Investigation on systematic deviations of double differential partial wet delay between GNSS and the PS-InSAR and ERA-5 model observations.

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Introduction

Motivation

- **GNSS**: Determines high-accuracy IWV (and ZWD) estimates with superior temporal resolution but constrained spatial resolution.
- **InSAR**: Enables IWV and ZWD derivation with exceptional **spatial resolution** via PS points (Hooper et al., 2007), but low **temporal resolution**. Also, double differential measurements.
- **Synergy**: Integration of **GNSS** and **InSAR**, enhanced by models like ECMWF **ERA5**, significantly improves tropospheric moisture characterization, particularly during summer (Fersch et al., 2022; Kamm et al., 2023).

Approach

The research directly assesses interferometric phase delay as partial wet delay by comparing GNSS and ERA5 in temporal and spatial difference domains. The approach is novel because it evaluates ERA5 and InSAR derived ZWD in the original InSAR acquisition domain (double differential) rather than using integrated InSAR ZWD products.

Project and Dataset

- **Case Study:** Central Europe, spanning the France-Germany-Switzerland border (Fig. 1). approx. 260x240 km².
- **Time:** March 2015 to July 2019 (Fig. 2).
- **InSAR**: 4.2 mio PS points, 169 epochs (Sentinel 1A/B, descending orbit, passing time: 17:26 local time).
  - Variable: Interferometric phase observations.
- **ERA5**: 0.25x0.25° grid.
  - Variable: Integrated Water Vapor (IWV) interpolated at 4.2 mio PS points for 169 epochs.
- **GNSS**: 25 GNSS stations with hourly solutions. Each epoch is interpolated at Sentinel 1 passing time.
  - Variable: Tropospheric zenith wet delay (ZWD).

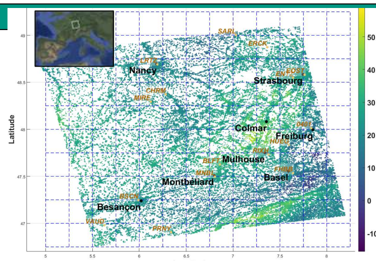

Fig. 1. *Study area with PS points (D_t pZWD) from 28-Mar-2015, GNSS station location (orange) and the ERA5 data grid (blue).*

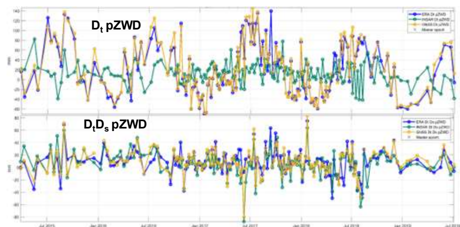

Fig. 2. *InSAR, ERA5 and GNSS pZWD timeseries for LRTZ GNSS station (near Nancy). Upper plot: single difference domain (reference epoch 66), lower plot double difference domain (reference epoch 66 and station DD: "0401").*

Methodology

1. Data Stacks

- InSAR Phase observations → InSAR slant delay → InSAR partial zenith wet delay (Dt pZWD)
- ERA5 0.25x0.25° grid → (Bilinear interpolation) → ERA5 at 4 million FS → ERA5 Model Zenith wet delay (ZWD)
- **GNSS ZWD** 25 stations → **16 GNSS stations** chosen based on **local analysis,** condition: (number of PS points > 2) within 50m.
- **ZWD*** 169 epochs x [16x3] PS → (mean) → **ZWD#** 169 epochs x 16 → (master: 66) → **D_t pZWD#** 169 epochs x 16 → **D_t D_S pZWD#** 16 Data stacks of 169 epochs x 16 (each)

D_t InSAR* #, ERA* #, GNSS #

2. Statistical Analysis (D_t D_s)

1. R^2 coefficient of determination
   - GNSS - InSAR
   - GNSS - ERA DD

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2}$$

2. KGE index
   - **R** Pearson correlation, **α** variability bias, **β** mean bias.

$$KGE = 1 - \sqrt{(R-1)^2 + (\alpha - 1)^2 + (\beta - 1)^2}$$

Global analysis
- n = 169 epochs

Seasonal analysis
- Winter (n = 42)
- Spring (n = 42)
- Summer (n = 40)
- Autumn (n = 45)

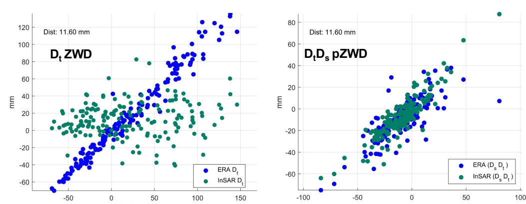

Fig. 3. *Scatter plots for LTRZ GNSS station in D_tZWD (left) and D_tD_s pZWD (right) - DD: "0401". Global analysis: 169 epochs - 4 years.*

