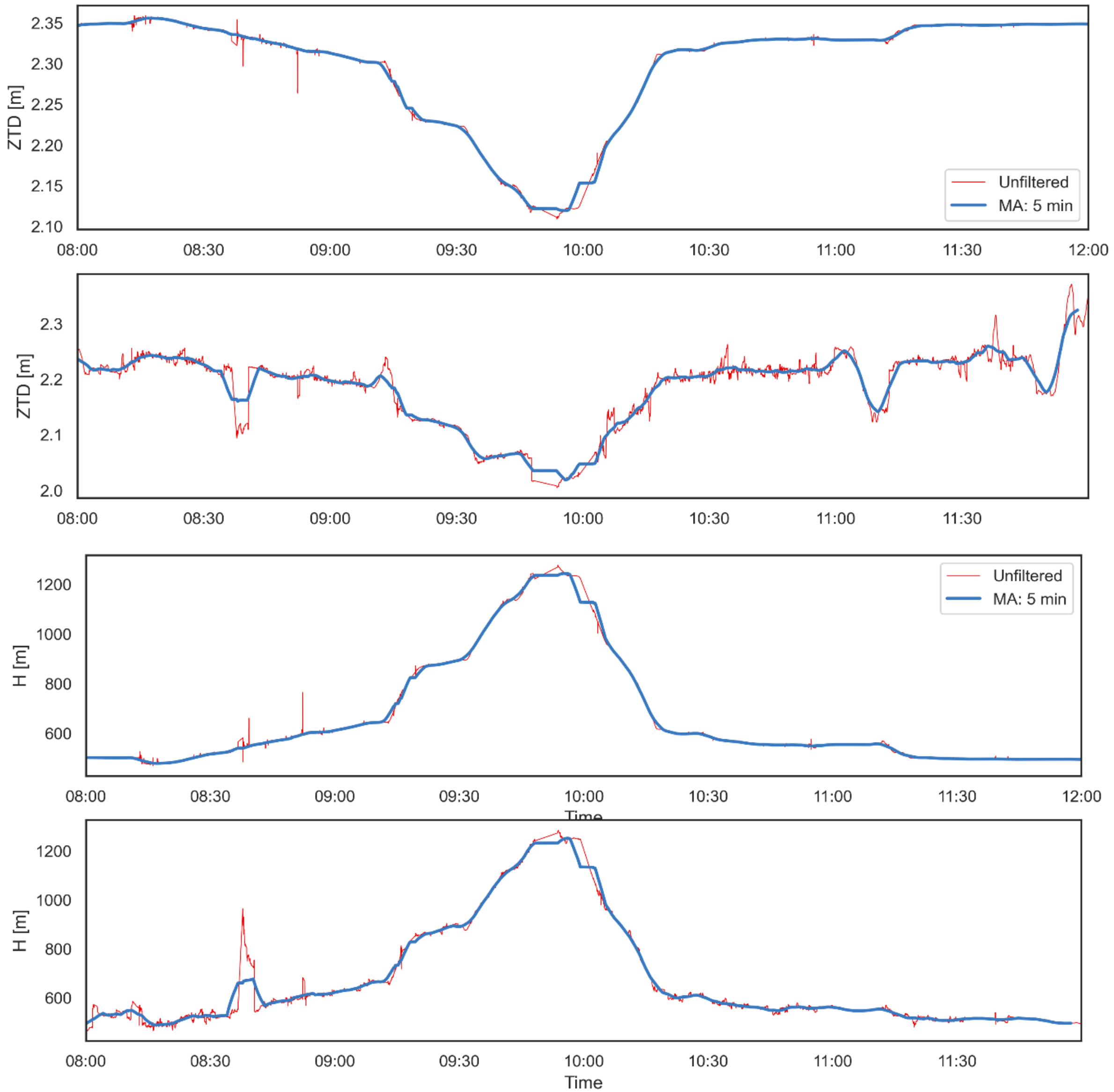
Parameter	CSRS-PPP	SGAMP	PPPW/PPPW-HC
Mode	Kinematic SF-PPP	Kinematic DF-PPP	Kinematic SF-PPP
GNSS		GPS + GLONASS	
Ambiguities		Float	
Orbits/Clocks		IGS Final	
Ionosphere	GIM	SEID/IF-LC	EGNOS
ZHD (a-priori)	VMF1	Saastamoinen	
σ_{Code}		1-10 m	
σ_{Phase}		0.1-0.5 m	
$\sigma_{Position}$		10 m	
σ_{ZWD}		0.005 m/sqrt(s)	

