

Generation of the first national-scale Precipitable Water Vapor (PWV) Maps in Italy based on the New ASI Fiducial GNSS Network

Ilaria FERRANDO¹, Elisa BERTAZZINI¹, Rosa DELORENZO¹, Bianca FEDERICI¹, Saba GACHPAZ¹, Francesco GAMBETTA¹,
Abubakr ALBASHIR¹, Gabrio PINNIZZOTTO¹, Paola SALMONA¹, Catia BENEDETTO², Francesco VESPE², Domenico SGUERSO¹

¹ Department of Civil, Chemical and Environmental Engineering (DICCA), University of Genoa, Genoa, Italy
ilaria.ferrando@edu.unige.it

² Telecommunications and Navigation Office, Italian Space Agency (ASI), Matera, Italy

XI Hotine-Marussi Symposium, Genova 2026

11-09-2026

Outline

- **Background**
- **Project Contribution**
- **G4M Procedure architecture**
- **First National-scale PWV map from G4M**
- **Case Study**
- **Conclusion**

Background

1. Challenge

GNSS positioning accuracy is affected by atmospheric propagation biases caused by:

- Ionosphere: dominant effect → removed via the iono-free (dual-frequency) combination.
- Troposphere: frequency-independent → must be estimated as an unknown.

Tropospheric bias modifies the real satellite-receiver distance → **Zenith Total Delay (ZTD)**

$$ZTD = ZHD + ZWD$$



ZHD: due to the mix of gases in atmosphere, ~ 90% of ZTD, easily modeled

ZWD: due to the presence of water vapor in atmosphere → extremely variable
related to Precipitable Water Vapor (PWV) → maximum quantity of condensable water vapor.

- **PWV observations support severe-weather analysis and provide a basis for studying atmospheric condition and anomalies.**

Background

2. Challenge and Gap

Main limitation: station-based ZTD/PWV describes isolated points, not a continuous field.

$$PWV = f(ZWD, P, T, \dots)$$

Challenge (a) — ZTD supplied as station time series:

- ZTD is available only at the discrete locations of the GNSS network.
- Network coverage and density vary strongly across the territory.

Challenge (b) — Pressure and Temperature from meteorological networks:

- P and T, not the GNSS network.
- GNSS and meteorological stations are generally not co-located. are provided by a separate meteorological network
- Observations must be matched in time and space before ZWD/PWV can be computed consistently.

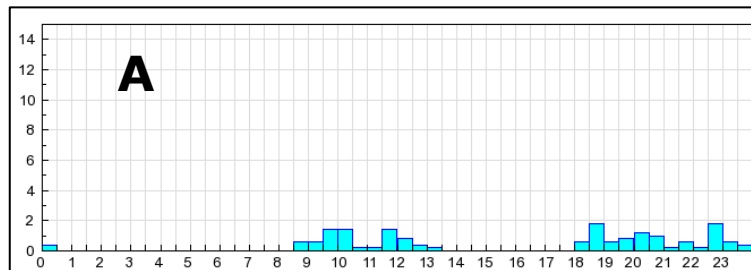
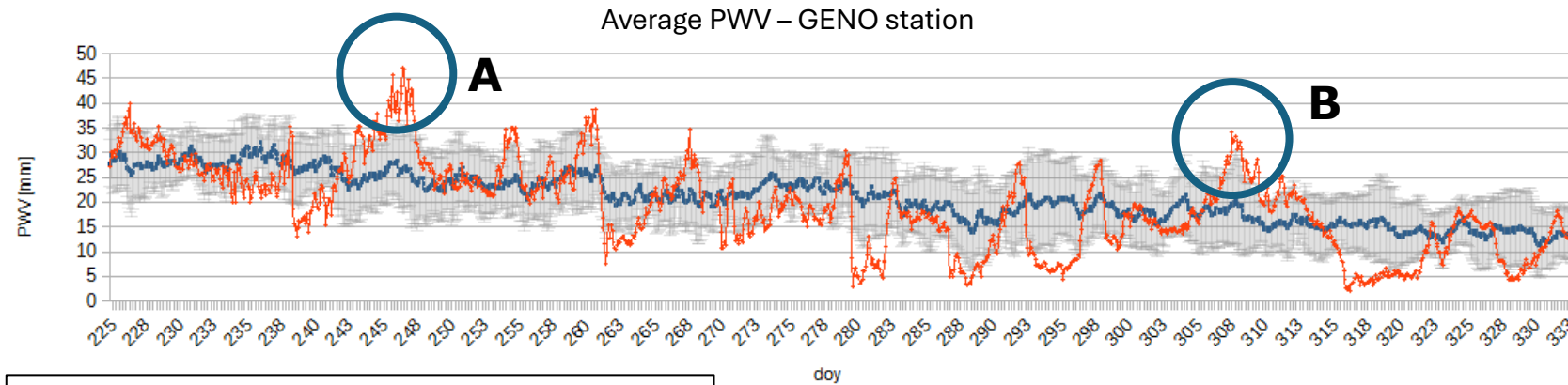
Background

1D PWV approach limitation: an example of severe event

2011 NOVEMBER the 4TH SEVERE EVENT ON GENOA (ITALY)

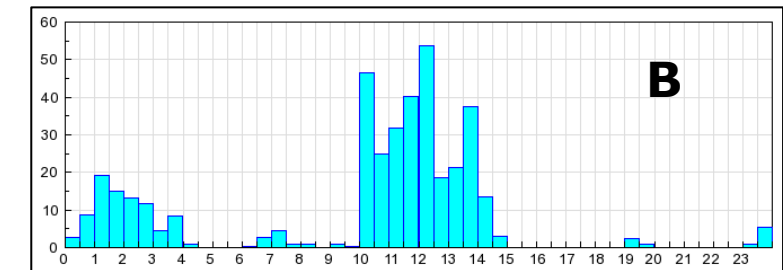
Stationary and self-healing storm over Genoa (Italy)

- intensity: up to **180mm/hour** and 390mm/6h
- flooding of Bisagno and Fereggiano rivers.
- 6 persons died and extensive damages.

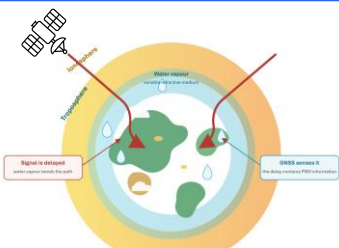


A. No meteorological event

B. 4th November 2011 severe event

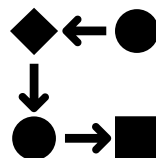


The Big Picture



Invisible water in the air

The atmosphere holds moisture we cannot see but it fuels the storms we cannot ignore.



Automated Procedure

Combining non-collocated GNSS and meteorological records into one continuous, automated workflow



Italy's first national water vapor map

High spatial and temporal nationwide 2D view of atmospheric water vapor content.



