

Analysis of atmospheric water vapor variability associated with seismic activity: first experiences starting from ASI's national GNSS fiducial network

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THE GOAL

Investigate possible relationships between atmospheric anomalies and seismic activity by exploiting GNSS-derived tropospheric parameters.



Characterize the temporal behaviour of **ZTD and PWV** from GNSS observations.



Identify and quantify anomalous variations in the tropospheric signal.



Investigate their temporal relationship with seismic events, while accounting for meteorological variability.

GNSS
observations

Atmospheric
anomalies

Seismic
events

TROPOSPHERIC PARAMETERS

GNSS
observations

ZTD is equal to
 $ZHD + ZWD$

$ZWD \rightarrow PWV$

- **ZHD** → hydrostatic component, related to the atmospheric dry gases
- **ZWD** → wet component, related to atmospheric water vapour
- **PWV** → integrated water vapour content in atmospheric column

In this study, we initially focus on ZTD time series and use them to investigate anomalous tropospheric behaviour. They provide a starting point for developing and testing our anomaly detection methodology.

LITERATURE REVIEW

GNSS meteorology

- PWV as a high-resolution indicator of atmospheric water vapour

Bevis et al. (1992), GPS Meteorology: Remote Sensing of Atmospheric Water Vapor Using the Global Positioning System

- Long-term ZTD/PWV time series for atmospheric and climatological studies

Pacione & Vespe (2003), GPS Zenith Total Delay Estimation in the Mediterranean Area for Climatological and Meteorological Applications

Seismic-related atmospheric anomalies

- Atmospheric/PWV anomalies investigated around major earthquakes

Guo et al. (2023), Analyzing correlations between GNSS retrieved precipitable water vapor and land surface temperature after earthquakes occurrence

- L'Aquila and Japan as relevant case studies

Wu et al. (2016), Geosphere Coupling and Hydrothermal Anomalies before the 2009 Mw 6.3 L'Aquila Earthquake in Italy

- Ionospheric studies provide methodological approaches for anomaly detection

Lyubushin & Rodionov (2025)

The Relationship between the Seismic Regime and Low-Frequency Variations in Meteorological Parameters Measured at a Network of Stations in Japan

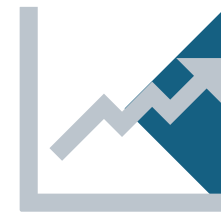
Common issue: the difficulty of distinguishing possible anomalous atmospheric earthquake-related variations from normal meteorological variability.

CAMPI FLEGREI



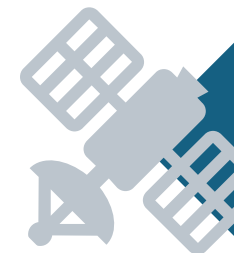
Active volcanic area

Ongoing volcanic and
bradyseismic activity



Shallow seismicity

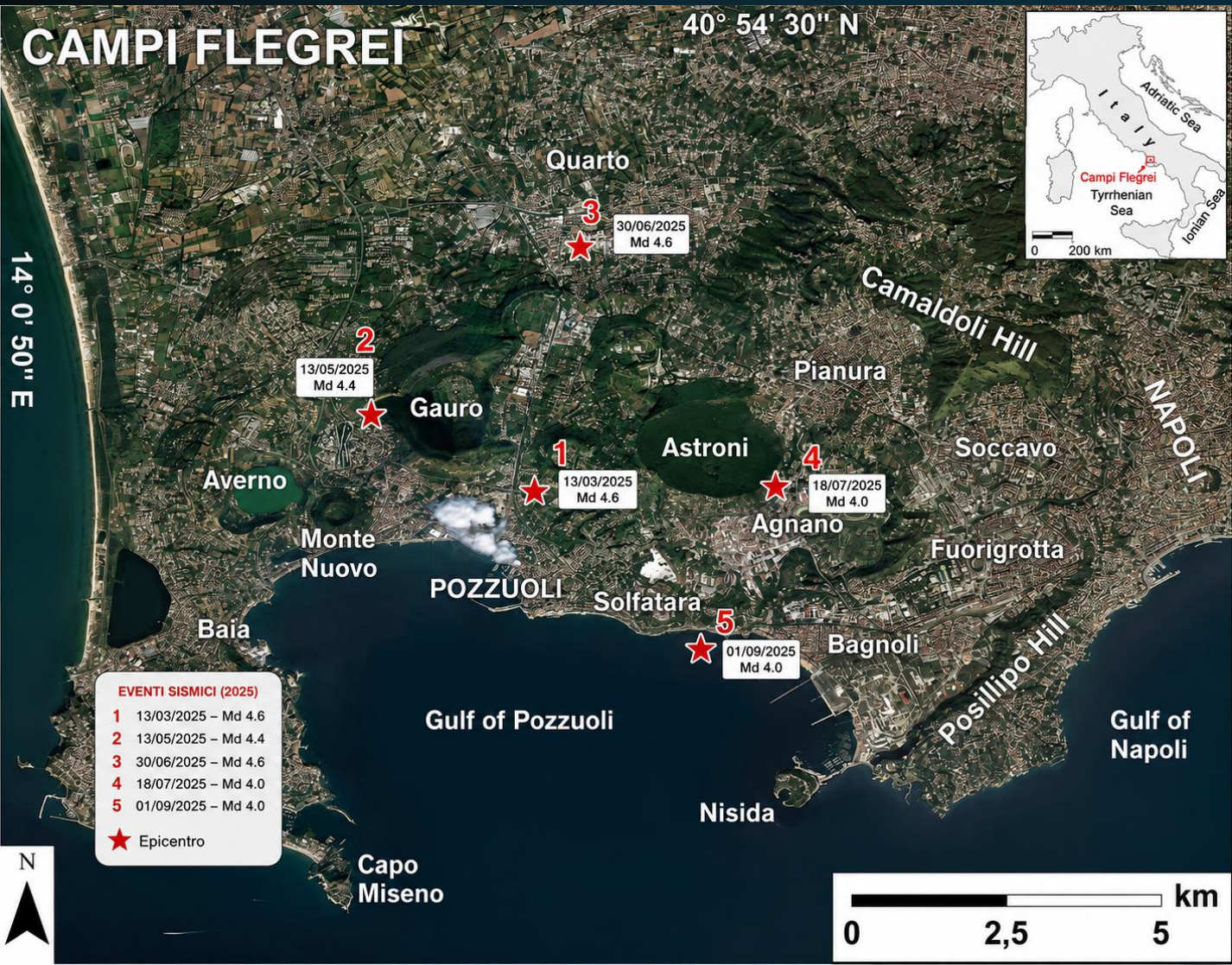
Frequent shallow
earthquakes, including
moderate-magnitude events