Seasonal R^2 GNSS-ERA (mean values) D_tD_s:	Winter	Spring	Summer	Autumn
BLFT	0.59	0.47	0.16	0.43
CHRM	0.65	0.40	0.29	0.48
PRNY	0.69	0.50	0.26	0.55
RIXH	0.22	0.20	0.09	0.22
HUEG	0.61	0.35	0.32	0.45
SARL	0.64	0.58	0.33	0.56
LRTZ	0.71	0.49	0.35	0.44
BSCN	0.60	0.48	0.36	0.52
MNBL	0.57	0.52	0.19	0.37
ENTZ	0.63	0.41	0.28	0.46
VAUD	0.72	0.54	0.36	0.45
EOST	0.62	0.45	0.26	0.49
MIRE	0.58	0.37	0.31	0.38
FHBB	0.66	0.46	0.33	0.56
0401	0.65	0.34	0.28	0.37
ERCK	0.64	0.54	0.32	0.56
Mean	0.61	0.44	0.28	0.46

Seasonal R^2 GNSS-InSAR (mean values) D_tD_s:	Winter	Spring	Summer	Autumn
BLFT	0.58	0.65	0.66	0.63
CHRM	0.63	0.64	0.67	0.62
PRNY	0.57	0.54	0.63	0.66
RIXH	0.19	0.25	0.37	0.21
HUEG	0.62	0.56	0.72	0.65
SARL	0.62	0.71	0.75	0.75
LRTZ	0.63	0.62	0.75	0.64
BSCN	0.58	0.54	0.66	0.62
MNBL	0.54	0.63	0.62	0.59
ENTZ	0.55	0.62	0.61	0.63
VAUD	0.60	0.54	0.52	0.60
EOST	0.60	0.60	0.59	0.70
MIRE	0.56	0.53	0.71	0.54
FHBB	0.68	0.68	0.73	0.71
0401	0.60	0.67	0.69	0.62
ERCK	0.56	0.70	0.72	0.70
Mean	0.57	0.59	0.65	0.62

Tab. 1. *Seasonal mean values for R^2 Data Stacks D_tD_s. The colors red, yellow, and green, indicate the low (<0.4), medium and high (>0.7) correlation, respectively. The data per stack is presented in Fig. 5.*

Results

Single Difference - D_t pZWD (Fig. 3, left):
- ERA5: Linear trend.
- InSAR: Nonlinear (atmospheric, orbit, deformation, error phase components).

Double Difference - D_sD_t pZWD (Fig. 3, right; Fig. 4):
- InSAR > ERA5 (higher R²).
- InSAR's higher spatial resolution captures local atmosphere anomalies.
- Global R²: InSAR 0.65 vs. ERA5 0.42 .

Seasonal analysis (Fig. 5 and Tab. 1):
- Summer: InSAR 2× better (R² 0.65 vs. 0.28).
- Spring/Autumn: InSAR remains superior.
- Winter: ERA5 slightly better (0.61 vs. 0.57).
- Worst correlation: RIXH near Mulhouse (Fig.1 and Tab. 1).
- ERA5 has better correlation during winter (Tab. 1).

KGE & Distance:
- KGE: Poor for both. In spring, InSAR reached acceptable KGE=0.66.
- PS-GNSS distance (3-30 m): No correlation impact (Fig. 4 and Fig. 5, y-axis).

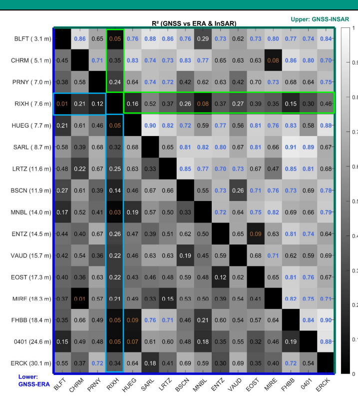

Fig. 4. *R² plot for GNSS and ERA (lower triangle) and GNSS-InSAR (upper triangle). Global analysis: 169 epochs - 4 years.*

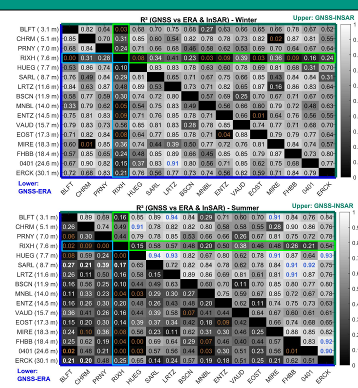

Fig. 5. *R² plots for GNSS and ERA (lower triangle) and GNSS-InSAR (upper triangle). The upper plots, represent the winter condition, while the lower plots show Summer.*

Conclusions

InSAR outperforms ERA5 reaching better correlation in the Double Difference domain - D_sD_t pZWD:
- Higher accuracy: Mean R² = 0.65 vs. 0.42 globally.
- Summer (mean R² = 0.65 vs. 0.28), showing its high-resolution advantage for atmospheric studies.

For InSAR, the double differencing effectively isolates systematic errors (orbital). Since the deformation in the study region is neglectable for the time span, it allows isolating the atmospheric component (and error).

⚠ **RIXH** station anomaly (R² = 0.29 InSAR, 0.17 ERA5) may suggest GNSS-specific errors (e.g., multipath), highlighting the need for station-level quality assessments.

Practical significance: InSAR's reliability during summer and its high spatial resolution make it a powerful tool for improving atmospheric models.

Future Work

- Refine atmospheric phase screen (APS) inversion to improve absolute ZWD estimates.
- Investigate RIXH's poor correlation to discriminate between GNSS artifacts and model limitations.

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