Severe weather monitoring

Early warning systems, seismic activity, extreme weather applications.

From an invisible atmospheric signal to a nationwide monitoring of PWV in Italy.

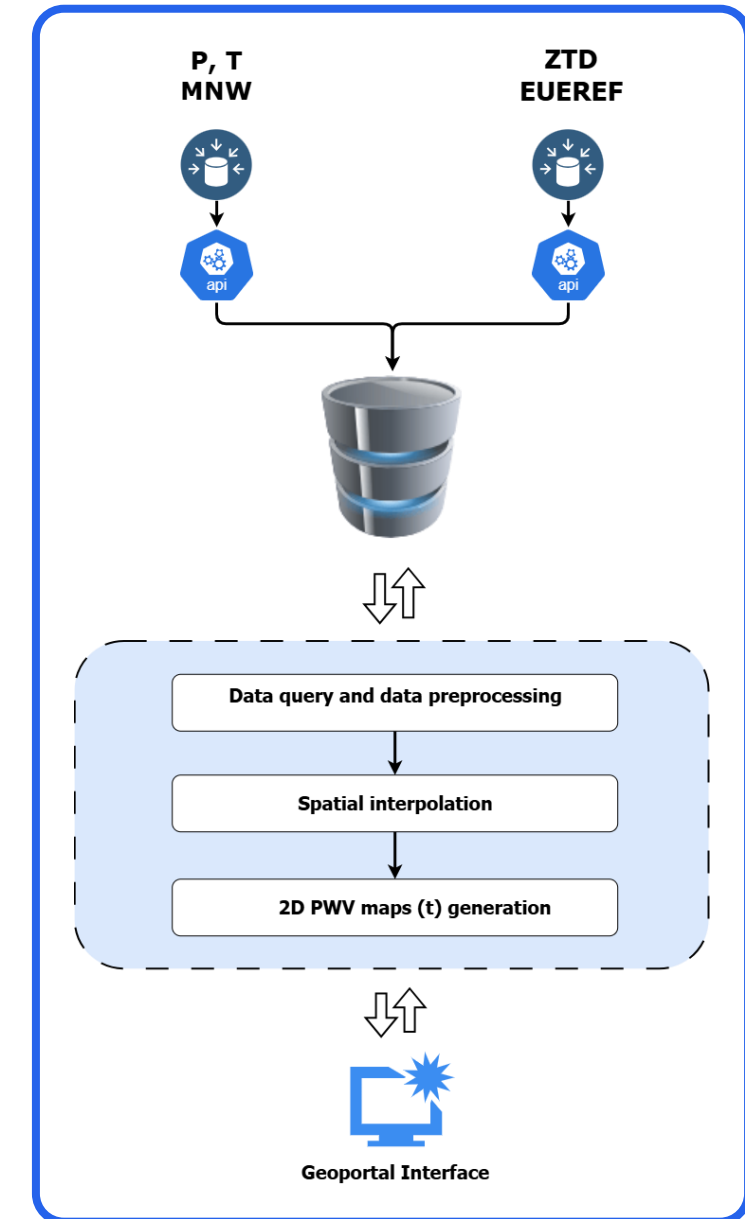
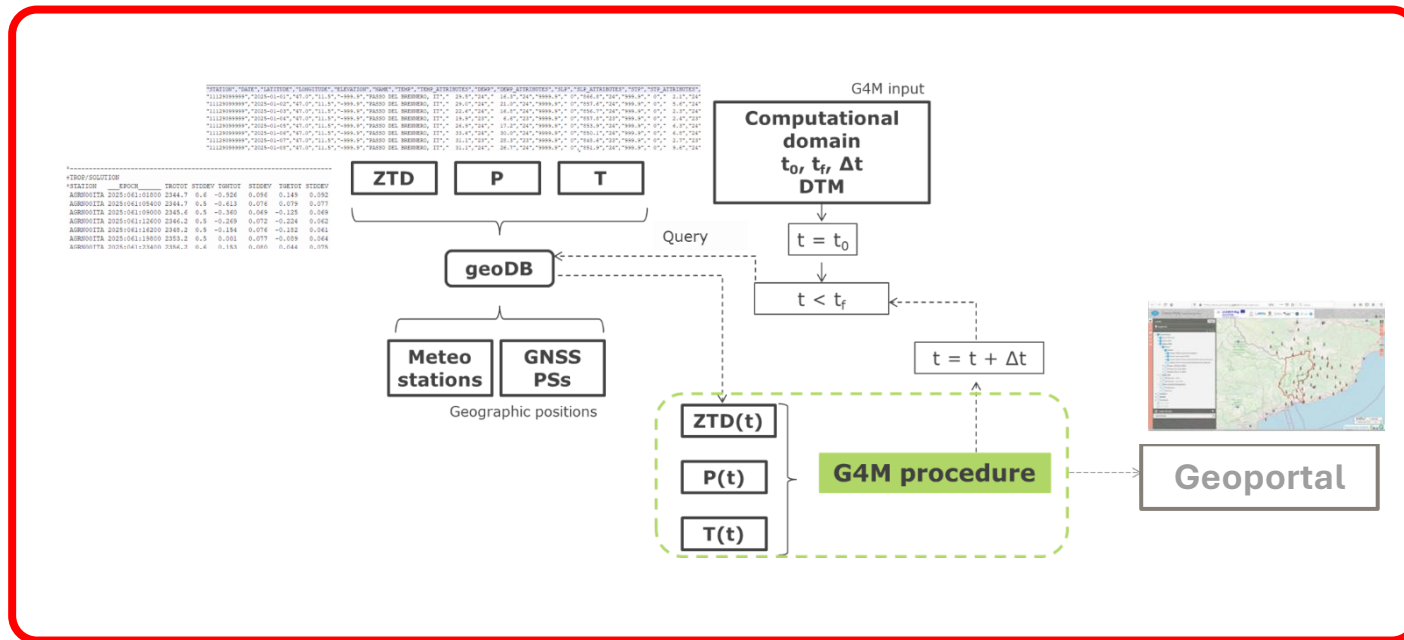
Project contribution

Research cooperation between the University of Genoa (UNIGE) Geomatics Laboratory and the Italian Space Agency (ASI).