GNSS & seismic observations

Availability of GNSS and
accelerometric
observations

SEISMIC EVENTS



Selected events: shallow earthquakes
with $M \geq 4.0$

Date	Magnitude	Depth
13 March 2025	4.6	2.4 km
13 May 2025	4.4	2.6 km
30 June 2025	4.6	3.9 km
18 July 2025	4.0	2.5 km
1 September 2025	4.0	2.3 km

The combination of relatively high
magnitude and shallow depth makes these
events particularly suitable for
investigating the possible response of the
surrounding atmosphere.

SHAKING MAPS

1

- RAN stations

2

- Peak Ground Acceleration measurements

3

- Station coordinates + epicentral distances

4

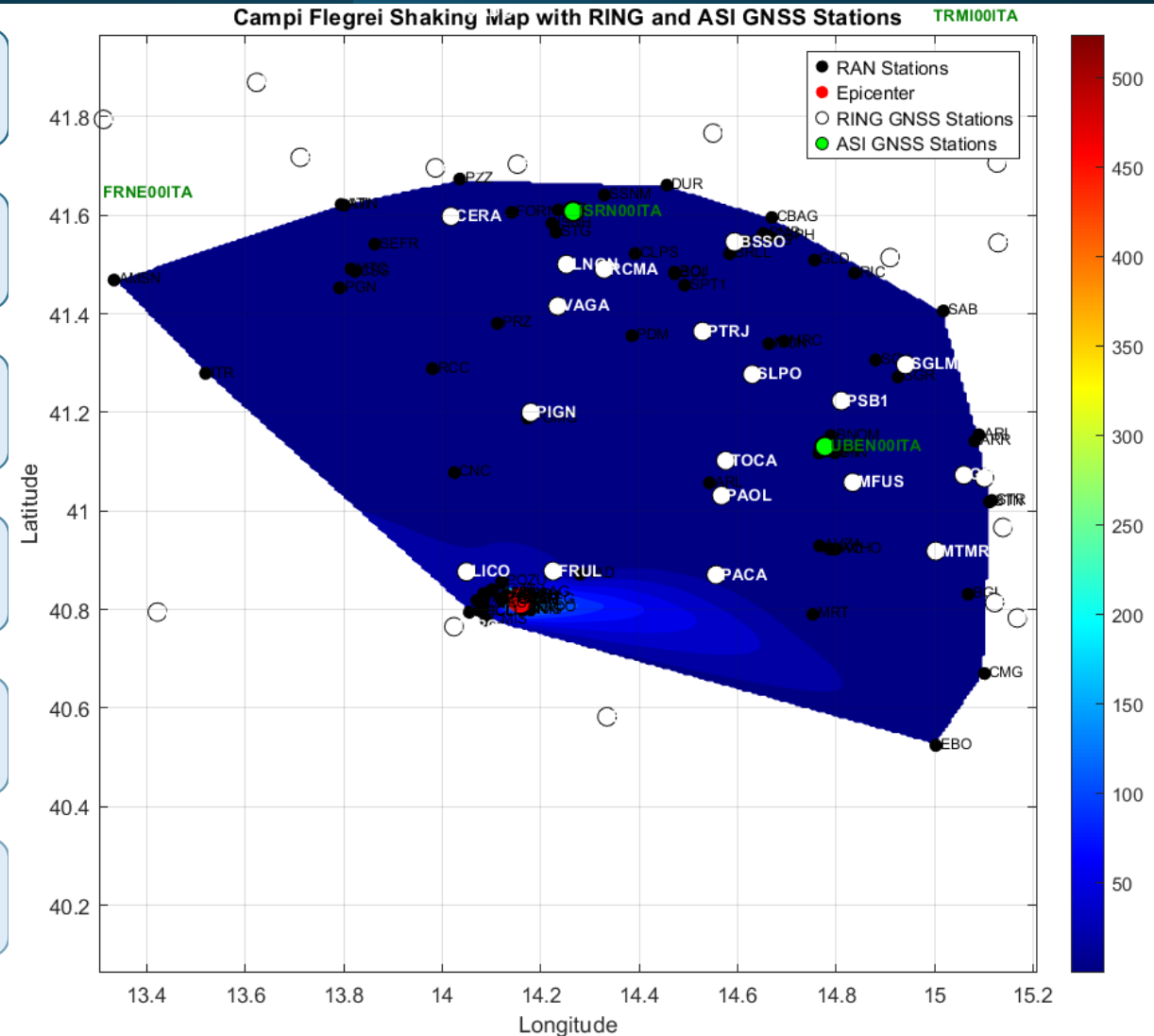
- Spatial representation of ground shaking

5

- Definition of the shaking area

6

- ASI e RING GNSS stations within the area



HOW TO OBTAIN ZTD TIME SERIES?