Noise analysis of PPP solutions: CS1

- Comparison: Original PPP output vs smoothed solution (5-min MA filter)
- CSRS-PPP and PPPW results (available for all CS)
- Shown here: CS1 and CS2 (next slide)
- Analysis for height coordinate and ZTD differences
    - Standard deviation (SD)
    - Root mean square error (RMS) of differences
- Strong negative correlation
- Noise level:
    - mm-cm ZTD
    - m-level height



Noise analysis of PPP solutions: CS2



Methodology: ZTD validation

Data: ERA5 reanalysis

- Newest reanalysis of ECMWF
- Horizontal resolution: 31 km, 37 vertical levels, temporal resolution : 1 hour
- ERA5-ZTD in good agreement with GNSS-ZTD in former studies (only few as ERA5 =new dataset)

Methodology:

- Refractivity from pressure, temperature, relative humidity (Essen and Froome, 1951)

$$N_{tot} = k_1 \frac{p}{T} - k_2 \frac{e}{T} + k_3 \frac{e}{T^2},$$

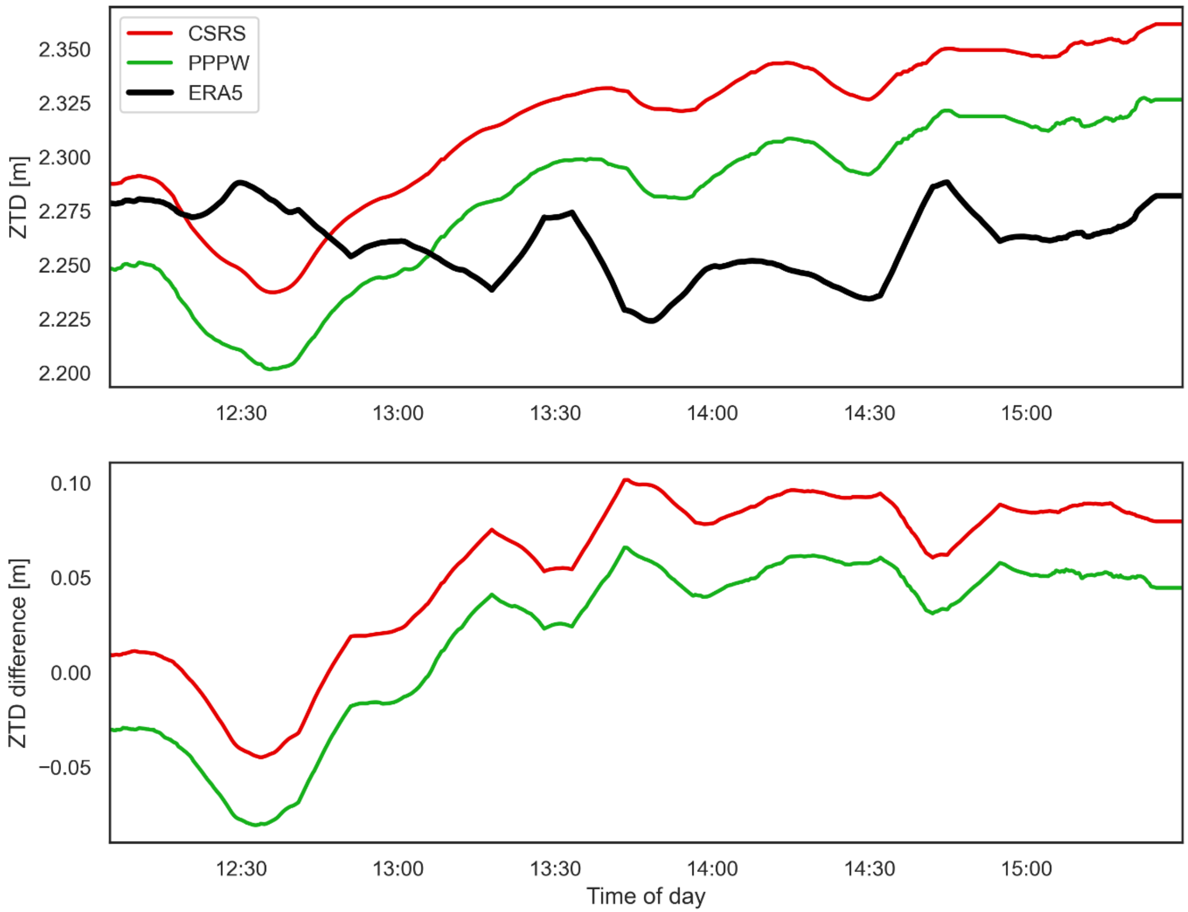
where $k1 = 77.689 KhPa^{-1}$, $k2 = 71.2952 KhPa^{-1}$ and $k3 = 375463 KhPa^{-1}$