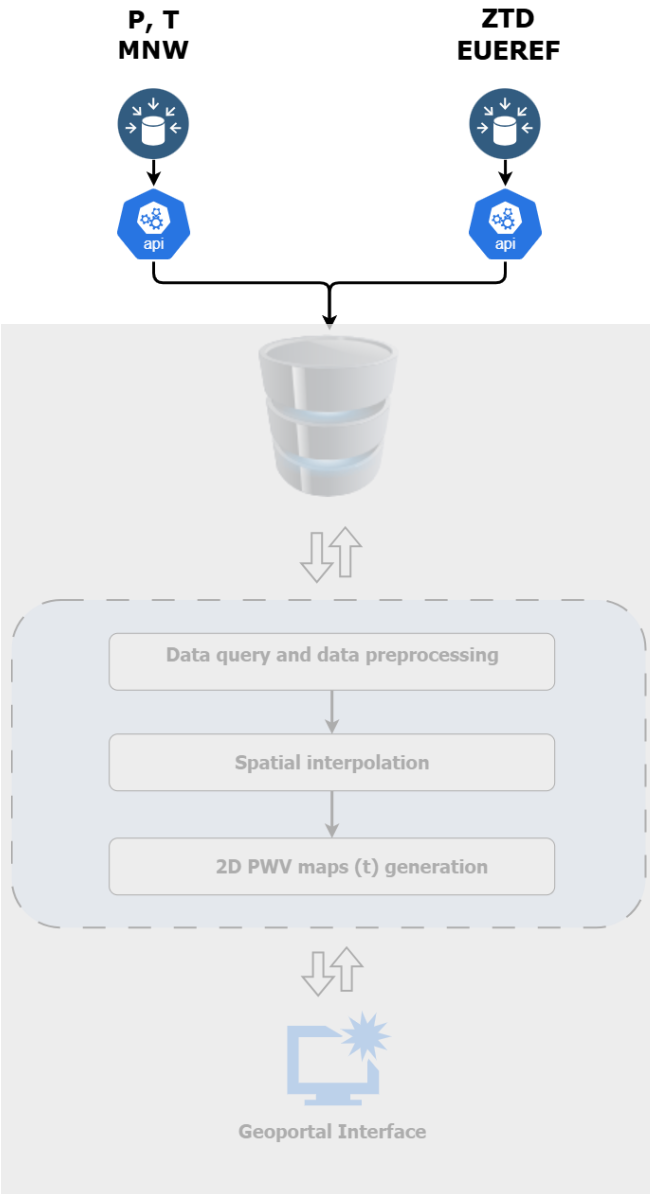
Goals:

- Generate high spatial and temporal 2D Precipitable Water Vapor (PWV) maps at Italian territorial extent to detect and analyze severe meteorological events.
- Deepen the knowledge about the relation between PWV field anomalies and seismic activity.

G4M (GNSS for Meteorology): automatic procedure developed by UNIGE to move from station-based PWV(t) to 2D national PWV(x,y,t) maps



Data Sources: distribution and availability



GNSS network



ASI GNSS PS network: GNSS data from ASI's "New National GNSS Fiducial Network": multi-constellation network, 45 Permanent Stations

Meteorological data networks



NOAA network: A global and long-term stable meteorological network. provides global hourly and sub-hourly P&T measurements collected from a network of fixed stations. It Act as the reference network to validate MNW.



Meteonetwork (MNW): Citizen Weather Stations (CWSs) initiative established in 2002 and continuously operating since then . The network is providing a high spatial density source of the meteorological observations over Italy.

Data distribution and availability: Meteorological stations

Meteorological data networks



NOAA network



Meteonetwork (MNW)

Meteorological Data Coherence Assessment for Tropospheric Monitoring Using ASI's National GNSS Fiducial Network

Ilaria Ferrando, Abubakr Khalid Ahmed Albashir, Bianca Federici, Gabrio Pinnizzotto, Catia Benedetto, Francesco Vespe, and Domenico Sguerso



Abstract

The established research cooperation between University of Genoa (UniGe) and Italian Space Agency (ASI) for the exploitation of the GNSS data acquired through the “New National GNSS Fiducial Network”, implemented by ASI, aims to develop and test the procedure named GNSS for Meteorology (G4M), deployed by UniGe’s Geomatics Laboratory, for creating Precipitable Water Vapor (PWV) maps covering the Italian territory. The focus of the present work is the coherence assessment between the meteorological data provided by National Oceanic and Atmospheric Administration (NOAA) and the ones made available by MeteoNetwork (MNW), a crowd-sourced sensors network. The comparison is based on the metrics of pressure and temperature differences, also accounting for the different sensors distribution, and on the application of Inter Quartile Range method, to select a set of reliable MNW stations for populating a meteorological DataBase for G4M procedure.

Keywords

Inter Quartile Range (IQR) · Meteorological DataBase (DB) · Precipitable Water Vapor (PWV) · Pressure (P) · Temperature (T) · Zenith Total Delay (ZTD)

1 Introduction

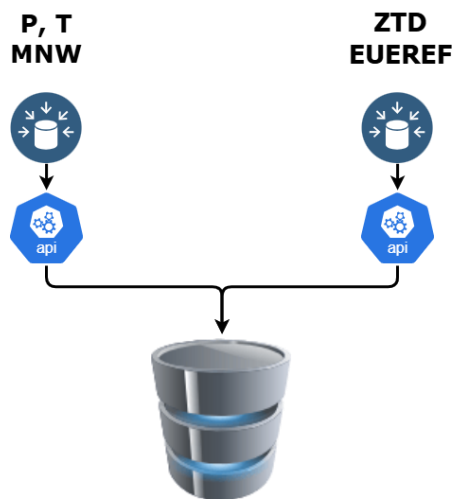
The present contribution assesses the coherence between the meteorological data provided by the National Oceanic and Atmospheric Administration (NOAA)¹ and those made available by MeteoNetwork (MNW),² a crowd-sourced sen-

sors network managed by an association of meteorology enthusiasts (Giazzi et al. 2022). The activity is part of the scientific cooperation between the University of Genoa (UniGe) and the Italian Space Agency (ASI) for the exploitation of the Global Navigation Satellite System (GNSS) data acquired through the “New National GNSS Fiducial Network”, implemented by ASI. This multi-constellation GNSS

We conducted extensive accuracy assessments to evaluate the near surface atmospheric P and T observations coming from the MeteoNetwork (MNW) observations over the Period between 2023–2025 including:

- External evaluation: against preliminary reference NOAA datasets.
- Internal evaluation: cross-validation among MeteoNetwork stations.

Database architecture Overview



Database Management System (DBMS)

This system is implemented using the PostgreSQL, an advanced open-source relational database management system.



Database Structure

The database is designed around **five** main tables.

1. Meteorological Networks table

Stores network meteorological network metadata.