A procedure to calculate ZTD directly from RINEX observation files.

Three software solutions tested:



CSRS-PPP — online service

Geodetic Survey Division of Natural Resources Canada



PRIDE PPP-AR III — software open-source

Wuhan University Satellite Navigation and Positioning
Technology Research Center



RTKLIB demo5 — software open-source

Tokyo University of Marine Science and Technology



Comparison with ASI official ZTD products

Evaluation of statistical indices:
BIAS, RMSE, Pearson correlation



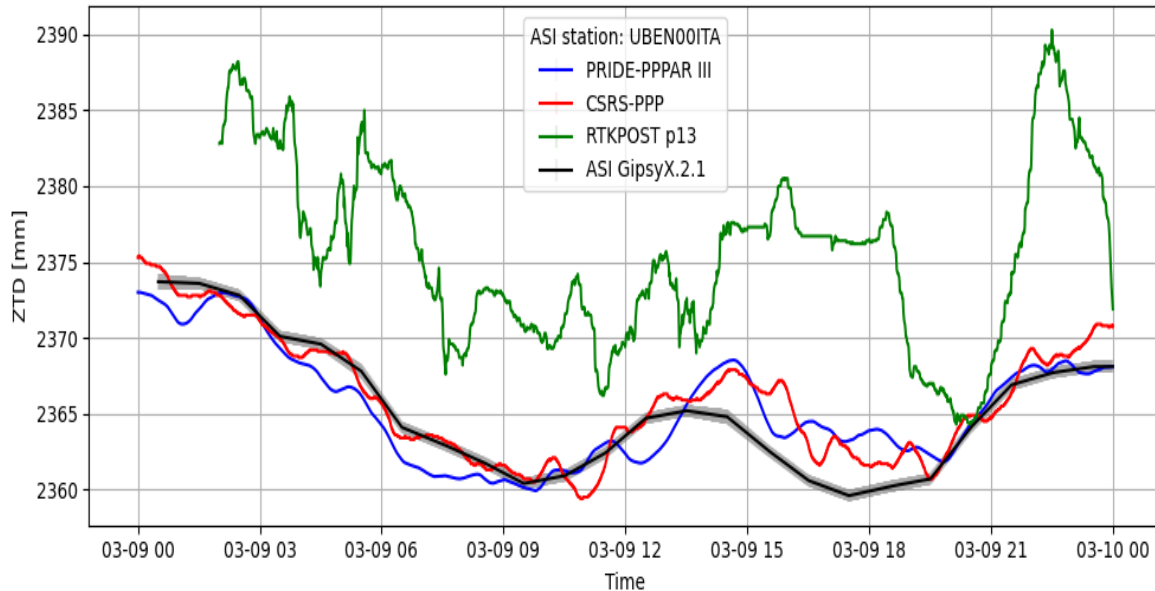
Automatic
management of
GNSS precise
products