- ZTD through vertical integration
- Correction for model top (Saastamoinen, 1972)
- 3D interpolation to train track (lat,lon,time)

$$ZTD_m = 10^{-6} \cdot \int N_{tot}$$

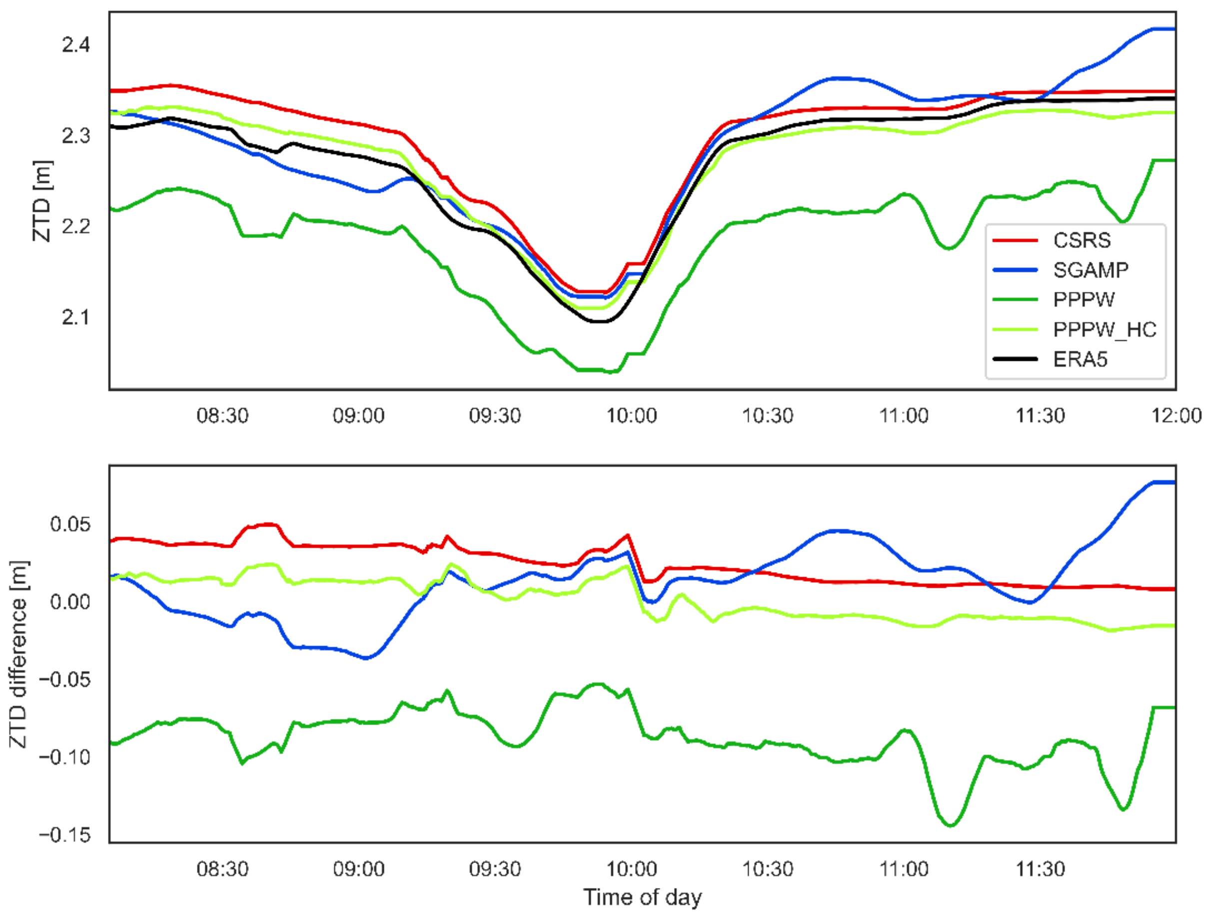
CS1: Validation using ERA5

- GNSS solutions agree well
- Contrary patterns between ERA5 and GNSS in first hour
  - ERA5 errors?
  - Local water vapour anomaly?
- Overall correlation distorted from first hour
- Large improvements when analysing only 13:30 – 15:30