2. Meteorological stations information table

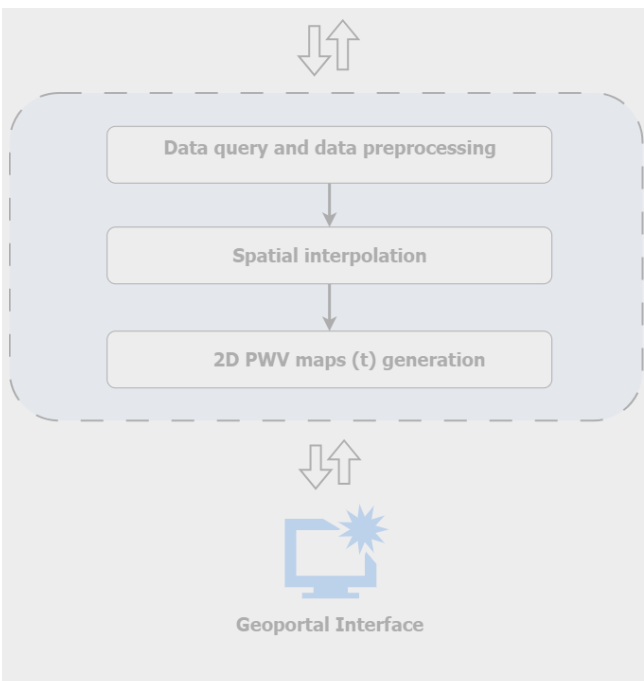
Contains stations-level information

3. Meteorological observations table

Stores real-time meteorological measurements (temperature, pressure, timestamp)

Linked to both:

Meteorological stations information table (spatial and administrative reference)
Meteorological Networks table (data source and traceability).



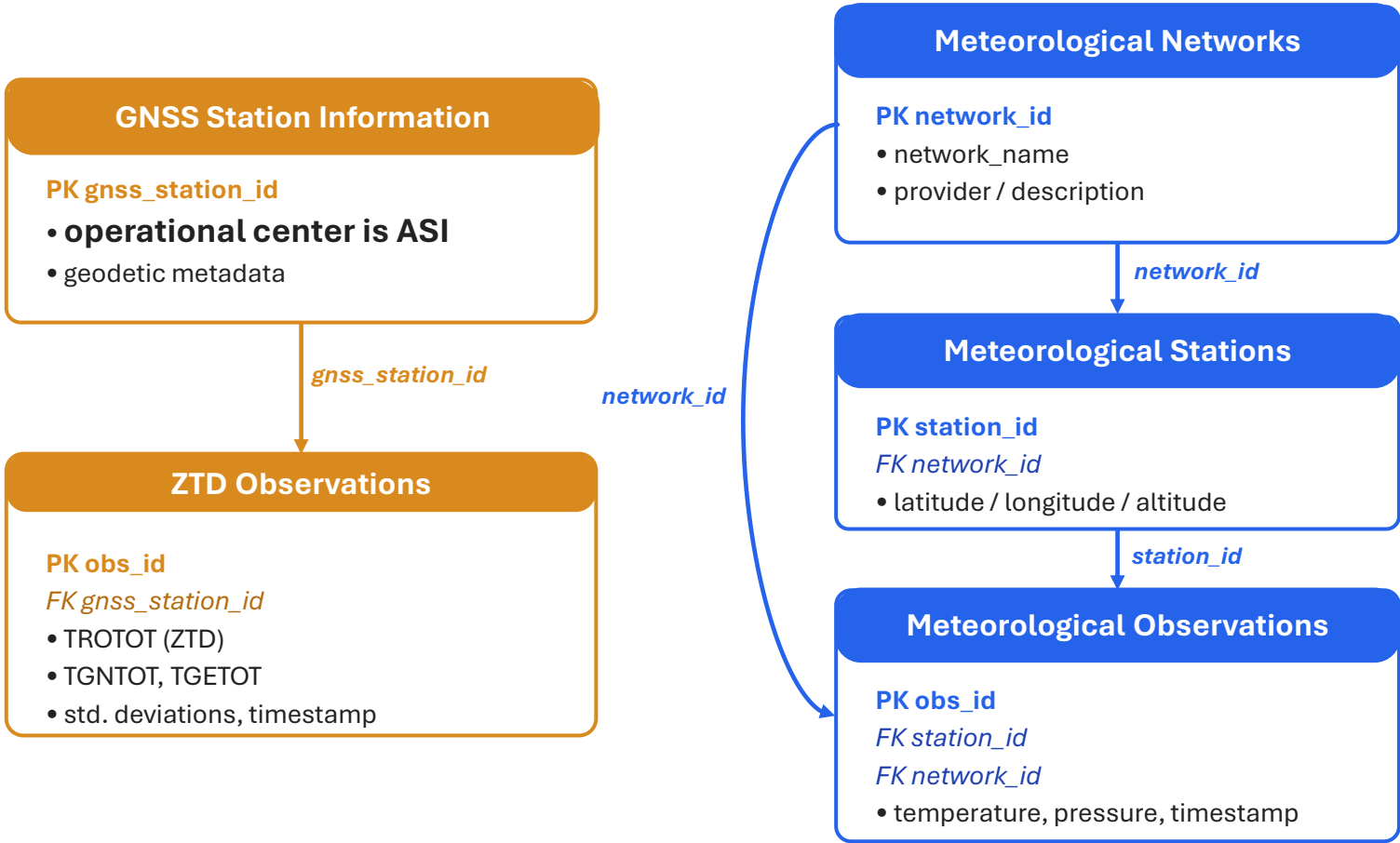
Database Structure (Cont.)

4. GNSS station information table

Contains metadata for ASI GNSS Permanent stations

5. ZTD observations table

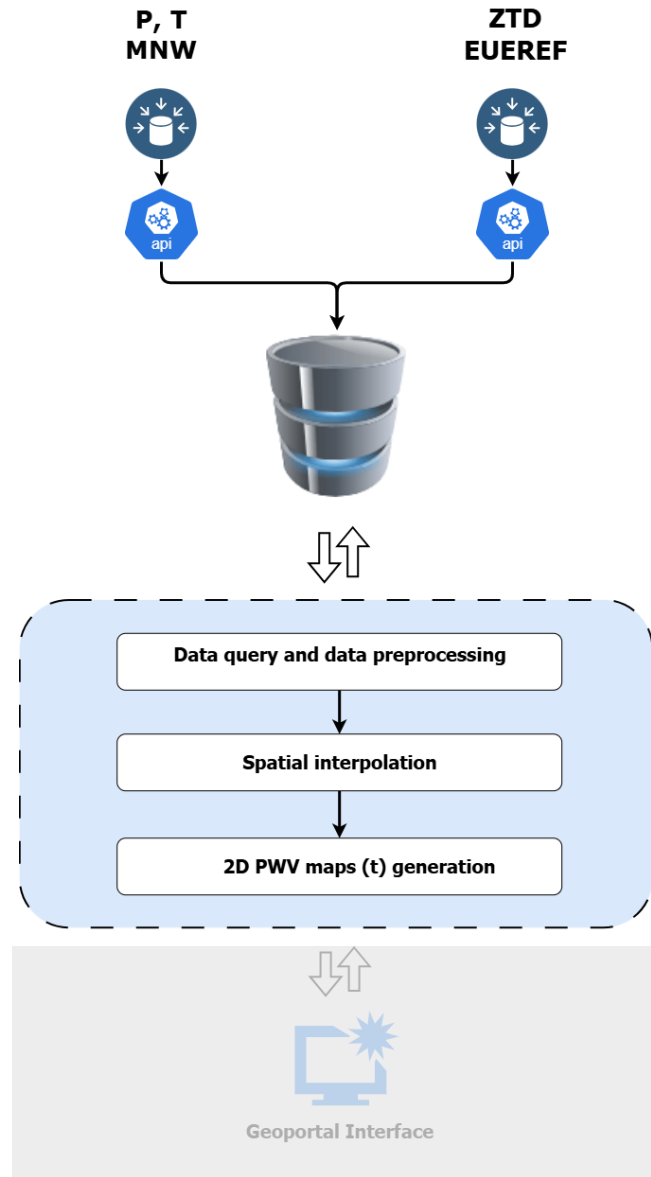
Stores hourly atmospheric delay parameters and their standard deviations