Explicit
association of:
RINEX + NAV + SP3
+ CLK + ATX + ERP

SOFTWARE COMPARISON

**First daily results for selected days
in 2009 and 2025 for 5 ASI GNSS stations**

Different Zenith Total Delay elaborations vs. ASI GipsyX, date: 2025-3-9

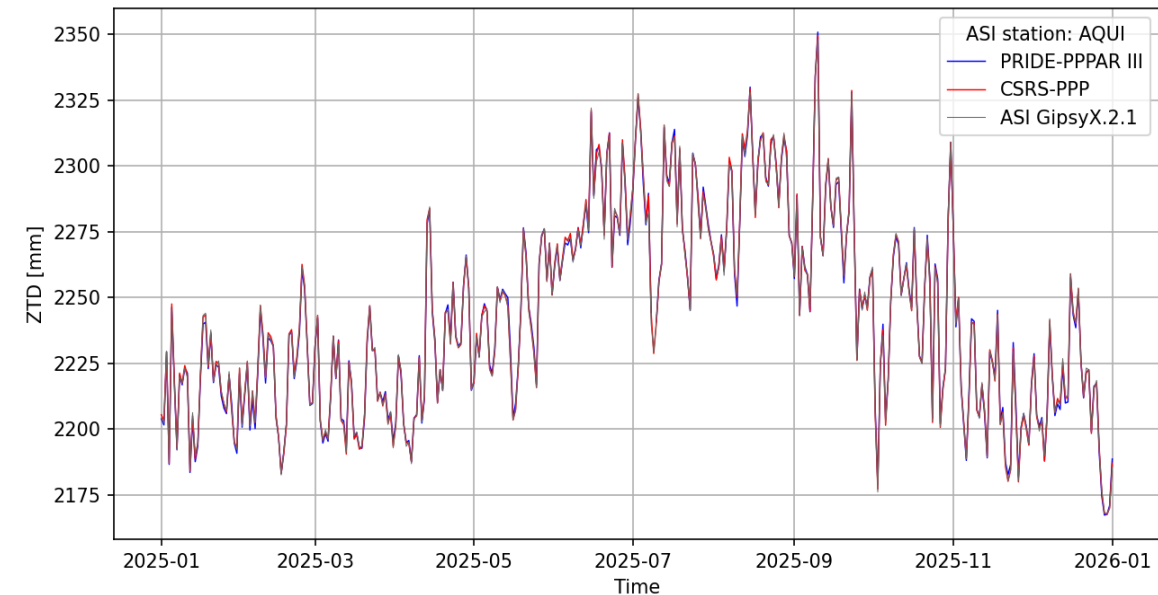


	BIAS [mm]	RMSE [mm]	Pearson coeff.
CSRS-PPP	0,68	1,61	0,93
PRIDE PPP-AR	0,17	1,95	0,88
RTKLIB p13	11,00	12,00	0,61

Best performance obtained by CSRS-PPP and PRIDE PPP-AR overall

**Extension to year-long
time series**

ZTD solutions compared with ASI GipsyX, resample on 1440min
AQUI: 2025-01-01 to 2026-01-01