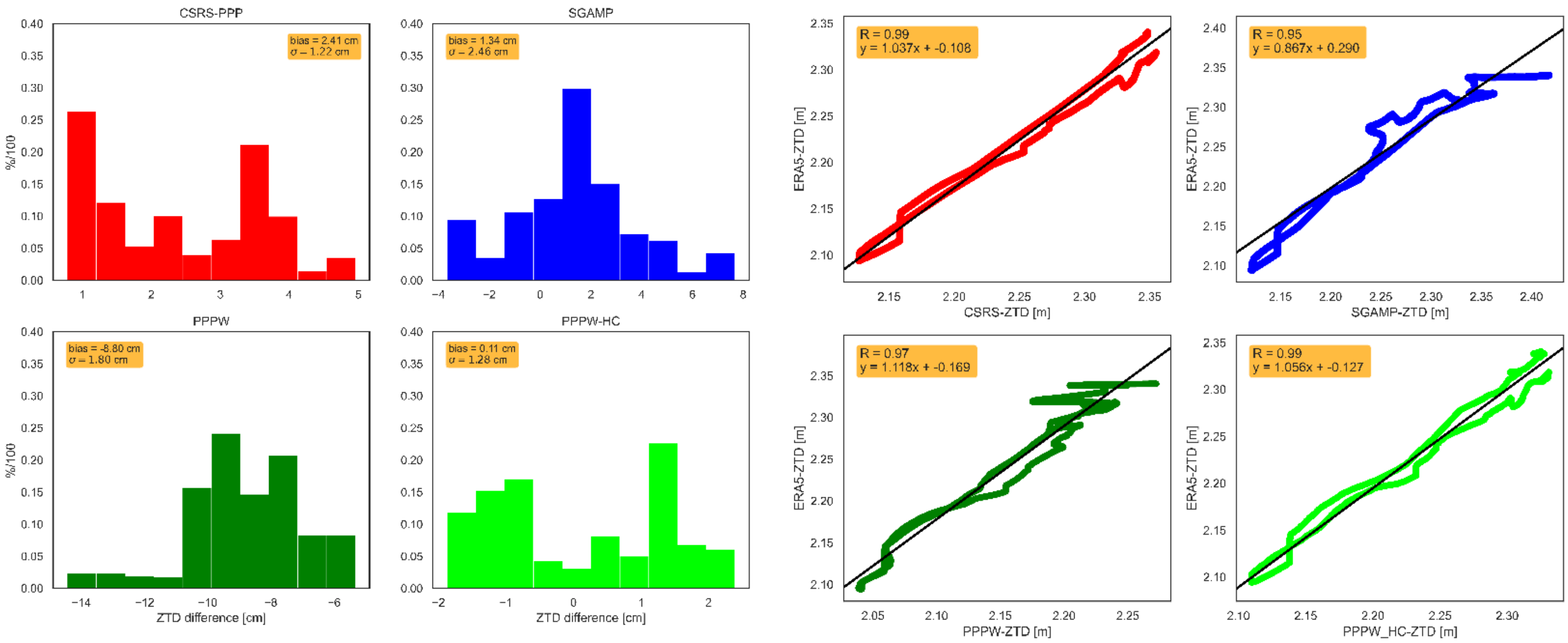


CS2: Validation using ERA5

- Correlation between GNSS-ZTD and ERA-ZTD very high
- Larger bias (~5-10 cm) for PPPW solution
- PPPW-HC solution performs best (only ~ 1 mm bias)
- SGAMP with good performance (bias = 1.34 cm)