Database retrieving procedures:

1. Meteorological data extractor @15 min.
2. ZTD data extractor @ hourly polling (EUREF/BKG rapid SINEX, 01D01H).

From Database Queries to 2D PWV Mapping: G4M Automated Processing Pipeline



1 Time and space initialization

User defines AOI, start/end time, step frequency and grid resolution.

2 GeoDB filtering and retrieval

Queries the GeoDB to extract ZTD from GNSS stations and P/T from meteorological stations

3 Spatial interpolation

GRASS GIS natural neighbor interpolation generates continuous ZTD, P and T rasters for each epoch.

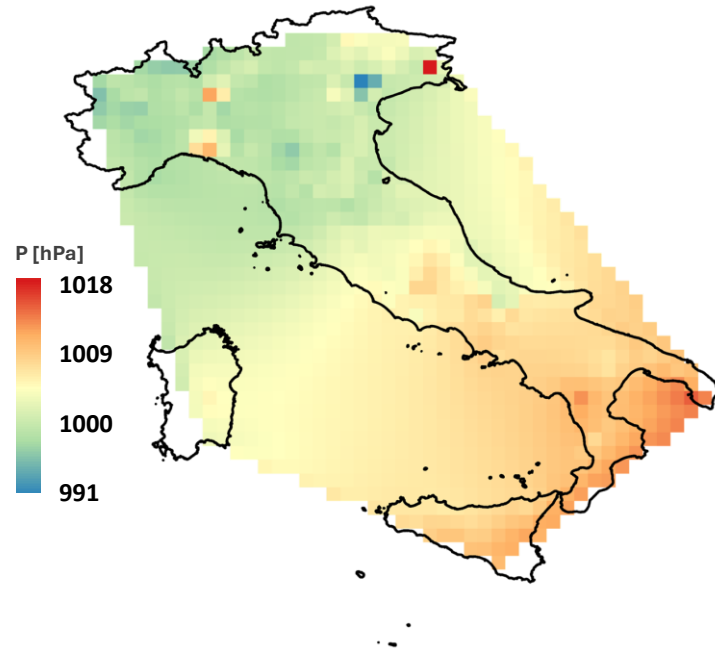
4 PWV map generation

ZHD, ZWD and PWV conversion models are applied to the aligned grids.

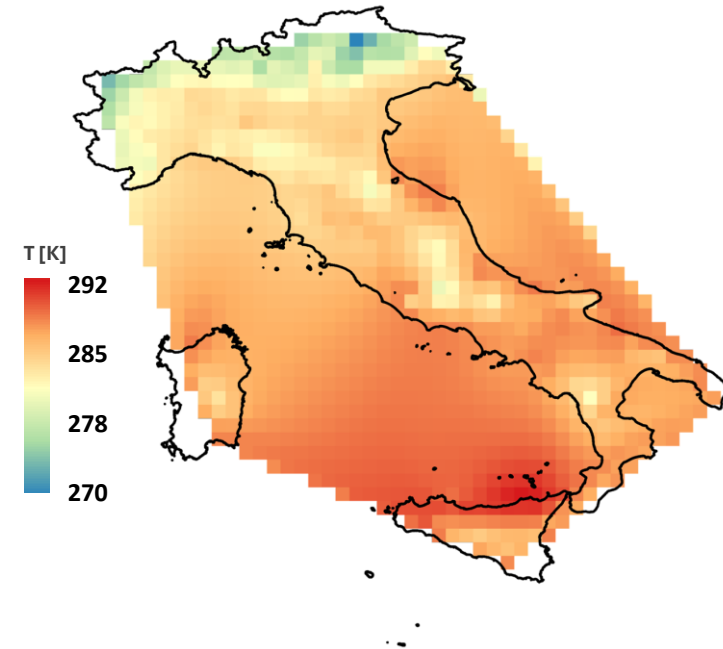
Output: 2D Maps ZTD, pressure, temperature and PWV

First National-scale maps from G4M

- Pressure and temperature data from the quality-controlled meteorological records → from the GeoDB.
- Hourly natural-neighbour interpolation over the entire Italian AOI.
- Output: nationwide pressure and temperature fields.
- Map shows the trend of lower pressure and temperature trend in the north and higher toward the south.



