From Surface Motion to Differential Settlement: An Infrastructure-Aware Approach Using Copernicus Sentinel-1 InSAR over Rome Metropolitan Area

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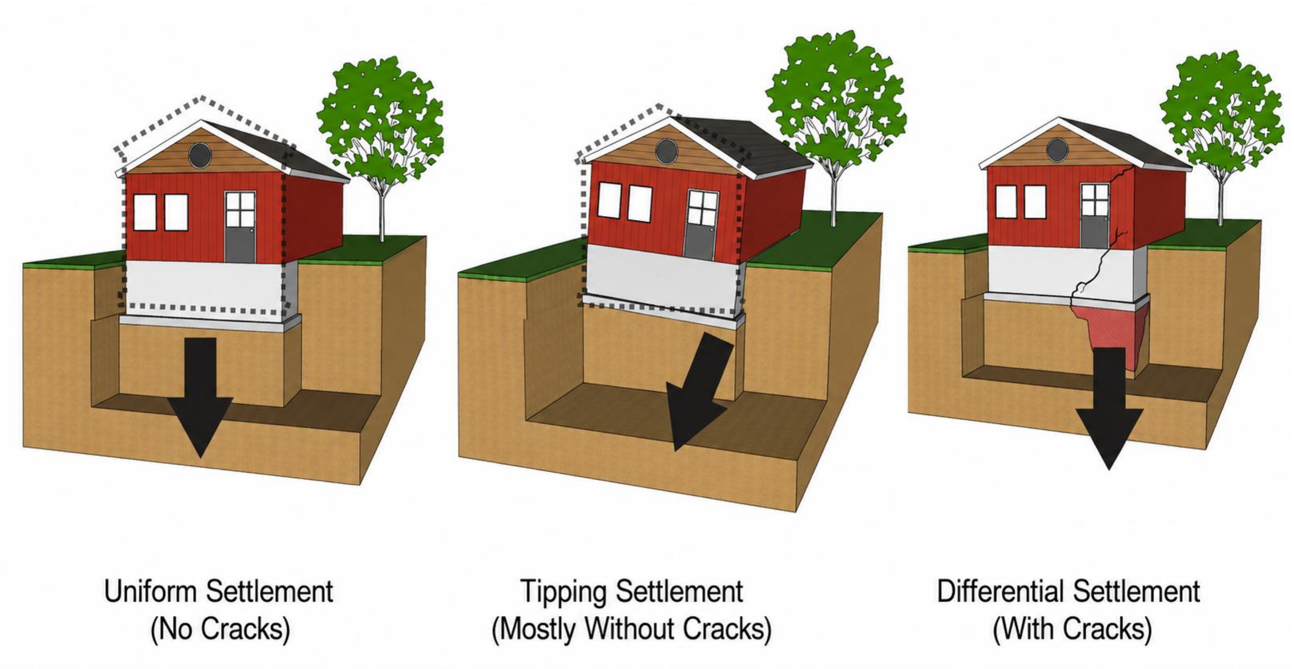
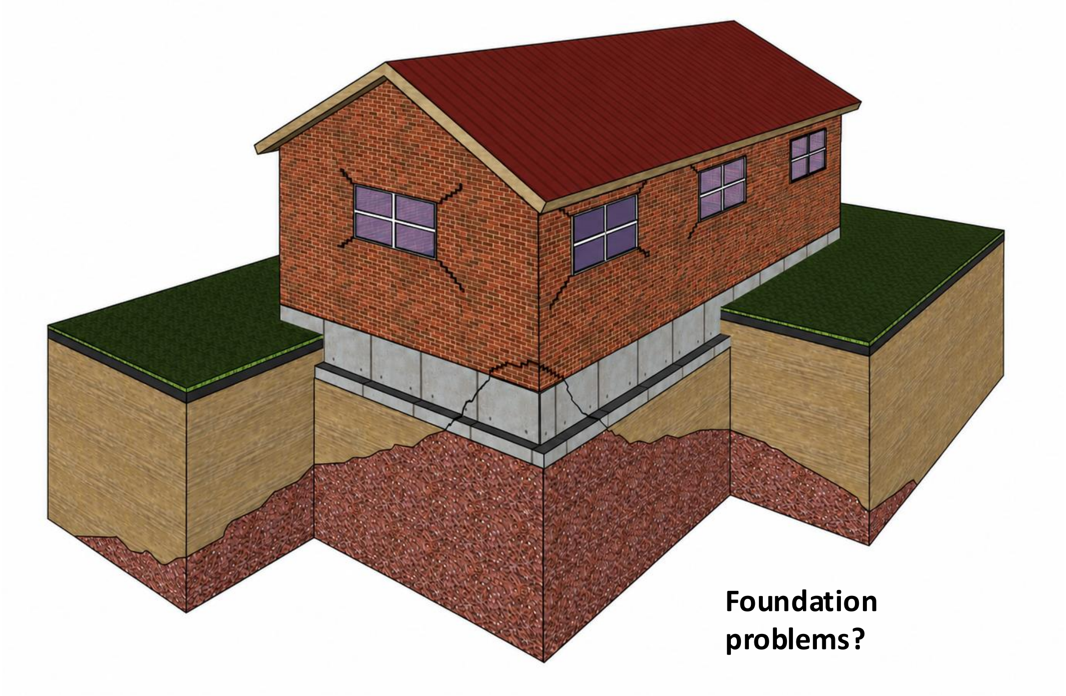
Types of Settlement

Structural damage is primarily related to differential settlement rather than absolute settlement.

Uniform or near-uniform ground movement can often be accommodated by a structure, whereas spatially variable settlement generates strain, leading to cracking and structural distress.





Fundamental issue in engineering geology, geotechnics, and structural health monitoring.

Does the observed damage originate from a foundation problem, from ground deformation, or from a combination of both?

Literature Review and Terminology

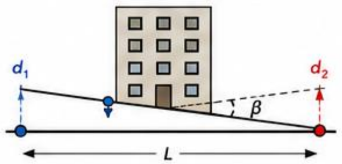
Year	Study	Main Metric
1956	Skempton & MacDonald	Angular distortion (β)
1975	Burland & Wroth	Angular distortion, deflection ratio, tensile strain
1989	Boscardin & Cording	Angular distortion + horizontal strain damage matrix
2020	Fernández-Torres et al.	InSAR-derived angular distortion
2021	Cigna & Tapete	InSAR-derived angular distortion (β) and horizontal strain (ε) for subsidence risk assessment
2022	Yang et al.	PSI differential motion (ΔV) characterization; Building-Ground Differential Motion
2024	Shahbazi et al.	Building-scale deformation gradients
2026	Li et al.	Structural Differential Settlement Index (SDSI)

Majority of studies focus on cumulative displacements and not motion rates.

Remote Sensing	Geotechnical Engineering
Displacement	Settlement (predominantly vertical)
Velocity	Settlement Rate
Differential Motion	Differential Settlement
Displacement Gradient	Settlement Gradient
Tilt / Slope	Angular Distortion / Relative Rotation
~Strain	Ground / Structural Strain
	Structural Stress

Angular Distortion

Relative rotation between two points



Differential Motion and Related Metrics

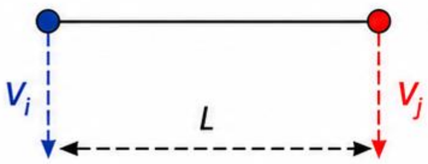
Difference in motion rate between points

$$\Delta V = V_j - V_i$$

Units: mm/yr

Difference in motion rate between two observation points.