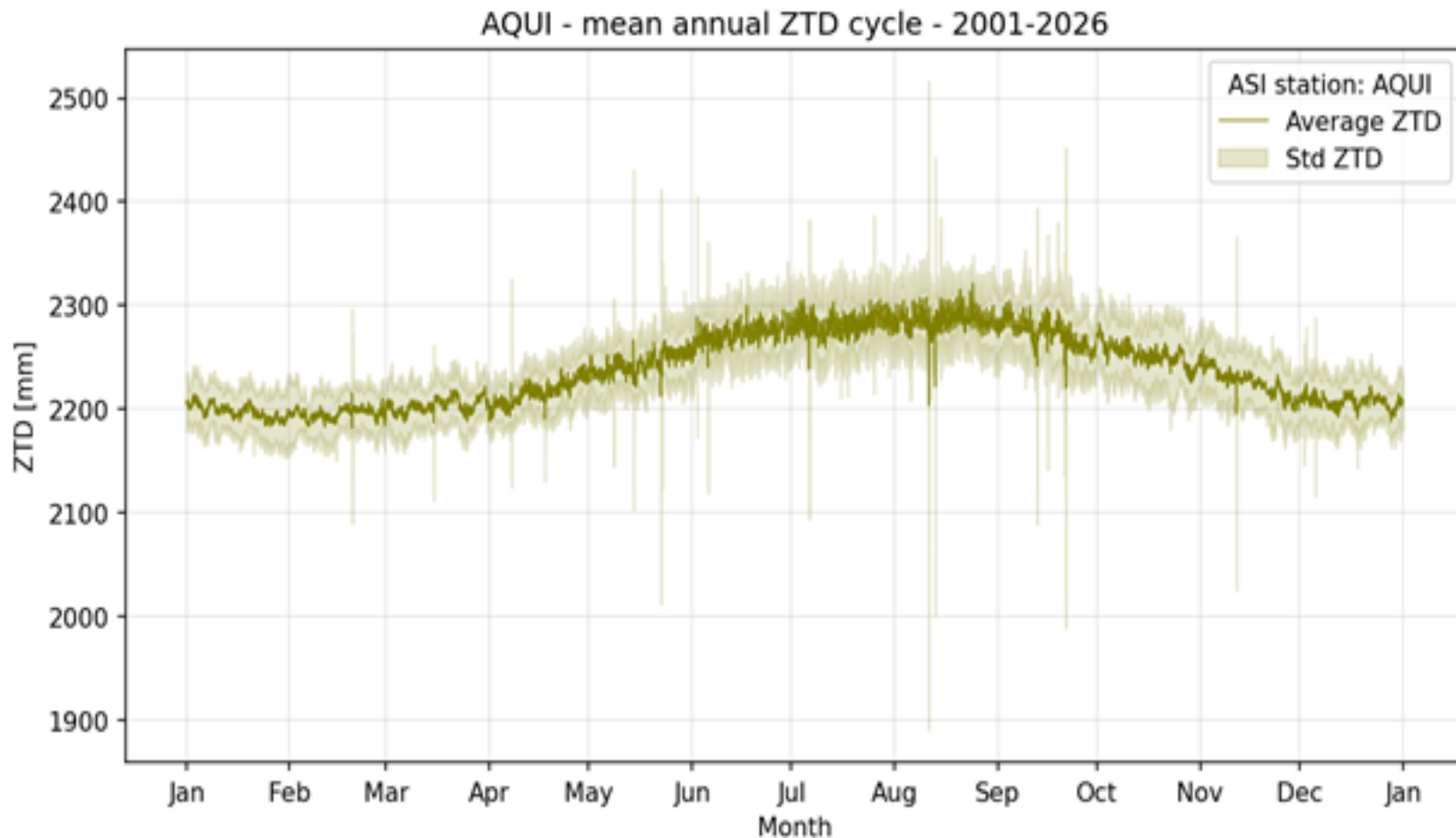


	BIAS [mm]	RMSE [mm]	Pearson coeff.
CSRS	0,17	2,73	0,998
PRIDE	0,04	3,56	0,996

**Excellent agreement with the reference also for
2009 AQUI time series**

DEFINITION OF THE ANNUAL ZTD REFERENCE

Multi-year average approach

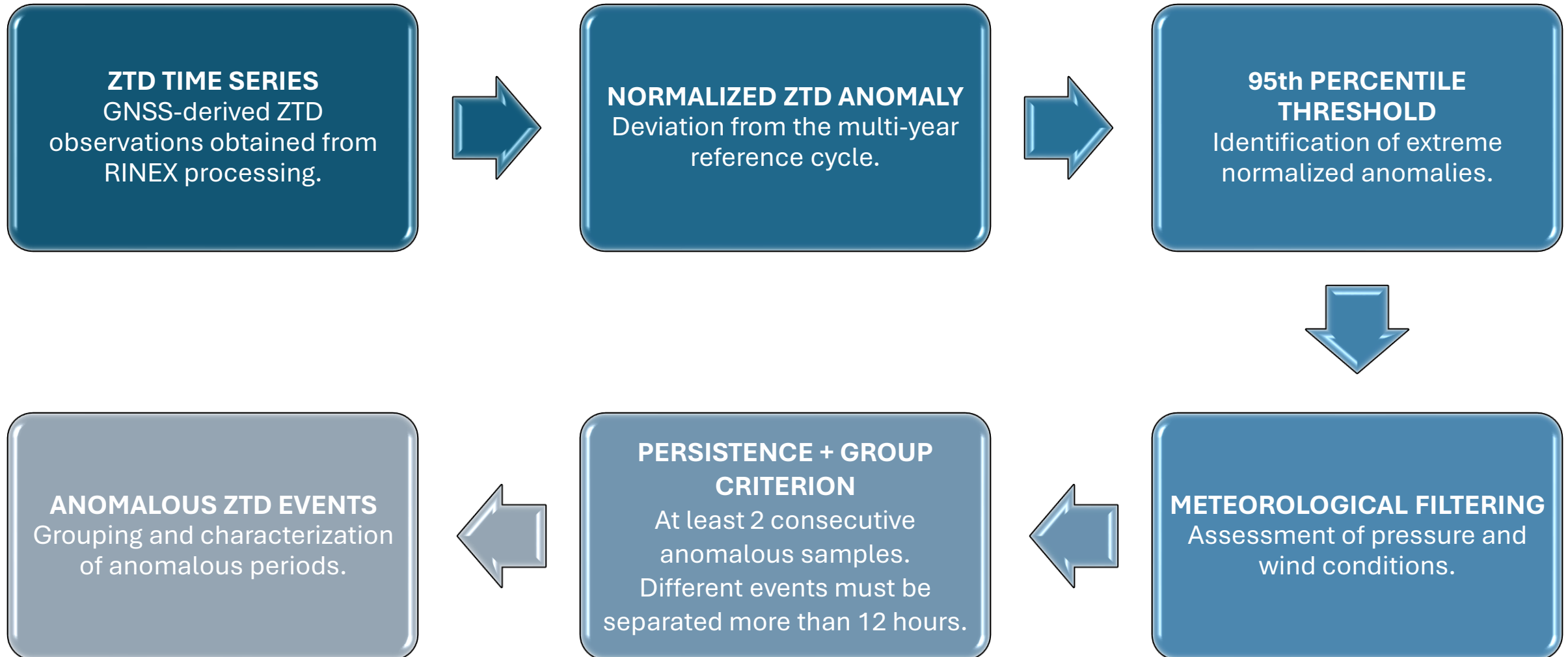