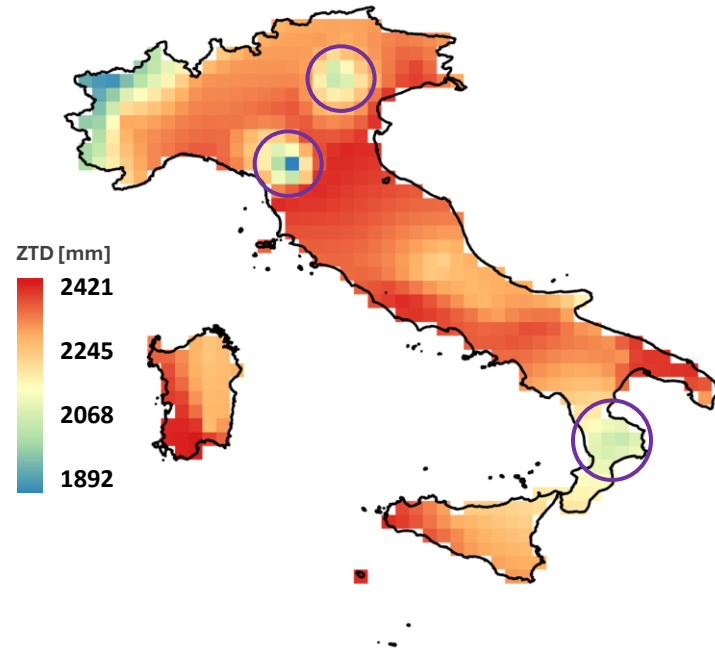
Pressure map



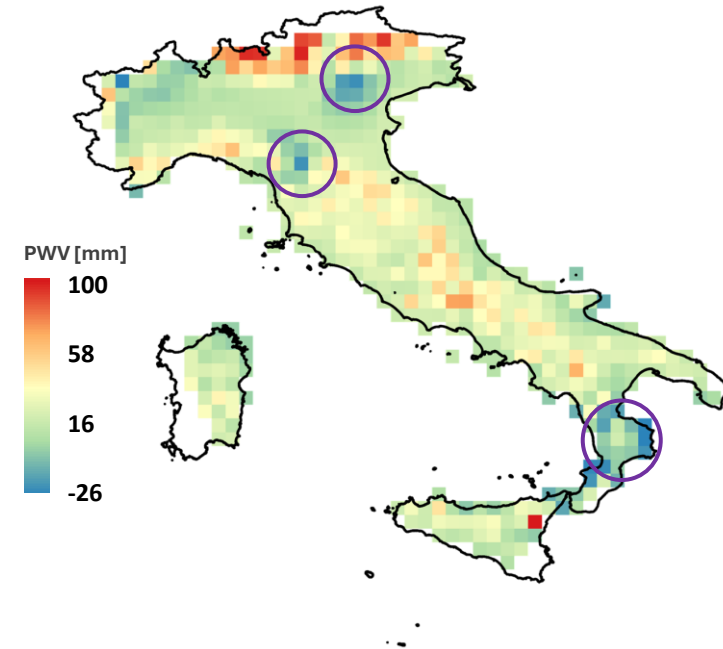
Temperature map

First National-scale PWV map from G4M

- ZTD from the full ASI Fiducial GNSS Network records → from the GeoDB.
- Hourly natural-neighbour interpolation over the entire Italian AOI.
- Output: nationwide ZTD and derived PWV fields.
- PWV pattern follows the spatial behaviour of the interpolated ZTD field, but local extremes appear where ZTD support is sparse or changes sharply between stations.



Zenith Total Delay (ZTD) map



Precipitable Water Vapor (PWV) map

Case study: Comparison with ERA5 datasets

Case study:

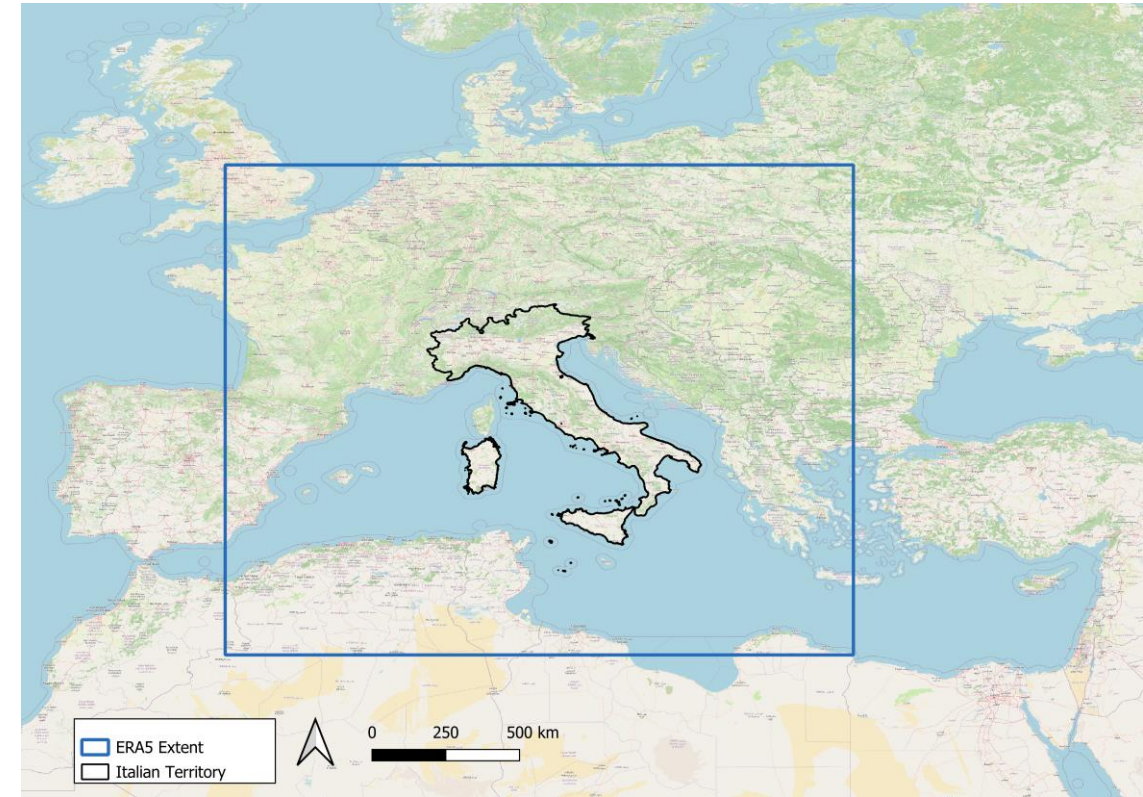
- 14 March 2025, extreme precipitation in the Emilia-Romagna region.
- Compare 24h interpolated fields of G4M with their corresponds fields of ERA5.

ERA5 reference fields:

- Hourly (pressure, temperature and Total column water vapor (TCWV)).
- Spatial resolution of $0.25^\circ \times 0.25^\circ$.

Project GeoDB data (G4M inputs):

- Same AOI and spatial resolution defined by the extent of the ERA5 raster.
- Hourly (ZTD, P, T) extracted from the GeoDB.
- G4M automatically retrieves the observations and interpolates the observations in an hourly time step.