Differential motion normalized by distance

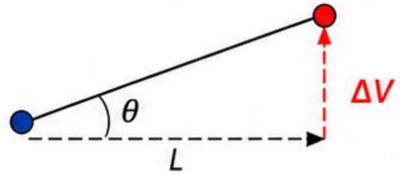


$$G_v = \frac{V_j - V_i}{L} = \frac{\Delta V}{L}$$

Units: mm/yr/m

Differential motion normalized by separation distance.

Gradient expressed as slope (percentage)

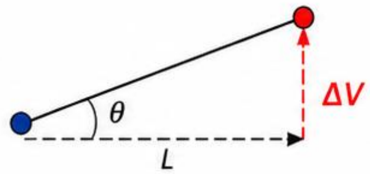


$$\text{Slope (\%)} = \frac{\Delta V}{L} \times 100$$

Units: %/yr

Gradient expressed as percentage slope.

Inclination angle / Tilt



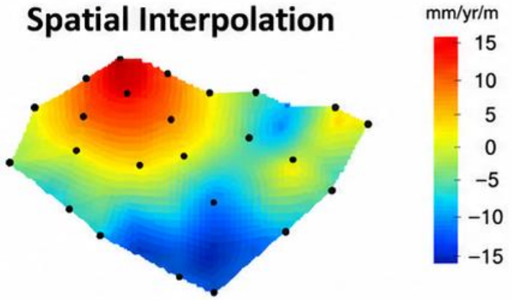
$$\theta = \arctan\left(\frac{\Delta V}{L}\right)$$

For small angles: $\theta_{rad} \approx \frac{\Delta V}{L}$

Units: °/yr (or rad/yr)

Gradient expressed as angular deformation.

Gradient derived by Spatial Interpolation



$$\text{Slope (degrees)} = \arctan\left(\sqrt{\left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2}\right)$$

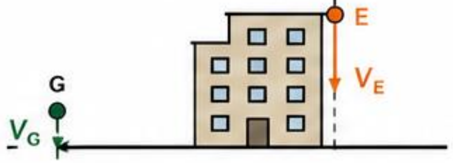
Units: °/yr (or rad/yr)

Where $\partial z/\partial x$ and $\partial z/\partial y$ are spatial derivatives of the interpolated velocity surface (z).

Essentially different representations of the same geometry

Building-Ground Differential Motion

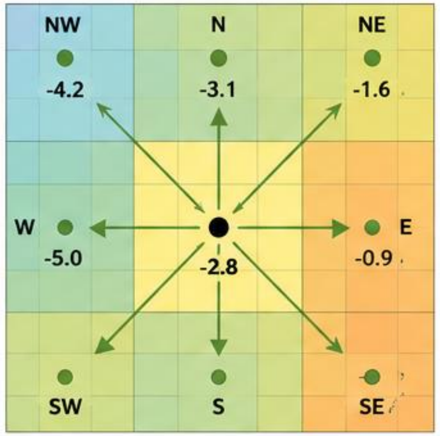
Relative motion between structural element (E) and adjacent ground (G)



Differential **Mo**tion (**DiMo**) algorithm

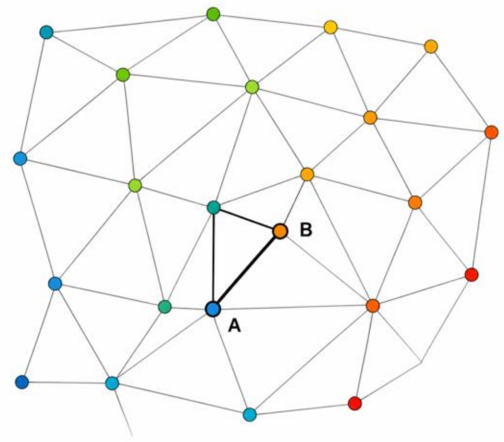
DiMo-Grid

Computed between center pixel and 8 surrounding pixels



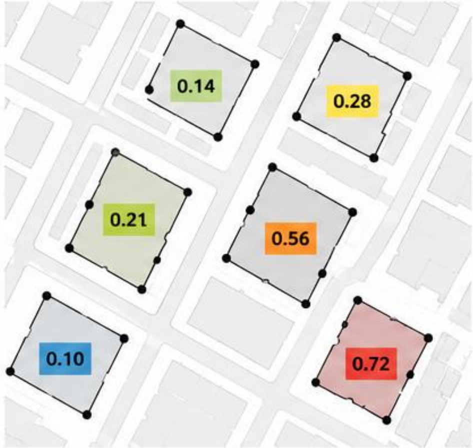
DiMo-Tri

Computed along edges of a triangulation (Delaunay) connecting PS targets



DiMo-Struct

Summarized within each structure using interpolated PS on the structure.



Regardless of the processing approach, differential motion is computed using the **same underlying formulation** and reported as **gradient** (mm/yr/m), **slope angle** (°), or **slope percentage** (%).

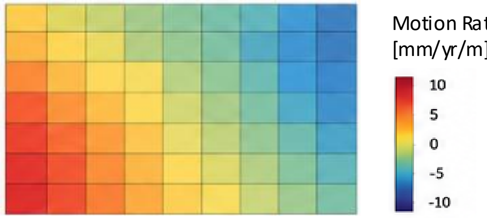
Apart from average DiMo rates the framework is computing the complete DiMo time series allowing the characterization of the **temporal evolution of differential motion**.

DiMo Processing Workflows

DiMo-Grid

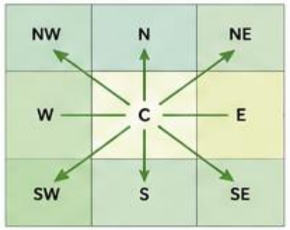
STEP 1

Compute average PSI rates for each grid cell



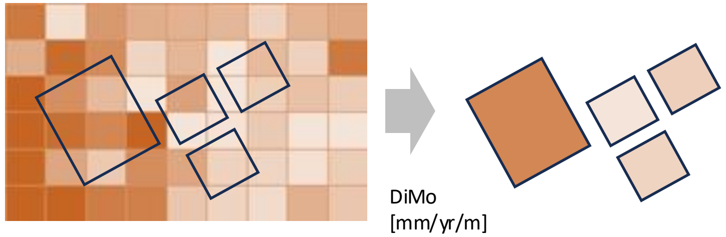
STEP 2

Compute DiMo between the central grid cell and its 8 neighboring cells



STEP 3

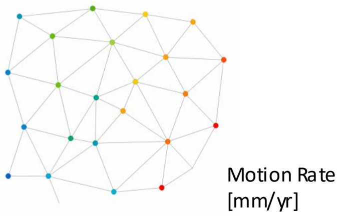
Assign grid-based DiMo values to structures