Mean ZTD cycle
 $\langle \text{ZTD} \rangle = 2238 \text{ mm}$

Variability
STD = 28 mm

Currently
preferred
approach

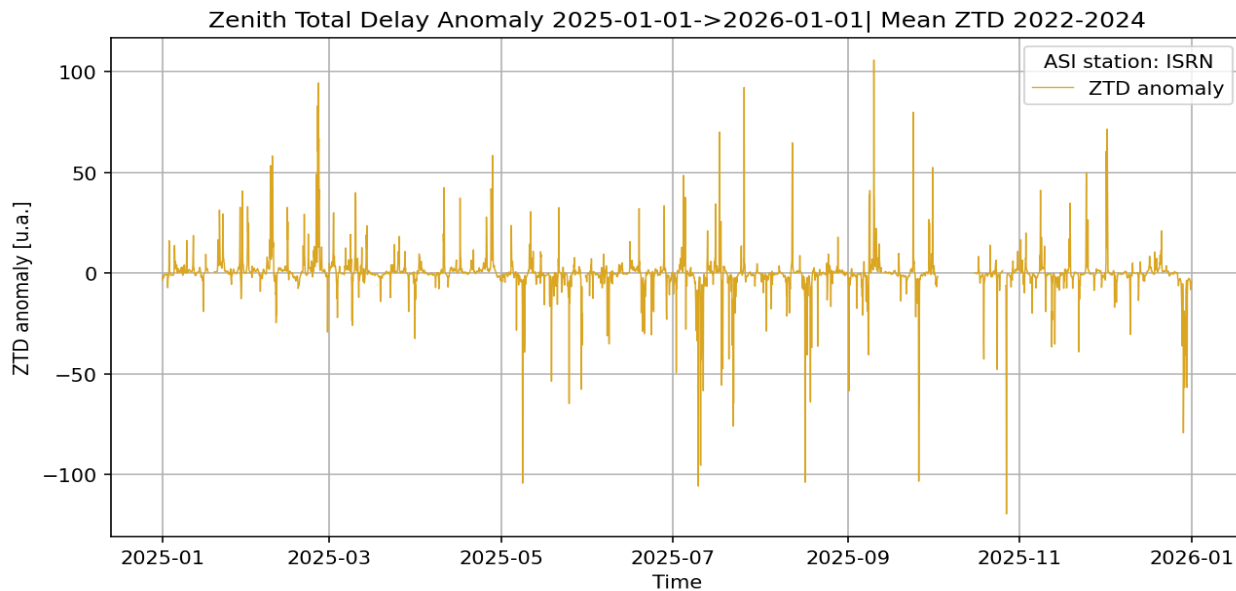
PRELIMINARY ZTD ANOMALY DETECTION



PRELIMINARY APPLICATION: CAMPI FLEGREI 2025

Period analysed:
January–December 2025