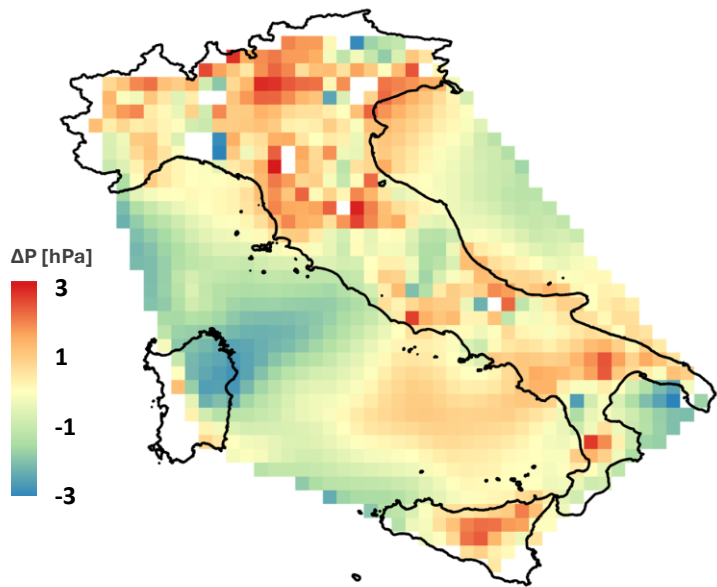


Results: Comparison with ERA5 datasets

Residual results, maps at 00:00 UTC

$$\Delta X (X_{\text{ERA5}} - X_{\text{G4M}})$$

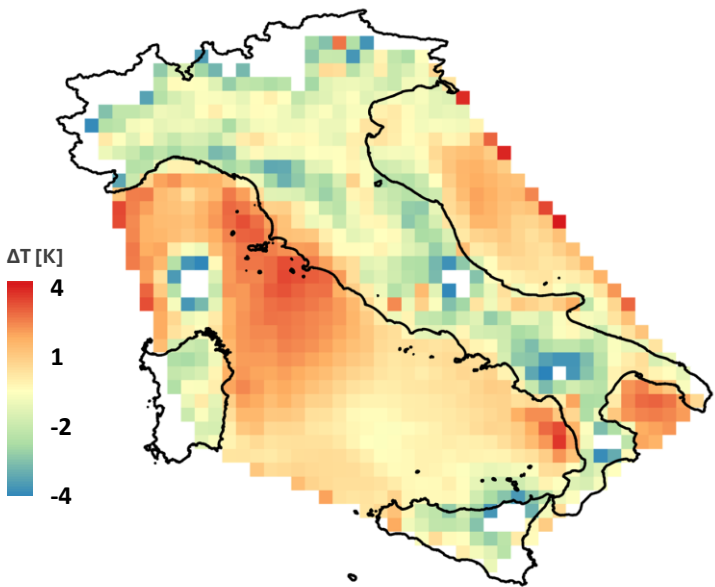
For each of the three parameter, the hourly residuals was estimated with respect to ERA5 data, then the Interquartile Range (IQR) method was used to detect and remove the outliers.



$$\Delta P (P_{\text{ERA5}} - P_{\text{G4M}})$$

Mean: -0.3 [hPa]

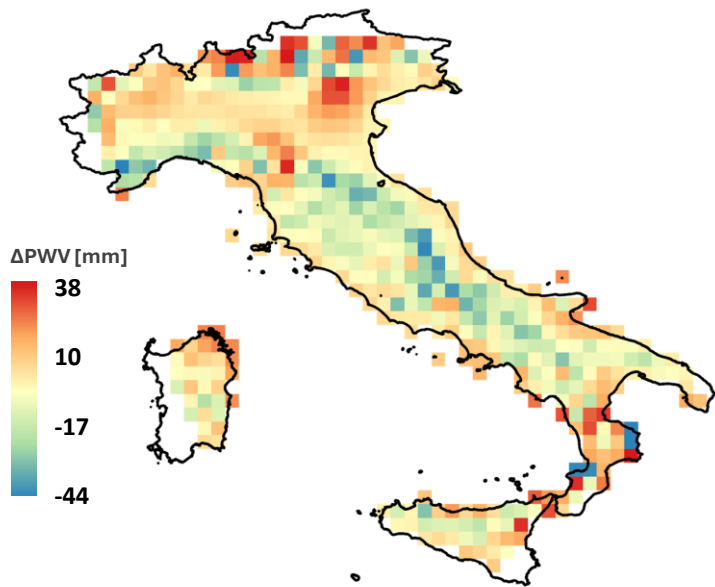
Standard deviation: 1.1 [hPa]



$$\Delta T (T_{\text{ERA5}} - T_{\text{G4M}})$$

Mean: 0.5 [K]

Standard deviation: 1.5 [K]



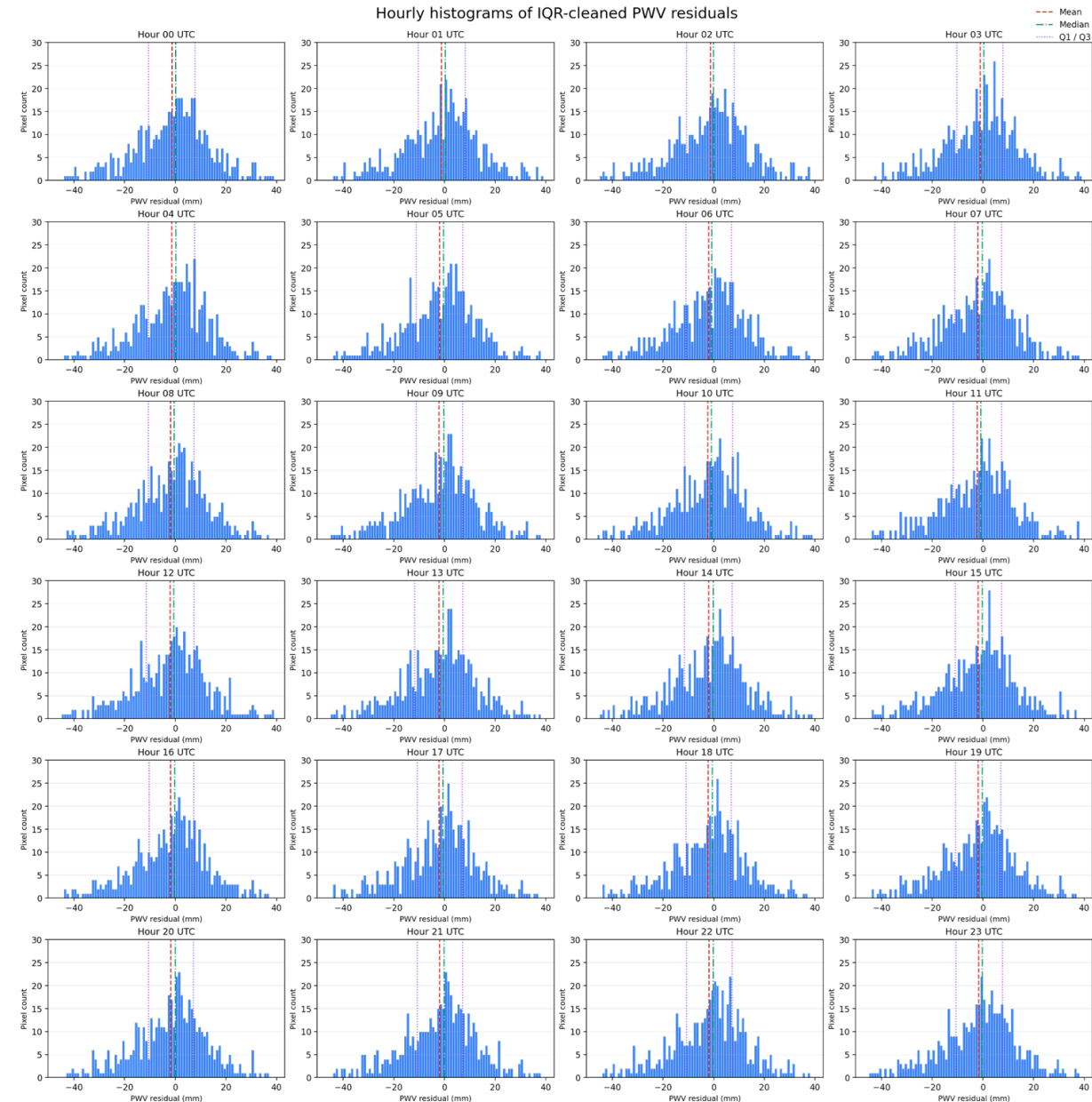
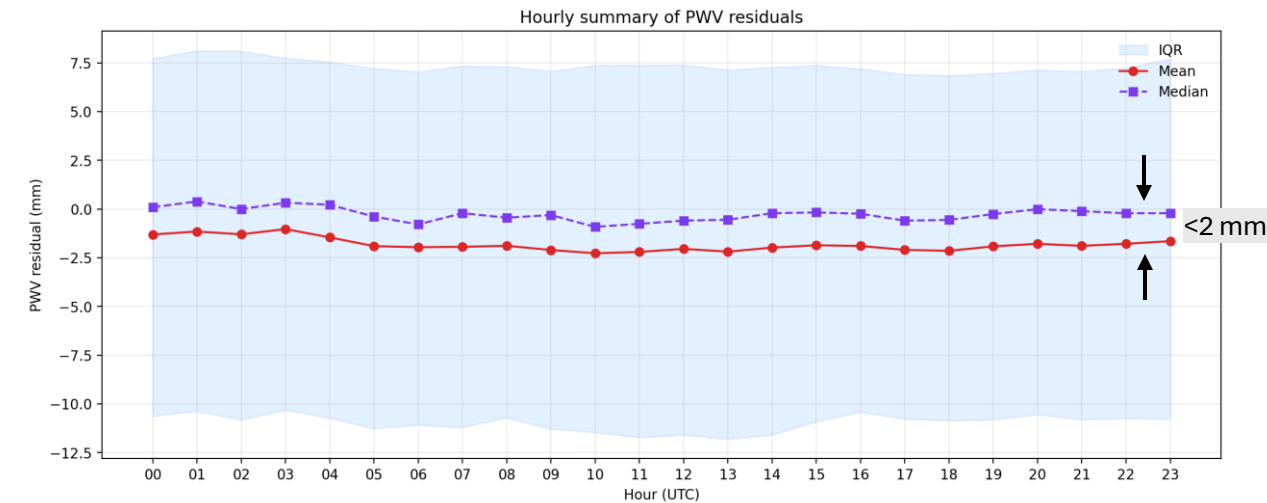
$$\Delta \text{PWV} (\text{TCWV}_{\text{ERA5}} - \text{PWV}_{\text{G4M}})$$