DiMo-Tri

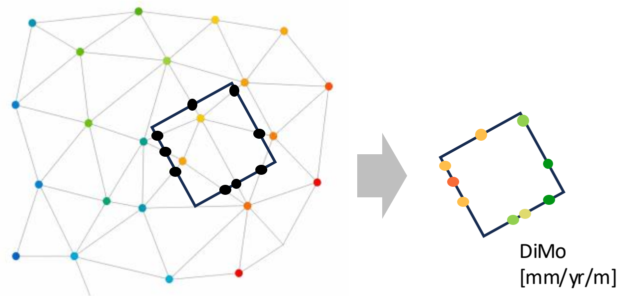
STEP 1

Apply Delauny triangulation to PSI measurements



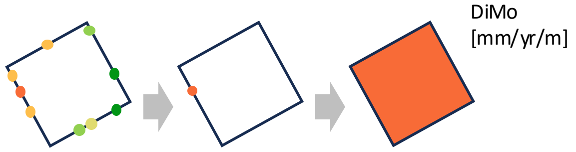
STEP 2

Identify intersections with structures and compute DiMo at each intersection point



STEP 3

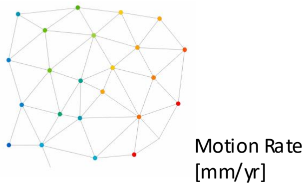
Select maximum DiMo value for each structure and assign attributes



DiMo-Struct

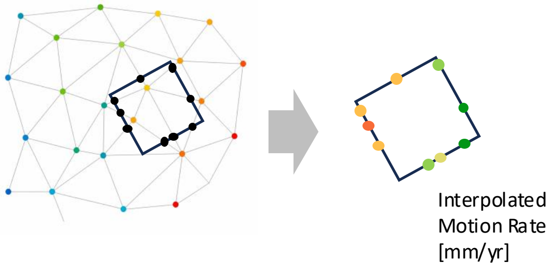
STEP 1

Apply Delauny triangulation to PSI measurements



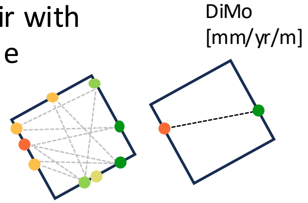
STEP 2

identify intersections and interpolate PSI motion rates to intersection points

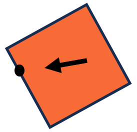


STEP 3

Evaluate DiMo for edge-point pairs and identify pair with maximum DiMo value



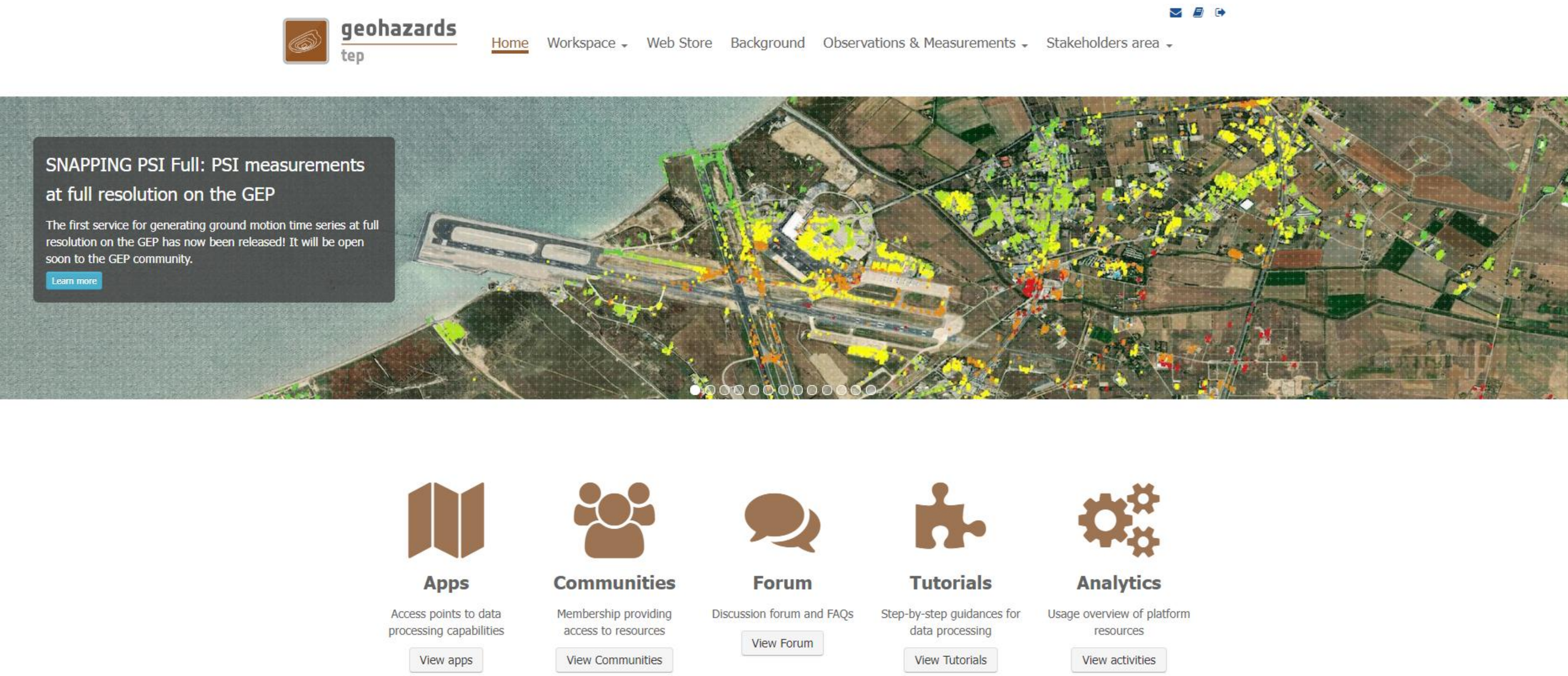
STEP 4



Assign maximum DiMo value and direction to structure

Geohazards Exploitation Platform | GEP

https://geohazards-tep.eu



SURFACE MOTION MAPPING | SNAPPING SERVICE

EO.Lab
Earth Observation
& Geospatial Applications Lab

A multi-temporal interferometric service that produces measurements of surface displacements based on ESA SNAP and StaMPS software packages