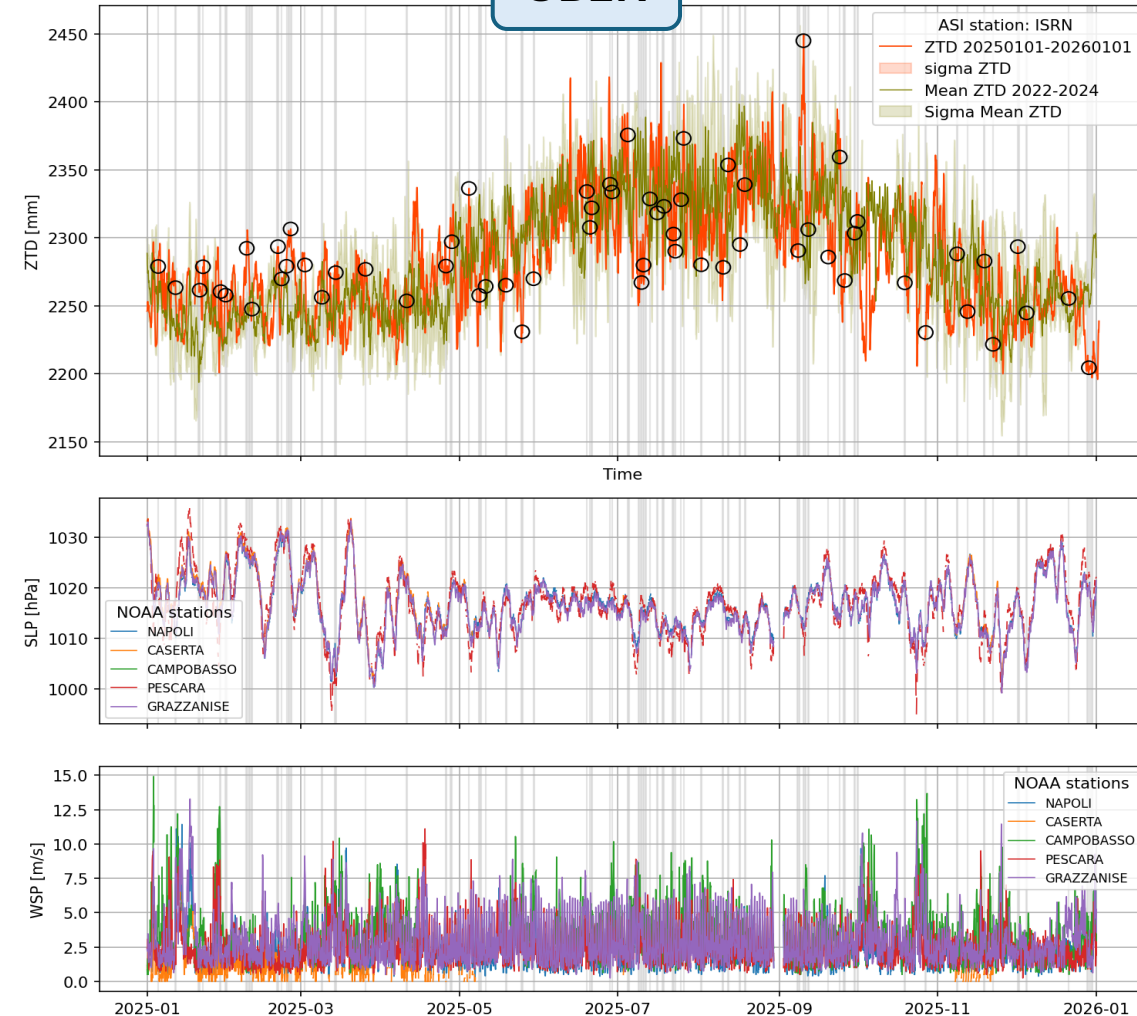
ISRN



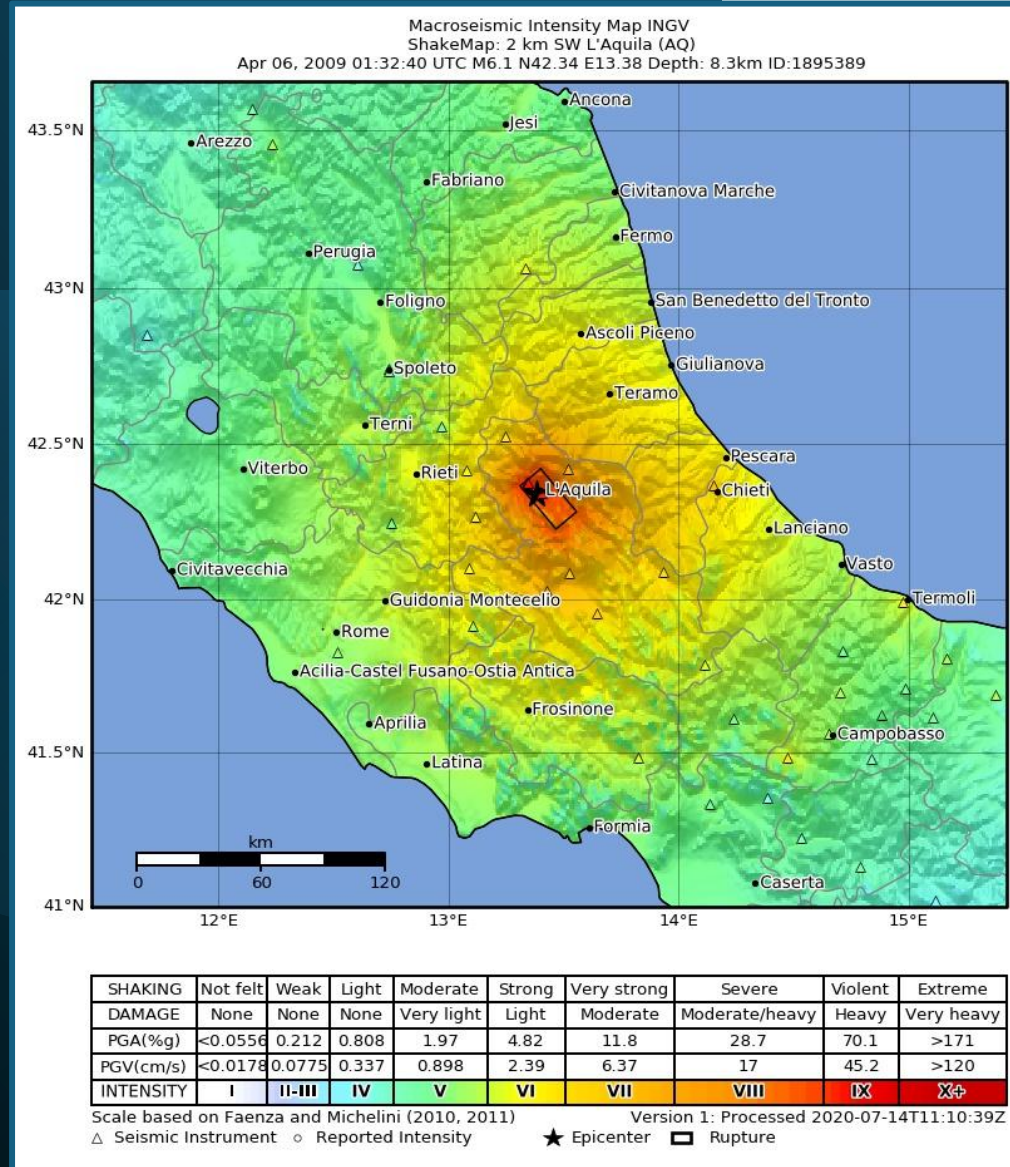
Several candidate anomalous ZTD events were identified, with some showing temporal proximity to seismic events.

STILL NOT EVIDENCE OF A CAUSAL OR PREDICTIVE RELATIONSHIP.
Further analysis are required.