Mean: -1.3 [mm]

Standard deviation: 14.9 [mm]

Results: hourly PWV comparison with ERA5

- The PWV residuals show the largest variability among the analyzed parameters, with a broad hourly IQR of approximately between -11 to +7 mm.
- Histograms, after IQR cleaning, are generally centred near zero.
- The mean residual remains close to -2 mm for most hours, while the median is generally near zero.
- Further investigation should examine the PWV residual map, interpolated ZTD field, and temporal correspondence between the G4M and ERA5 fields.



Conclusion and future work

- **Current implementation** establishes the operational backbone for national-scale PWV mapping.
- **Automated and reproducible:** easy to use for non-expert users.
- **Scalable:** the architecture extends to different spatial extents, GNSS and meteorological networks.
- **Computational efficiency:** $\sim < 5$ minutes for National scale at 1km x 1km spatial resolution.
- **Comparison** against ERA5 provides a first quantitative evaluation of the updated G4M interpolation chain.
- **Future work:** extend the validation to additional case studies and seasons; investigate the origin of the PWV anomaly to improve the interpolation; and develop the Geoportal to visualise and disseminate regularly updated, finalised national-scale PWV maps.

Acknowledgment

This research project is funded by the Italian Space Agency under Implementing Agreement No. 2024-25-HH.0, “Monitoraggio dello stato troposferico a livello nazionale e precursori sismici a partire dai dati della nuova rete fiduciale nazionale GNSS dell’ASI” (CUP: F33D24000060001)

References

- Benvenuto L., Ferrando I., Federici B., Sguerso D. (2020). The GNSS for Meteorology (G4M) Procedure and its application to four significant weather events. In: International Association of Geodesy Symposia, Springer, Berlin, Heidelberg. https://doi.org/10.1007/1345_2020_111
- Benvenuto L., Dabove P., Ferrando I., Sguerso D. (2021) Preliminary results on tropospheric ZTD estimation by smartphone. Remote Sensing, 13(22). <https://doi.org/10.3390/rs13224567>
- Benvenuto L, et al. (2020) The GNSS for Meteorology (G4M) procedure and its application to four significant weather event. In: Novák P, et al. (eds) International Association of Geodesy Symposia, vol 151. Springer, Cham, pp 137–145. https://doi.org/10.1007/1345_2020_111
- Bevis M, et al. (1992) GPS meteorology: Remote sensing of atmospheric water vapor using the global positioning system. J Geophys Res 97(14):15787–15801. <https://doi.org/10.1029/92JD01517>
- Ferrando, I. et al. (2026). Meteorological Data Coherence Assessment for Tropospheric Monitoring Using ASI's National GNSS Fiducial Network. In: International Association of Geodesy Symposia. Springer, Berlin, Heidelberg. https://doi.org/10.1007/1345_2026_356
- Ferrando I, Federici B, Sguerso D (2018) 2D PWV monitoring of a wide and orographically complex area with a low dense GNSS network. Earth Planets Space 70(54). <https://doi.org/10.1186/s40623-018-0824-6>
- Ferrando I. (2018). GNSS contribution to monitor severe rainfalls: an innovative procedure for wide and orographically complex area with existing infrastructures. Ricerche di Geomatica 2017, pp. 11-22, Antonio Vettore editor, ISBN: 978-88-942926-4-0
- Ferrando I., Federici B., Sguerso D. (2018). ZTD time series analysis of GNSS regional integrated networks. Geophysical Research Abstracts, 20, EGU2018-16622, EGU General Assembly 2018
- Ferrando I, Federici B, Sguerso D (2017) Zenith total delay interpolation to support GNSS monitoring of potential precipitations. Geam Geingegneria Ambientale E Mineraria 151:85–90. <https://unige.iris.cineca.it/handle/11567/888405>.

Thank you for your attention!!

Disturbance in the ZTD values

GNSS station: EKAR00ITA (Asiago)
Elevation: **1410.9** m

GNSS station: CIMO00ITA (Modena)
Elevation: **2224.6** m

GNSS station: SVLL00ITA (Savelli)
Elevation: **1209.3** m