Two step process

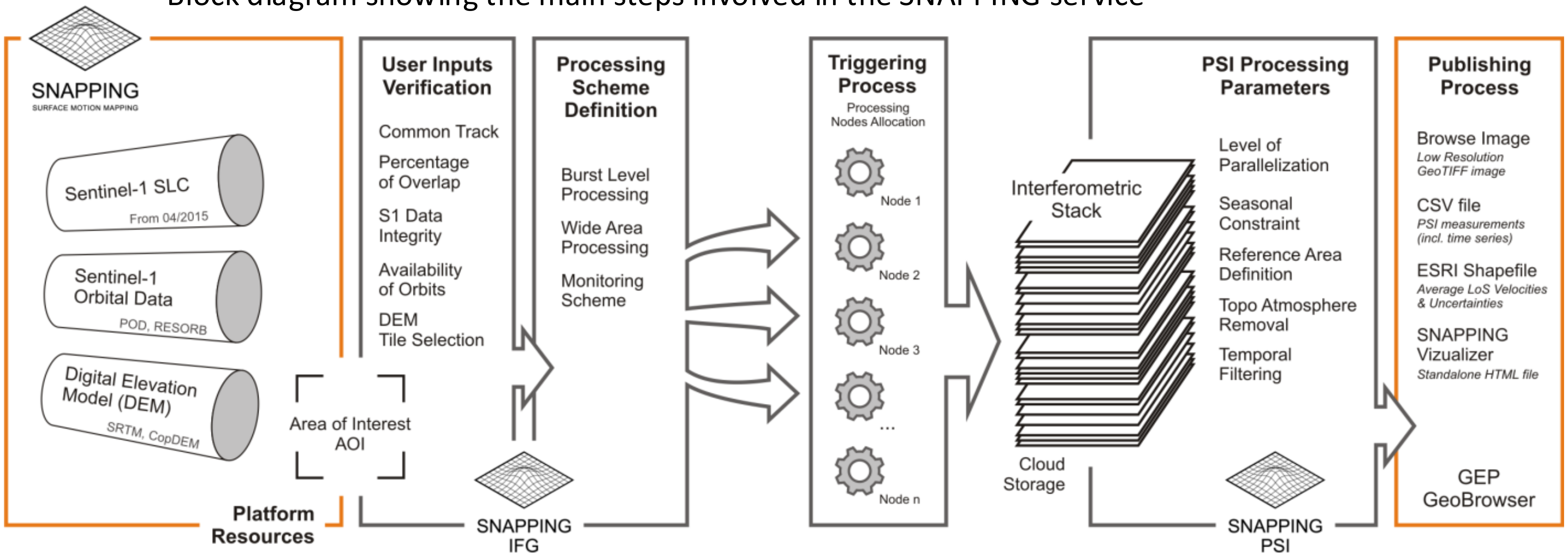
SNAPPING IFG

The first consists in setting-up **SNAPPING IFG** processing pipeline to generate the interferogram stack

SNAPPING PSI

In the second step the interferogram stack is channeled to the **SNAPPING PSI** pipeline for time series analysis

Block diagram showing the main steps involved in the SNAPPING service



On-line Tutorial

SNAPPING
SURFACE MOTION MAPPING

geohazards tep

Sentinel-1 PSI Processing | Rome City

Copernicus Sentinel-1 mission

Observation period: **01/2022-12/2024** (3yr)

Ascending 117: **87 dates**

Descending 022: **84 dates**

Automatic SNAPPING PSI processing on GEP

~2.37M
PS targets (A117)

~494 points/km²

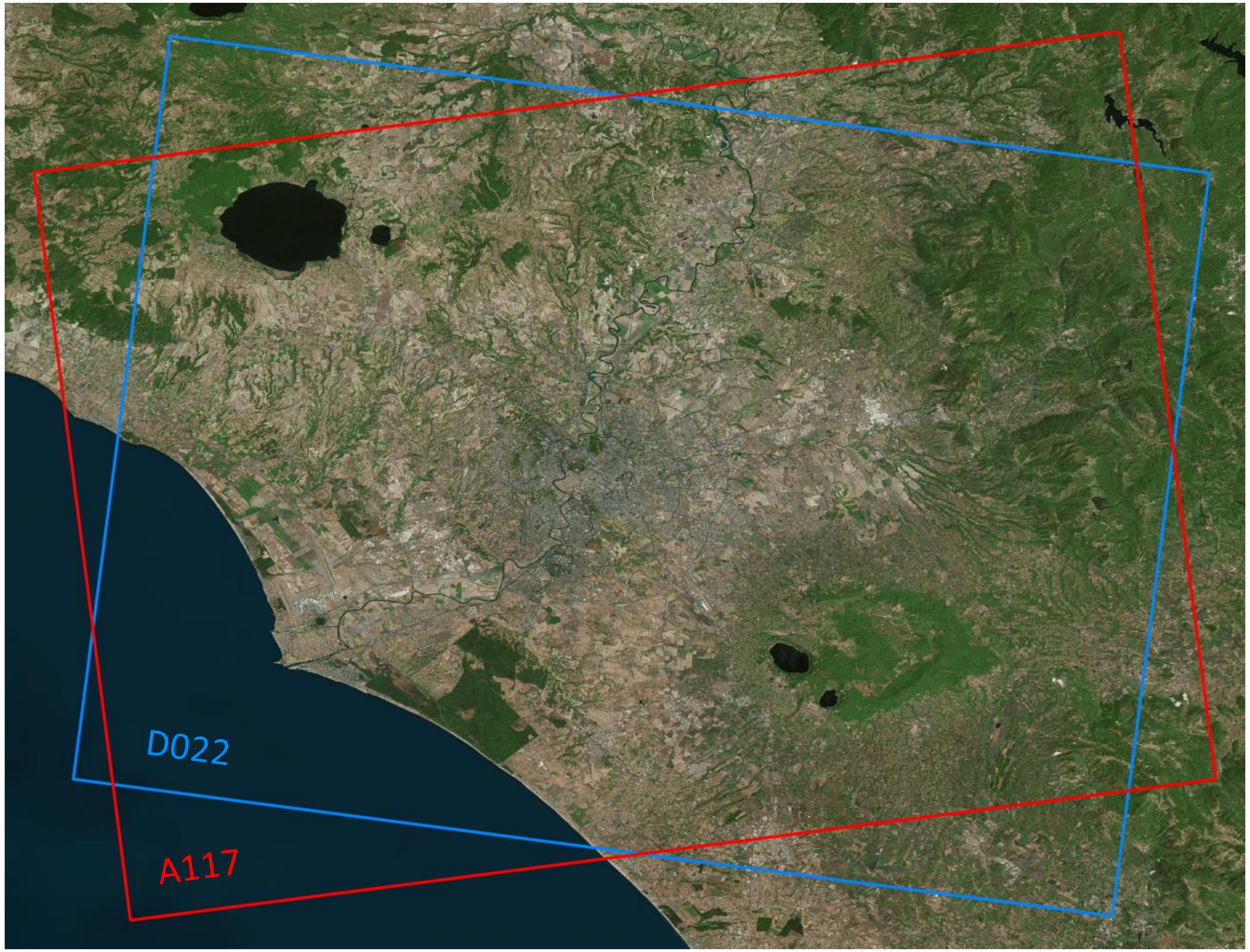
~2.77M
PS targets (D022)