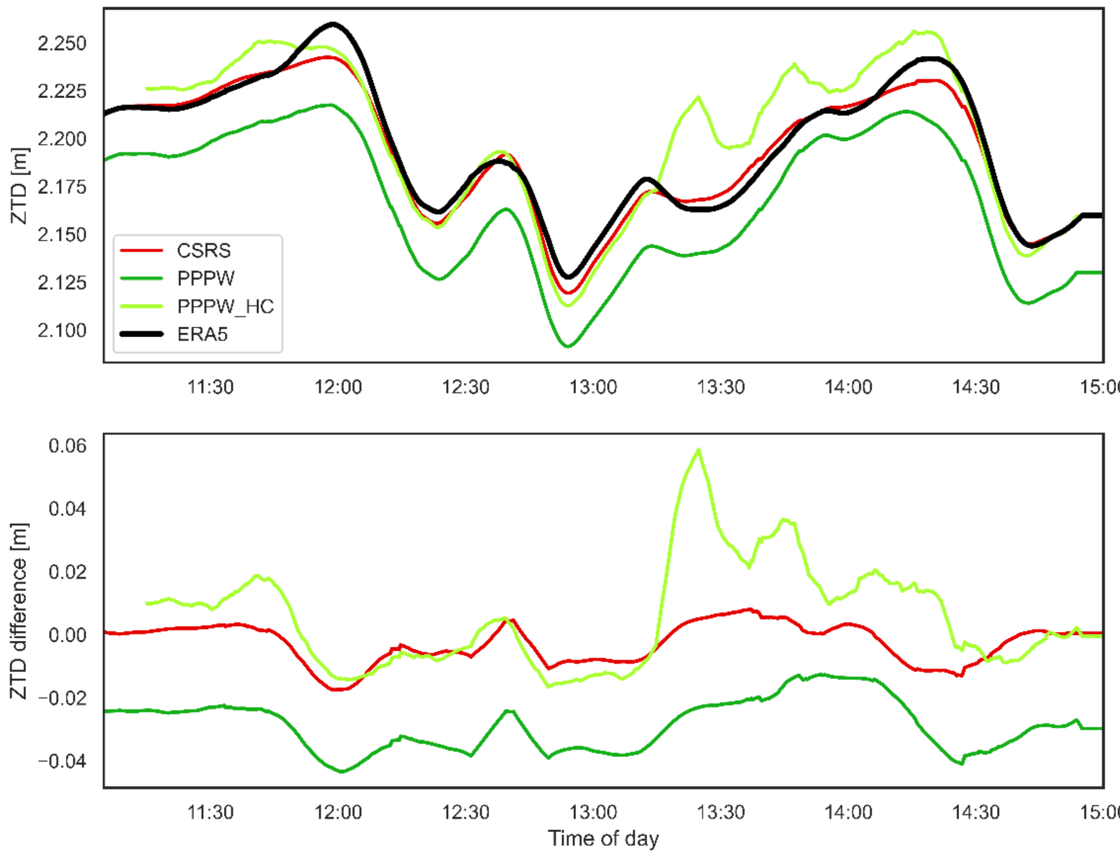
CS2: Validation using ERA5



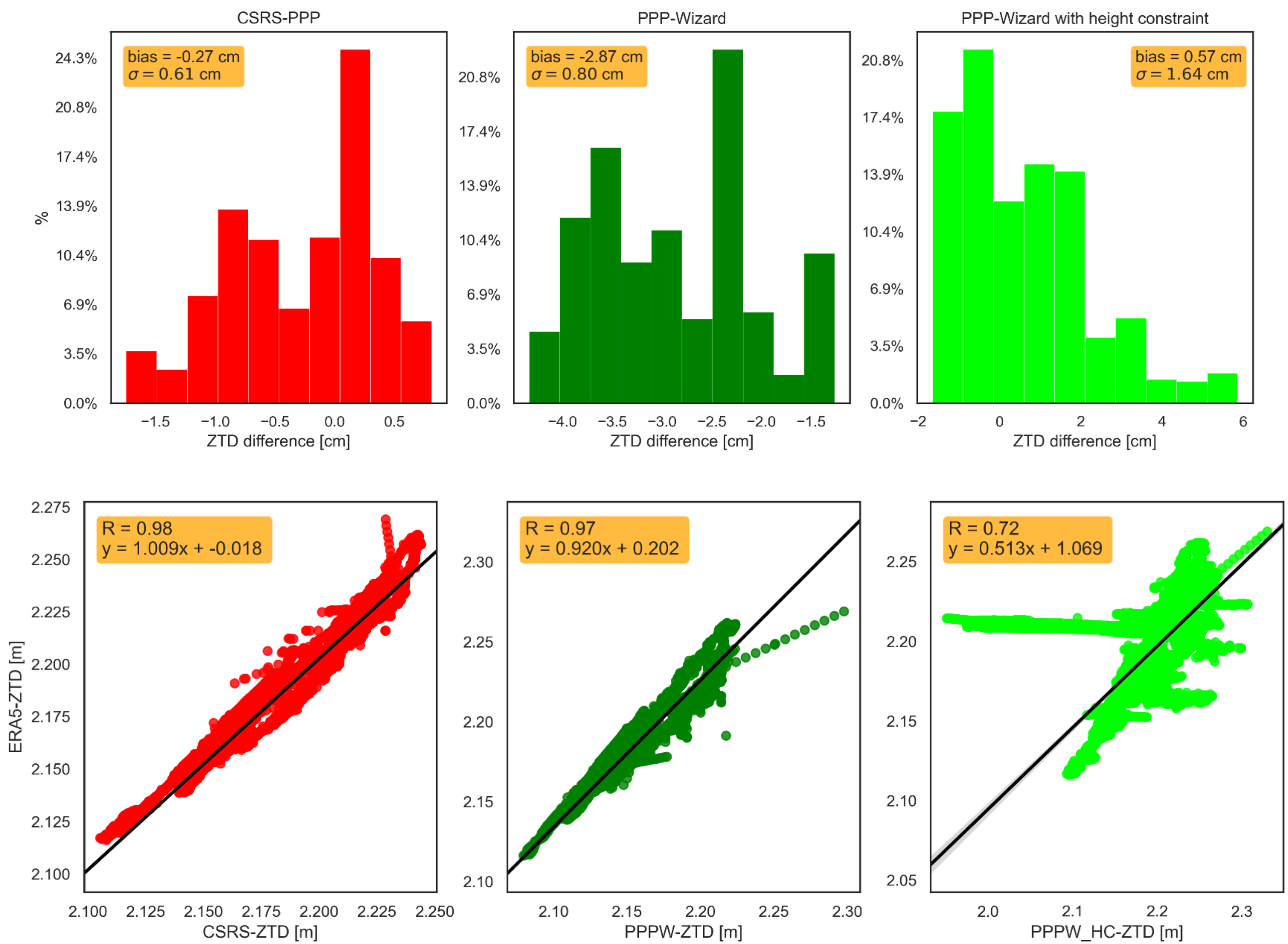
Validation: CS3

Findings:

- High correlation again
- Larger offset for PPP-Wizard solution
- CSRS-PPP with best performance
- Problems of PPPW-HC around 13:30 – 14:30
    - Interpolation errors? (wrong points in DB chosen)



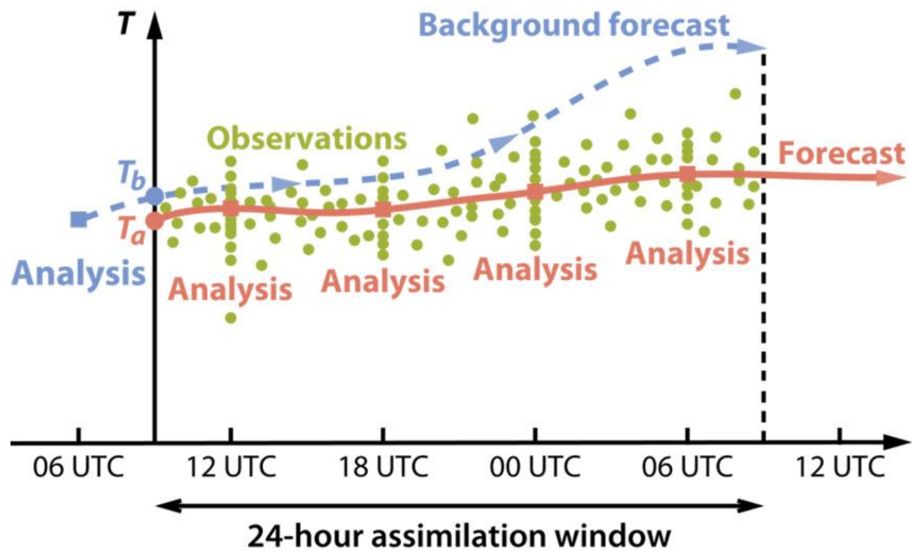
Validation: CS3



Methodology: Data assimilation

Basics:

- **NWP = initial value problem**, therefore strongly relies on quality of initial model state
- **Data Assimilation (DA)** = process of obtaining the statistically best combination between model state and the available observations
- Considering the **uncertainty of both observations and model** predictions



Basic concept of DA

$$J(x) = (x - x_b)^T B^{-1}(x - x_b) + \frac{1}{2}(H[x] - y^T)R^{-1}(H[x] - y).$$

WRF (Weather Research and Forecasting) Model:

- Open-source community model
- World-wide usage in NWP and other communities

Setup:

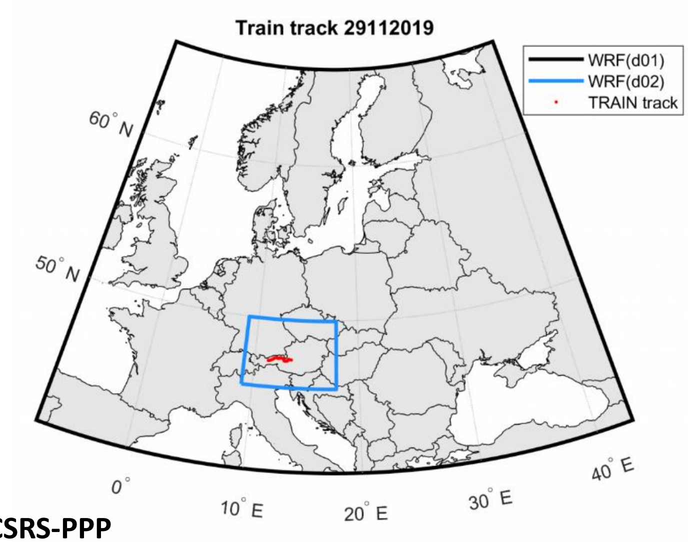
- WRF-DA system: 4D-Var
- Boundary conditions: ERA5