UBEN



L'AQUILA EARTHQUAKE



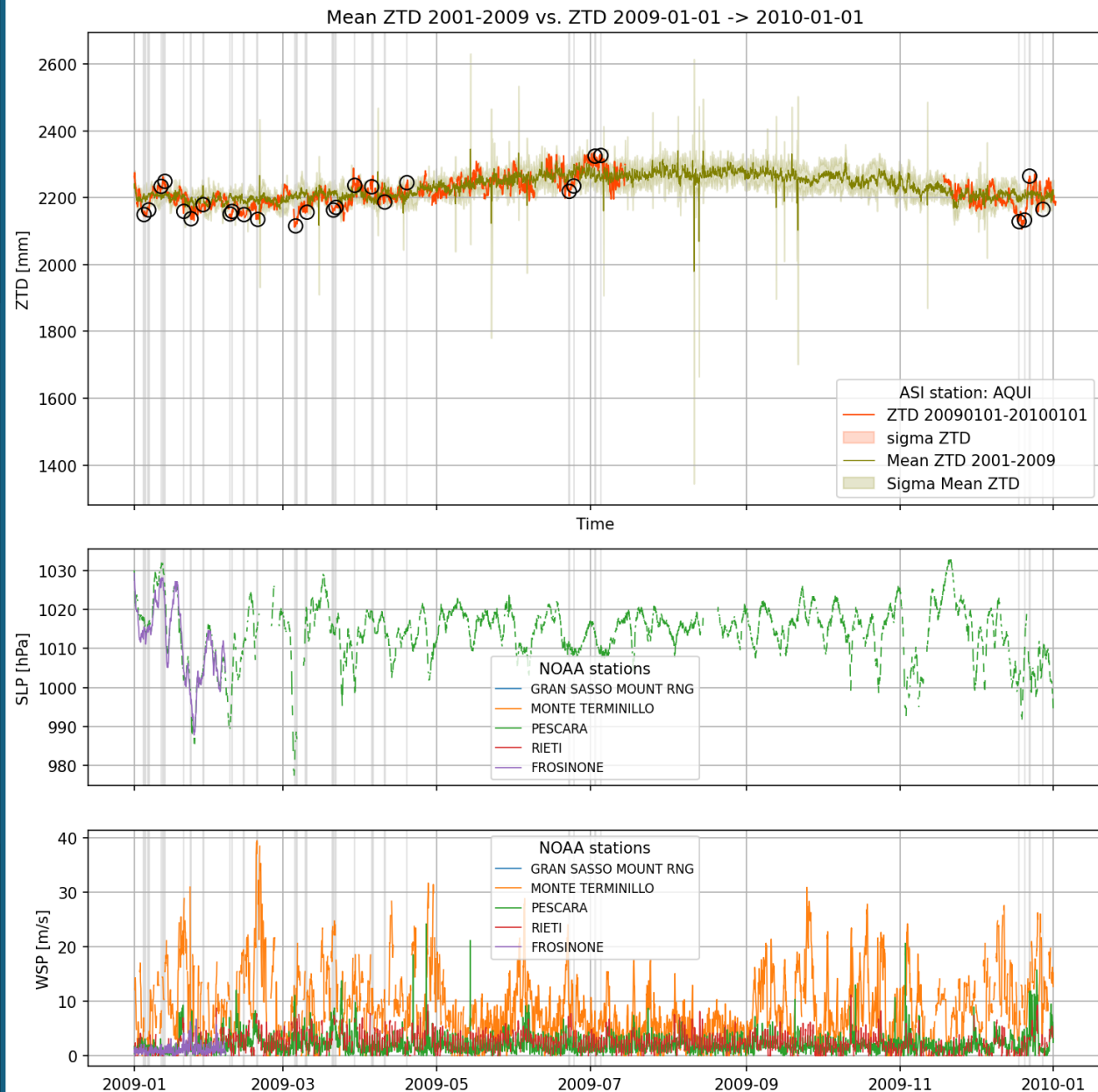
DATE	DEPTH	MAGNITUDE
06/04/2009	8.3 km	MW 6.1

Why L'Aquila?

- **Historical seismic event**
A well-documented MW 6.1 earthquake.
- **Long-term ZTD availability**
The AQUI GNSS station provides a long historical ZTD record.
- **Historical data processing test**
RINEX observations from 2009 were processed to assess the feasibility of reconstructing historical ZTD time series.

A historical case study to investigate the availability of long-term ZTD time series.

AQUI: LONG-TERM REFERENCE TEST



ZTD ANOMALY

Duration: 15 h

Peak ZTD anomaly: 5.22

95th percentile: 1.48

OBSERVED TEMPORAL PROXIMITY

An anomalous ZTD event was identified immediately before the main shock.

What changes with a longer reference?

More stable
seasonal ZTD
cycle.

Lower
sensitivity to
individual
years.

More reliable
estimate of
expected
variability.

**PRELIMINARY OBSERVATION:
REQUIRES CAUTIOUS
INTERPRETATION.**

LIMITATIONS

Short GNSS observational histories

Limited
robustness of
the
climatological
ZTD reference.

Data continuity and completeness

Gaps and
discontinuities
may affect the
anomaly
detection.

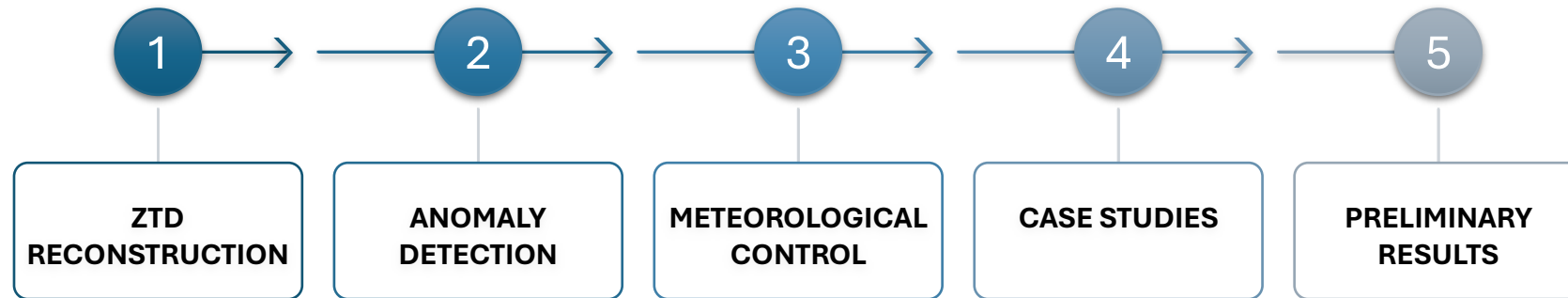
Empirical detection parameters

Thresholds,
persistence and
event-
separation
criteria still
require
sensitivity
analysis.

Meteorological variability

Atmospheric
effects cannot
be completely
separated with
the current
filtering
approach.

CONCLUSIONS & NEXT STEPS



NEXT STEPS

Test the procedure on PWV data obtained from G4M.

Extend the analysis to longer GNSS time series.

Increase the number of seismic and non-seismic case studies.

Improve the separation of meteorological and non-meteorological signals.

Assess the robustness of candidate anomalous events.

The current results are methodological and exploratory, rather than evidence of seismic precursors.

THANK YOU FOR THE ATTENTION



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fiduciale nazionale GNSS dell’ASI”
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