~586 points/km²

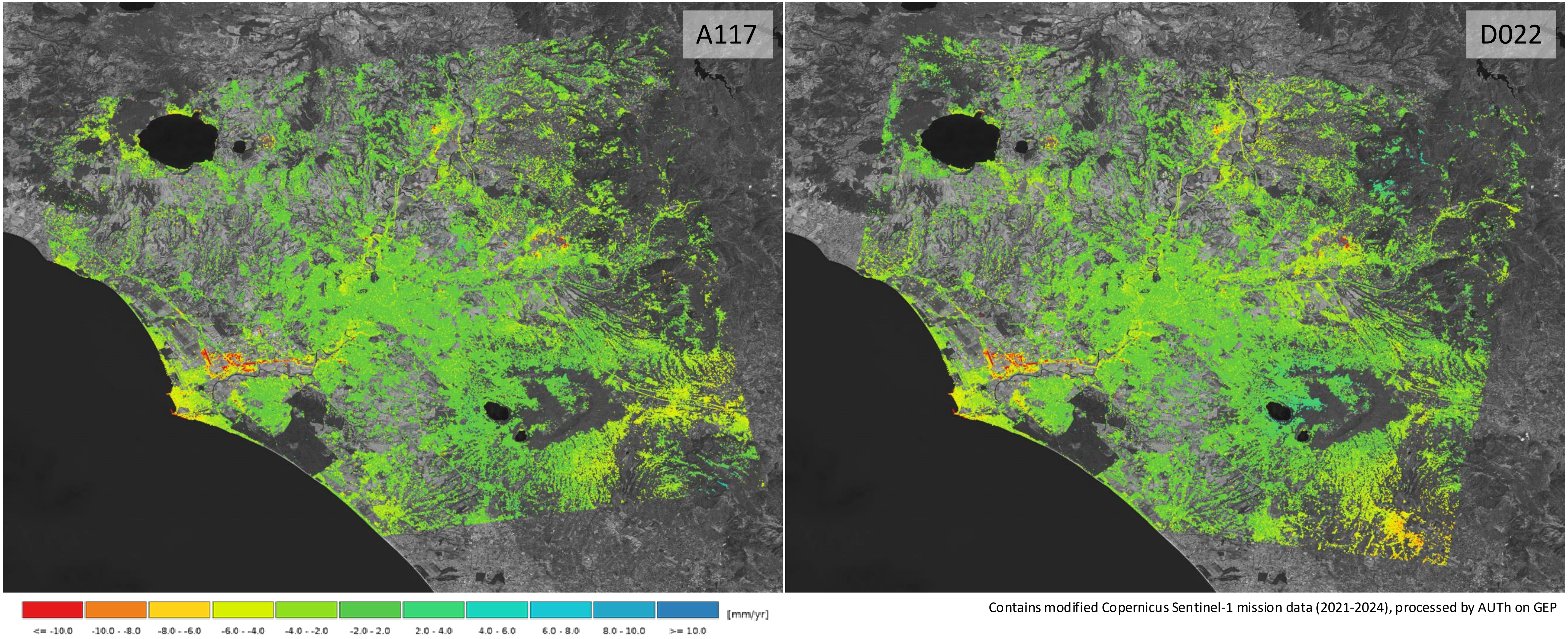
3D Decomposition (Up & E-W components)