Assimilation settings

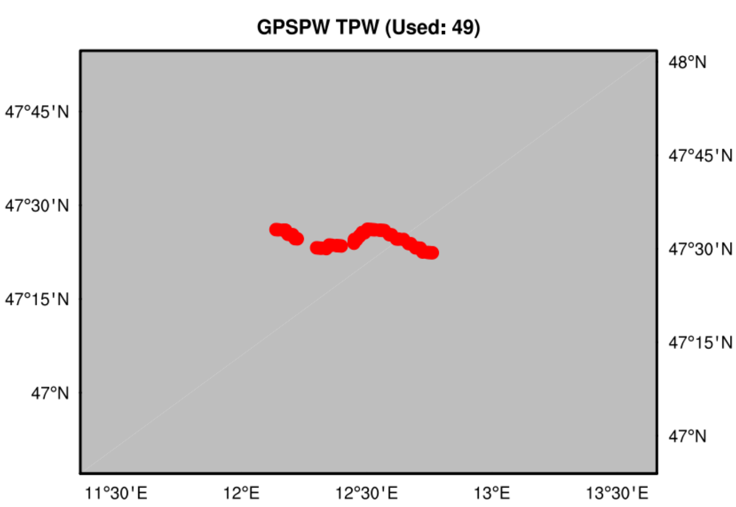
Parameter	Setting
Periods	CS2/CS3 (1 h each)
Horizontal resolution (d01,d02,d03)	30/10/3 km
Background data and boundary conditions	ERA5
Observation interval (GNSS-ZTD)	60 s
Assimilation method	4D-Var
Assimilation window	1 h
Observation operator	GPSZTD
Observation error (pre-defined in WRFDA)	0.5 cm
Error threshold	2.5 cm

Assimilation tests: CS3

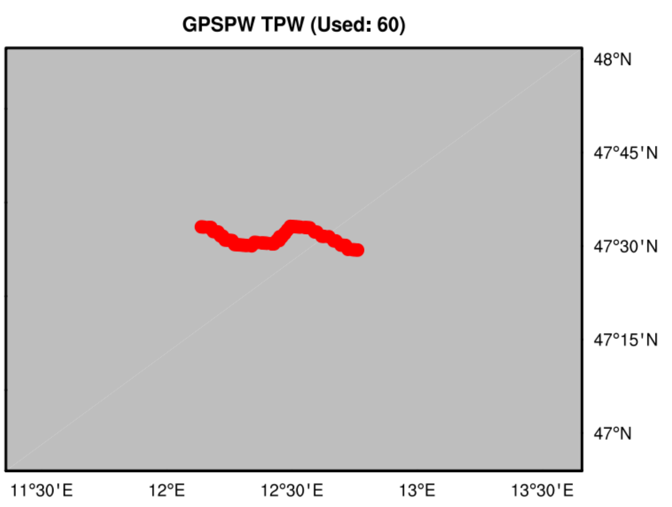
- Overall very promising results
- CSRS-PPP: 100 % of observations accepted
- PPPW: 82 % of observations accepted