~158k points
Grid Approach
100m spacing

~4.73M points
NNV approach
100m search radius

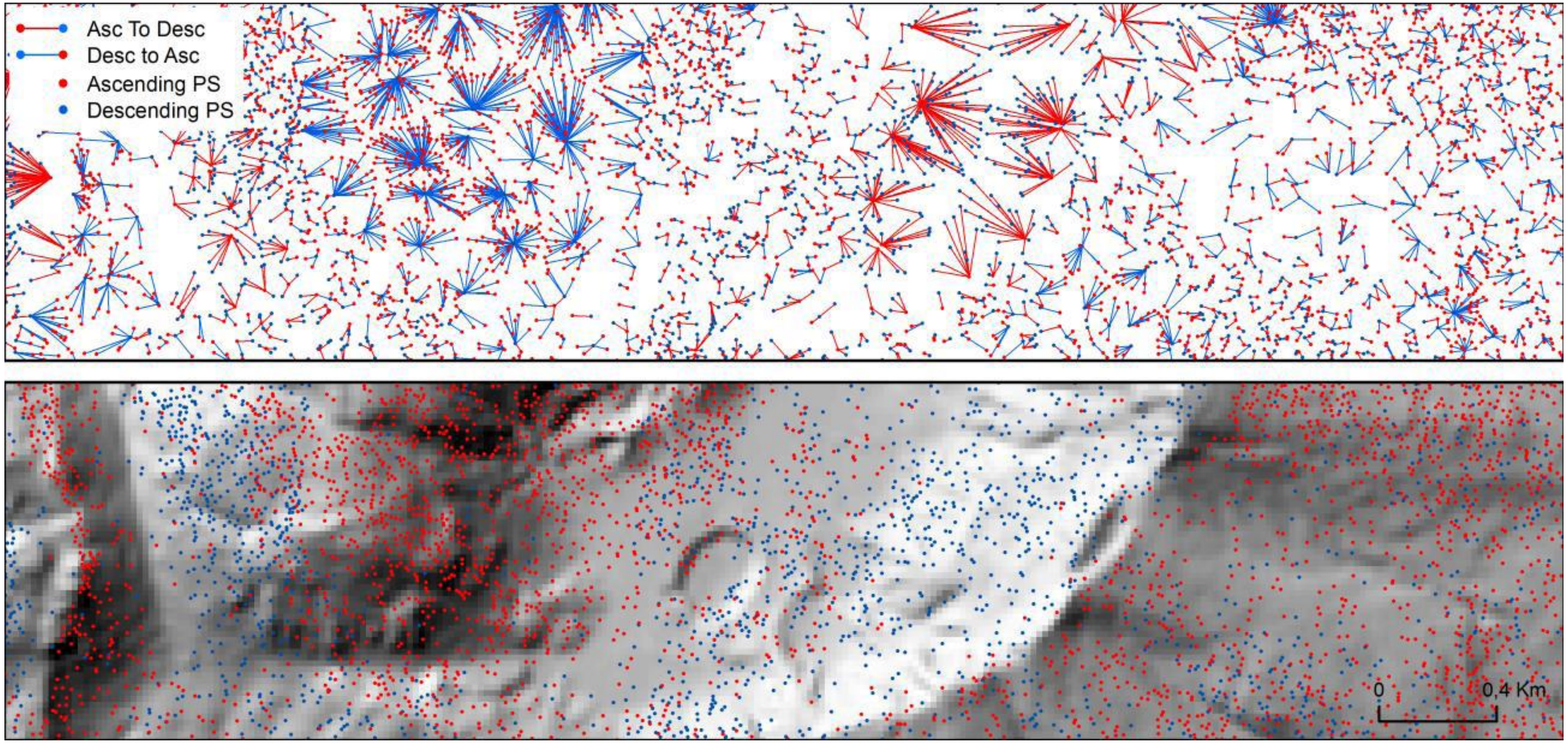


PSI LoS measurements over Rome | 01/2022-12/2024



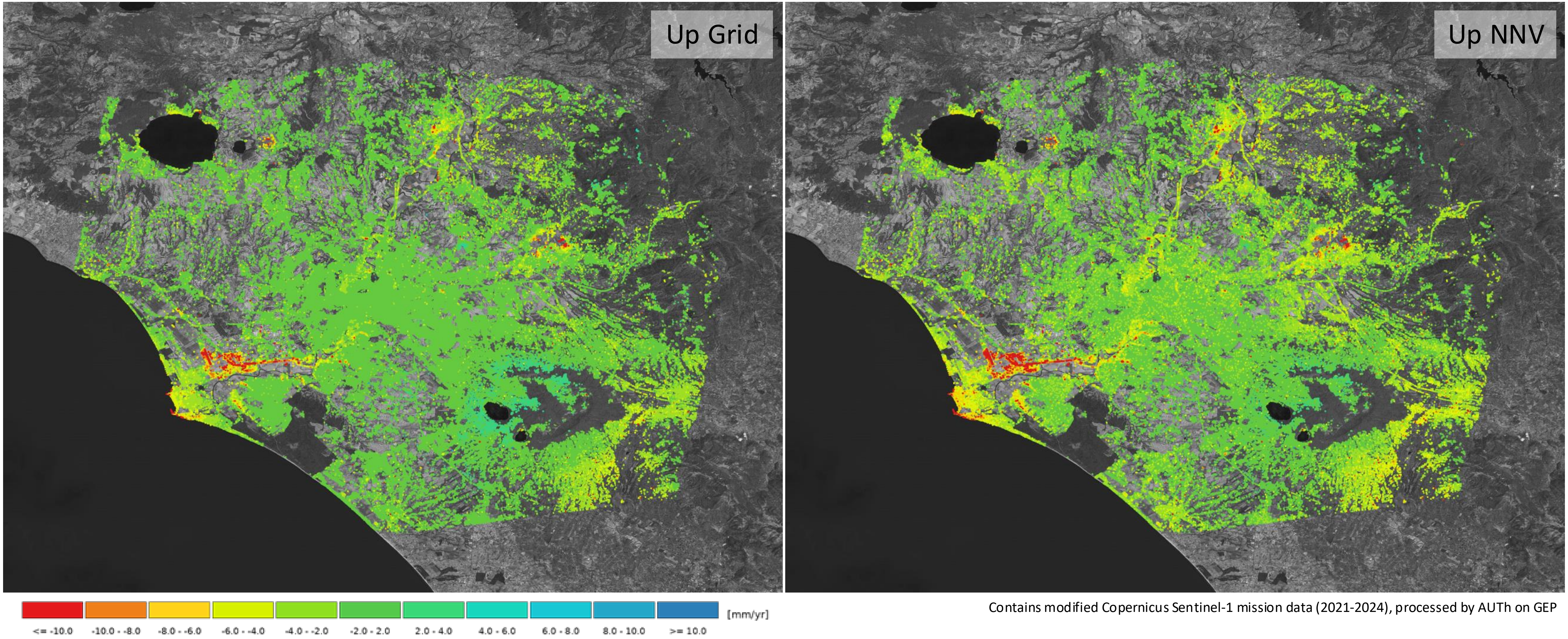
PSI 3D Decomposition | NNV approach

The Nearest Neighbor Vector (NNV) method calculates Up and East–West motion components by matching ascending and descending PS targets in the vector format and decomposing their LoS measurements.



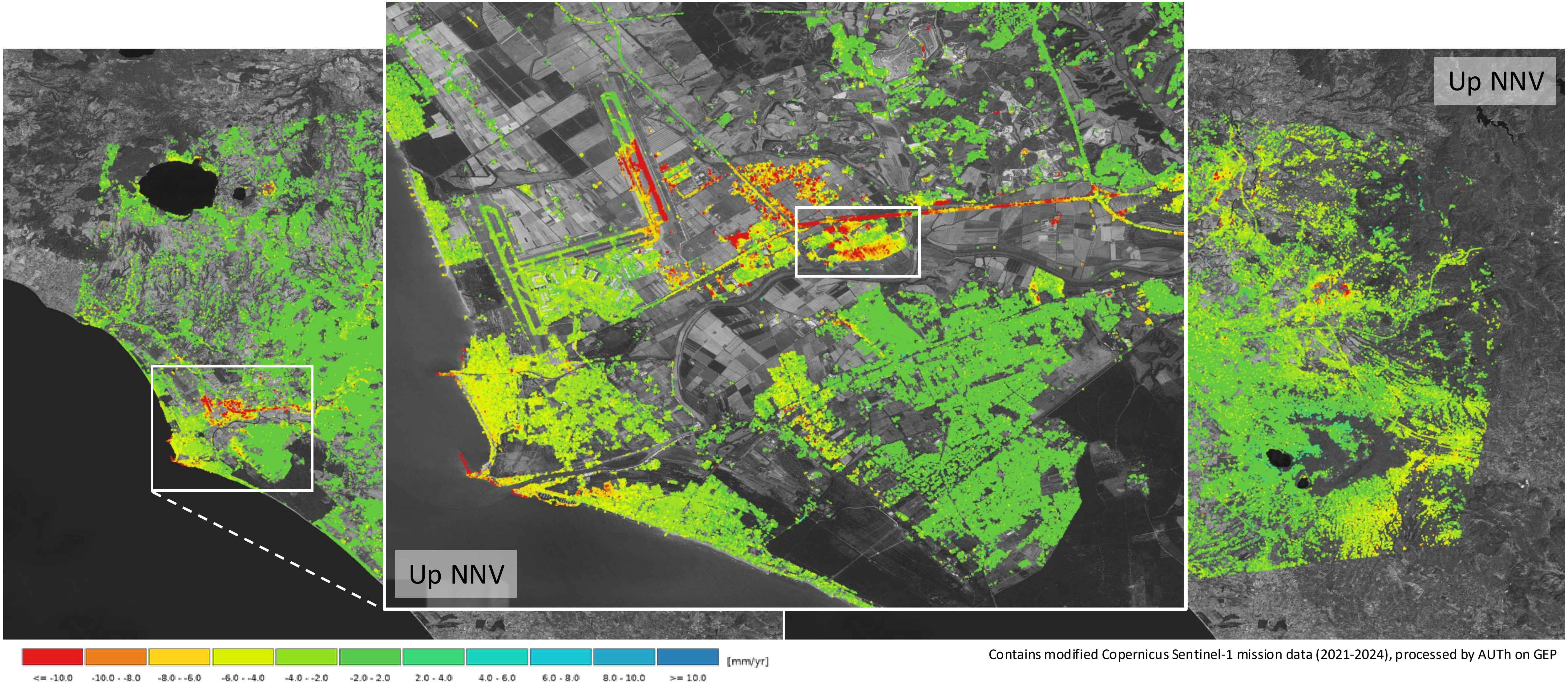
Foumelis, M., 2016. Vector-based approach for combining ascending and descending Persistent Scatterers Interferometric point measurements. *Geocarto International*, doi:10.1080/10106049.2016.1222636.

PSI measurements over Rome | Up & E-W motion components



Contains modified Copernicus Sentinel-1 mission data (2021-2024), processed by AUTh on GEP

PSI measurements over Rome | Up & E-W motion components



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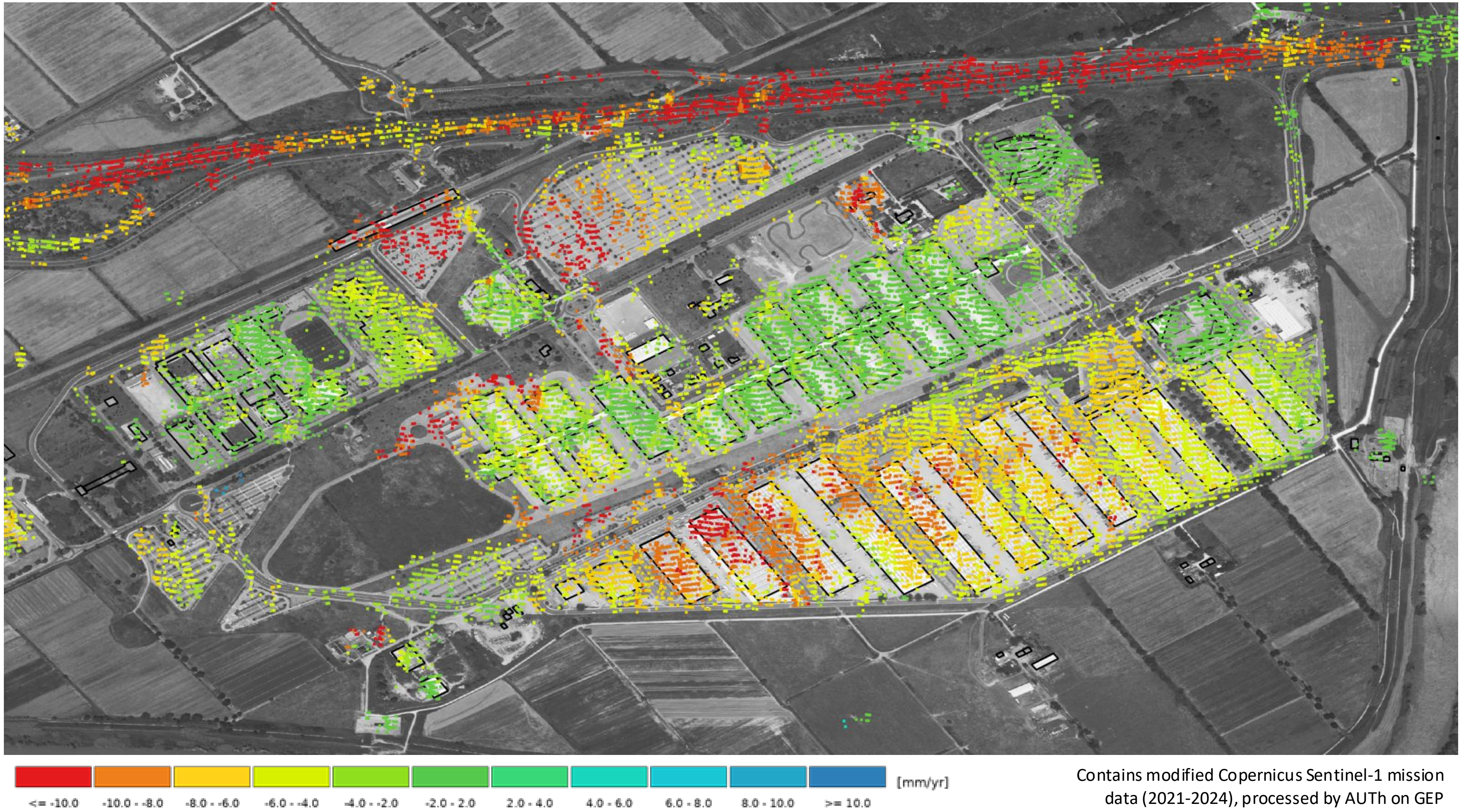
PSI measurements over Rome | Up motion components



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DiMo-Grid

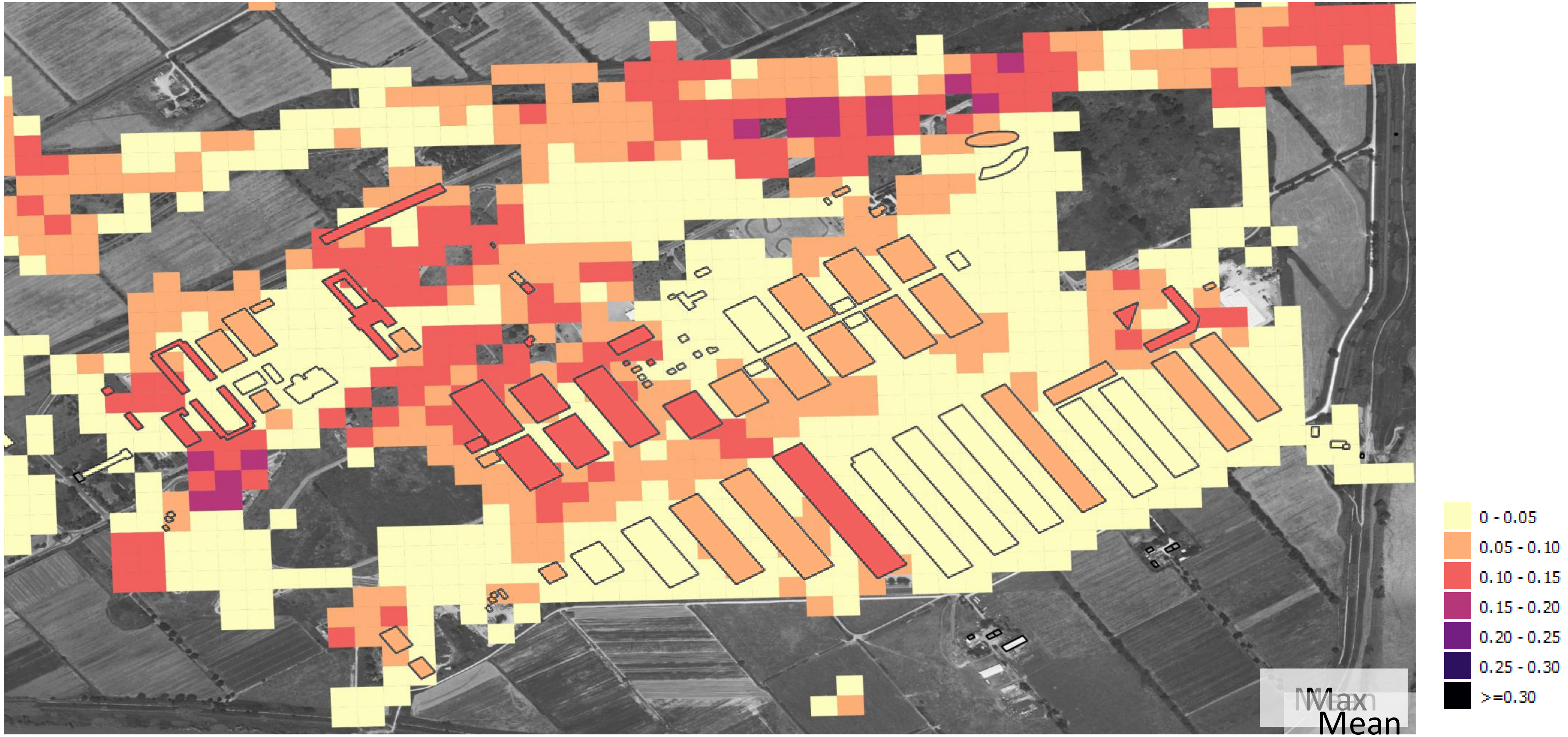
Differential motion across wider Rome is generally low, except for the FCO airport zone.

Elevated DiMo values are mainly confined to localized hotspots, several of which are located along the Tiber River corridor.