PPPW



CSRS-PPP

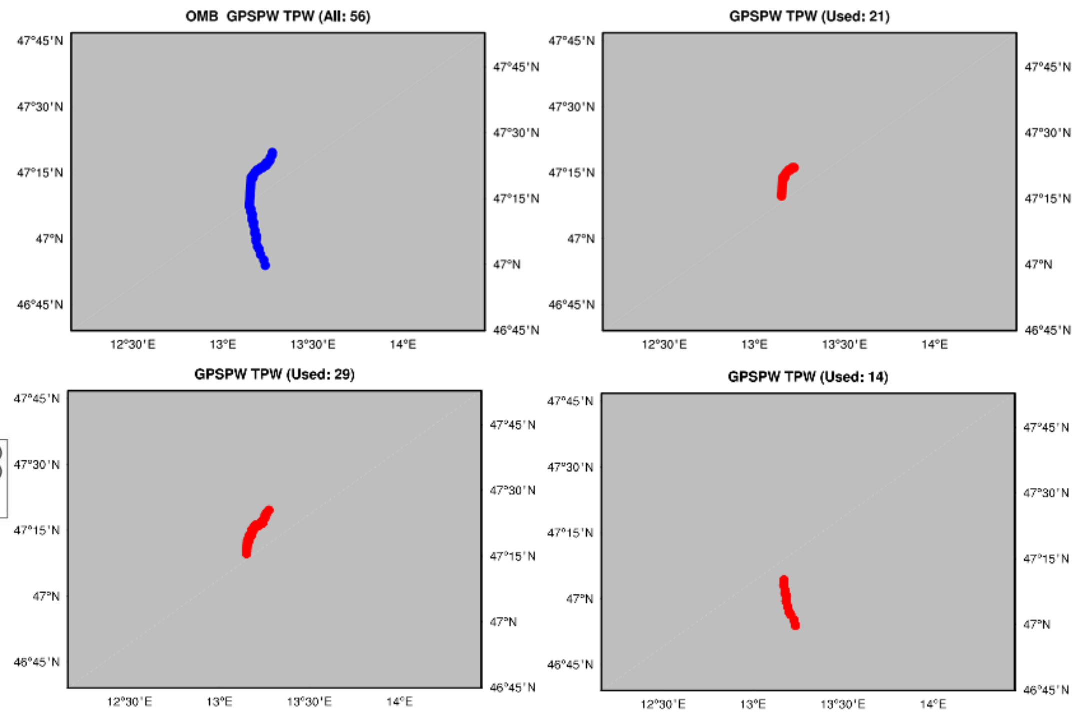


Assimilation tests: CS2

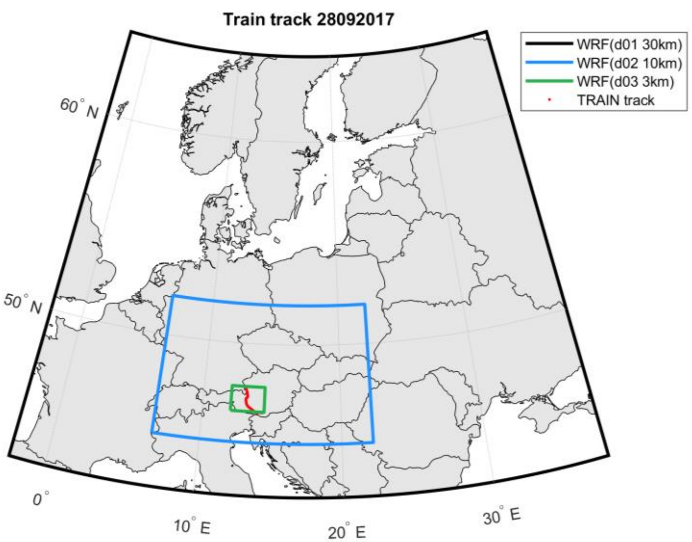
- Huge differences compared to CS3

- CSRS-PPP: none!
- PPPW-HC (29/56, ~52%)
- SGAMP: 21 (37.5%)
- PPPW: 14 (25%)

REF **SGAMP**



PPPW-HC **PPPW**



NRT operational mode

Required adaptations:

1. **Data transmission:** some sort of regular data transmission has to be set up (best a real-time stream, RTCM etc..)
2. **Orbit/clock products:** Real-time streams/ultra-rapid orbits/clocks instead of final products (investigate influence on quality of results!)
3. **Output interval:** To be refined, also in discussion with end users (NWP developers). This study: 1 min used

NRT operational mode

Suggestions for GNSS processing:

1. **SF-PPP approach:**
   - PPP-Wizard software: open-source C++ library, fully programmable, real-time capability
   - Extend for needed features:
     - better multipath/cycle slip management
     - VMF integration
     - Constrained PPP-mode (height, ionosphere,…)
2. **DF-PPP approach:**
   - PPP-Wizard or GAMP software
   - SEID algorithm directly in PPP (every epoch L2 is build and IF-LC is calculated)
3. **VieVS PPP (raPPPid):**
   - Extension: Cycle slip detection, appropriate settings for kinematic processing
   - Both DF and SF mode possible

NRT operational mode

Requirements for NWP usage

- **DA configuration:**
  - This study: 4D-Var, others also possible (depending on NWM used)
  - Hourly GNSS-ZTD data from reference typically arrive too late
  - Output interval under one hour for sure beneficial

Extension to advanced tropospheric parameters

- **Slant delays and horizontal gradients**
- **Gradients:**
  - Beneficial for GNSS-ZTD quality (literature) ----> not for this study (no impact)
  - Main challenge is interpretation of results, relative movement of train/weather has to be acknowledged

Conclusions and outlook

Data processing:

- Reasonable tropospheric parameters (ZTD) can be derived from train data
- Noise of PPP solutions in expected range for height, low for ZTD (filter settings!)
- Noise generally lower for CSRS-PPP compared to PPPW (often by factor 10)
- 3 – 4 processing schemes/software packages possible to use
- Pronounced offset between e.g. CSRS-PPP and PPPW, but correlation very high

Validation:

- Deviations from 1 mm – 8 cm depending on test case and software package, in general higher than required accuracy
- Nevertheless, deviations manifest themselves as (constant) bias, which might be removed in DA algorithm ------> how to do this for kinematic data???
- Different packages perform better for different test cases ------> no recommendation given
- SEID algorithm performs well, but pre-processing difficult (cycle slips/data gaps/…)

Conclusions and outlook

Assimilation:

- First assimilation tests successful, quality check in WRF was passed for 30 -100 % of observations (significantly different for the two test cases)
- Open questions:
    - Assimilation interval?
    - Bias correction for kinematic data?

NRT operational processing:

- NRT processing is possible but a number of adaptations have to be implemented
- Quality of results is expected to be lower due to usage of real-time orbit/clock products
- Benefit for real-time NWP applications nevertheless expected to be high
- High number of trains might be processed -----> very good horizontal resolution of dataset
- With larger number of trajectories available, full DA runs can be produced and verified