[mm/yr/m]

- 0 - 0.05
- 0.05 - 0.10
- 0.10 - 0.15
- 0.15 - 0.20
- 0.20 - 0.25
- 0.25 - 0.30
- >=0.30

DiMo-Grid



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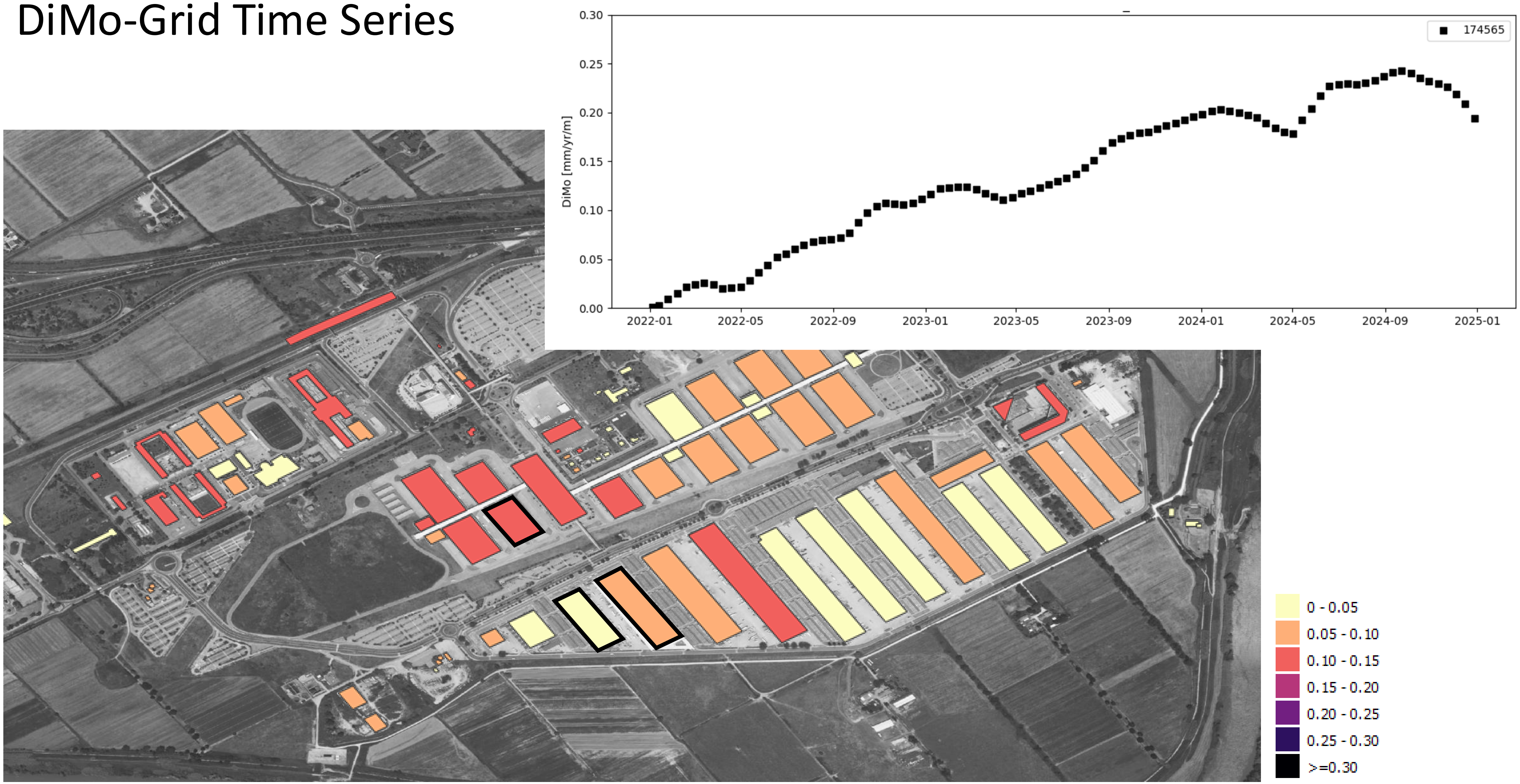
DiMo-Grid Time Series

DiMo-Grid



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DiMo-Tri

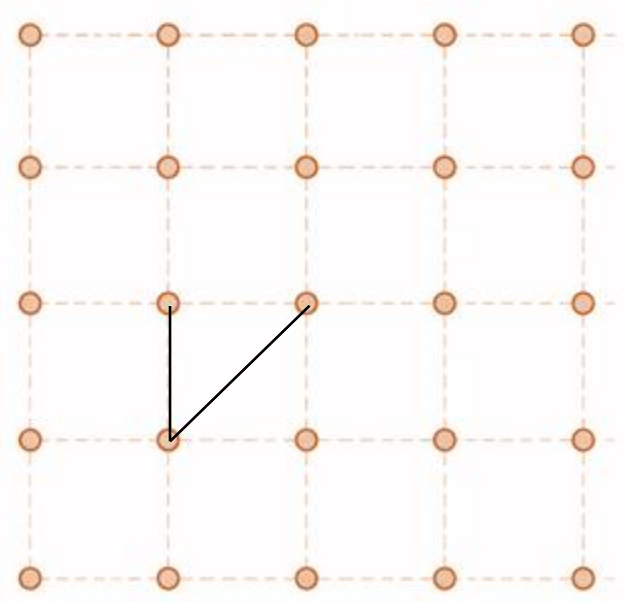
Contains modified Copernicus Sentinel-1 mission data (2021-2024), processed by AUTh on GEP

DiMo-Struct

Contains modified Copernicus Sentinel-1 mission data (2021-2024), processed by AUTh on GEP

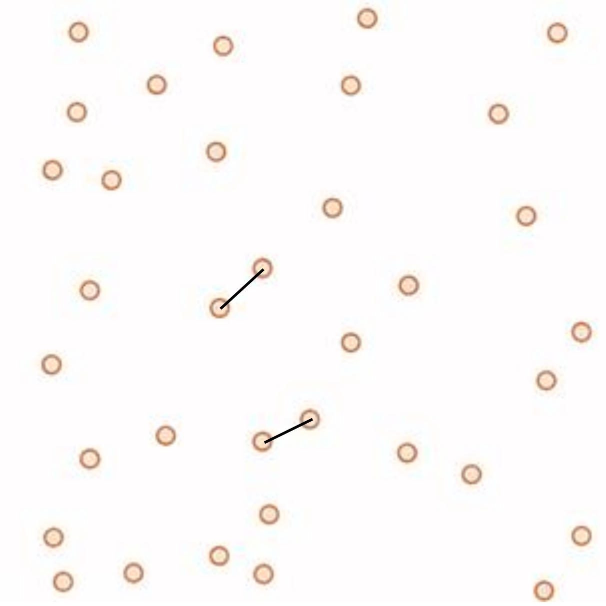
Scale Effect in Measuring DiMo

Regular Grid



Coarser scale → lower DiMo

Irregular Distribution



Finer scale → higher DiMo

DiMo has units of mm/yr/m, so it is inversely proportional to distance.

For same motion rate difference, shorter baselines lead to much higher DiMo values.

$$\mathrm{DiMo} = \frac{\Delta V}{L}$$

ΔV = velocity difference between two neighbors

L = distance (baseline) between the two points

Larger ΔV or smaller L result in higher DiMo values

DiMo is not an absolute property of the deformation field but a **scale-dependent metric**

Always interpret DiMo values with the baseline distance in mind!

Future Directions & Challenges

- Shift from MT-InSAR measurements to higher-level, actionable products.
- Promote harmonized terminology and metrics between remote sensing and engineering communities.
- Better quantify and normalize scale effects to improve comparability.
- Assess the suitability of different approaches for specific monitoring objectives.
- Develop an open-source code and QGIS plugin, including support for European Ground Motion Service (EGMS) products.

Thank you

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