A NOVEL ALGORITHM FOR POINT COHERENCE ESTIMATION IN SAR INTERFEROMETRY

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Introduction

- Synthetic aperture radar (SAR) interferometry (InSAR) is a powerful technology to monitor from satellite motions of the ground surface (typically due to subsidence, landslides, earthquakes, and volcanic phenomena), providing:
  - Millimetric precision and metric or sub-metric (depending on the satellite) spatial detail (making it possible to distinguish different parts of buildings or infrastructures)
  - Coverage of large areas.
- A key step of the InSAR technology is the identification of points (or clusters of points) providing a coherent backscattering over time:
  - Typically corresponding to man-made structures, rocks, or bare soil
  - Can be called persistent scatterers (PSs) regardless of whether the dominant diffusion mechanism is point-like or distributed.
- In this work, we propose a novel algorithm, which we will call Point Coherence Estimation (PCE), to:
  - Evaluate in a clean and simple way (without the need for articulated procedures and critical assumptions or approximations) the interferometric coherence of each single point in an interferometric image stack
  - (The method works with full-resolution points but can be also applied to points with degraded resolution for a multi-look or distributed scatterer processing)
  - Then select the coherent points, or PSs, based on their estimated point coherence (and related noise level).

Point Coherence Estimation (PCE) method for InSAR

- Well-known and accepted assumptions:
  - Large phase artefacts such as atmospheric delays or orbital effects are almost identical in points within tens or hundreds of meters
  - Phase noise (e.g., thermal noise and time, spectral, geometric decorrelation noises) is relatively small w.r.t. a phase cycle
  - Phase noise has statistically independent realizations in different points (possibly excluding adjacent pixels if the images are oversampled)
- Point coherence estimation (PCE) key ideas:
  - Based on the above assumptions, it is possible to derive a (linear) equation linking the relative temporal coherence between any two independent close points (which can be directly calculated because large artifacts cancel out in the phase difference) with the temporal coherences of each of the two single points
  - Considering a set of pairs of independent points within a certain distance, an overdetermined system of linear equations is obtained, whose solution provide a robust estimation of the coherences of each considered single point
- Coherence points or PSs are then identified based on their estimated point coherences (related with their phase noises)

Theoretical formulation (1)

Double (space-time) phase difference

$$\phi_{a,u} = [f_u(\vec{q}_a) + \delta_{a,u}]_{2\pi}, \quad a = (p, p') \in A, \quad u = (t, t') \in U,$$

Paramentric phase model

Phase residuals w.r.t. the model

Arcs connecting close points

Interferometric pairs

Temporal coherence

$$\vec{q}_a = \arg\max_{\vec{q'}_a} \left| \sum_{u \in U} w_{a,u} e^{j(\phi_{a,u} - f_u(\vec{q'}_a))} \right|$$

In the simplest case:

$$f = \frac{4\pi}{\lambda}(v_a(t - t') + h_a\, b_u / (r \sin\theta))$$

Phase noise

$$\delta_{a,u} = \epsilon_{p,u} - \epsilon_{p',u}$$

For arcs connecting close points spatially correlated artefacts cancel out and the phase residuals w.r.t. the model depend only on phase (thermal, decorrelation) noise differences

Theoretical formulation (2)

$$\gamma_{\mathrm{N}}(\delta_a)=\sum_{u\in U} w_{a,u} e^{j\delta_{a,u}}, \qquad a=(p,p')\in A, \qquad u=(t,t')\in U.$$

$$\Big\downarrow \lim_{N\to\infty}$$

Independent noise realizations

$$\gamma(\delta_a) = E_{\delta_a}\left(e^{j\delta_a}\right) = E_{\epsilon_p,\epsilon_{p'}}\left(e^{j\epsilon_p} e^{-j\epsilon_{p'}}\right) = E_{\epsilon_p}\left(e^{j\epsilon_p}\right)E_{\epsilon_{p'}}\left(e^{j\epsilon_{p'}}\right)^* = \gamma(\epsilon_p)\gamma(\epsilon_{p'})^*$$

$$\Big\downarrow$$

A somewhat more precise formula can be obtained for the case of finite N

$$|\gamma(\delta_a)|^2 = \left|\gamma\left(\epsilon_{p'}\right)\right|^2 \left|\gamma\left(\epsilon_p\right)\right|^2$$

The temporal coherence between a pair of independent close points is the product of the temporal coherences of the two single points

Theoretical formulation (3)

Both good points (PS ●) and bad points (noisy ●) in the equations

$$|\gamma(\epsilon_{p'})|^2 |\gamma(\epsilon_p)|^2 = |\gamma(\delta_a)|^2$$

Always valid **regardless** of the phase noise distribution probability

$$\Gamma(\epsilon_p) = \log|\gamma(\epsilon_p)|^2$$

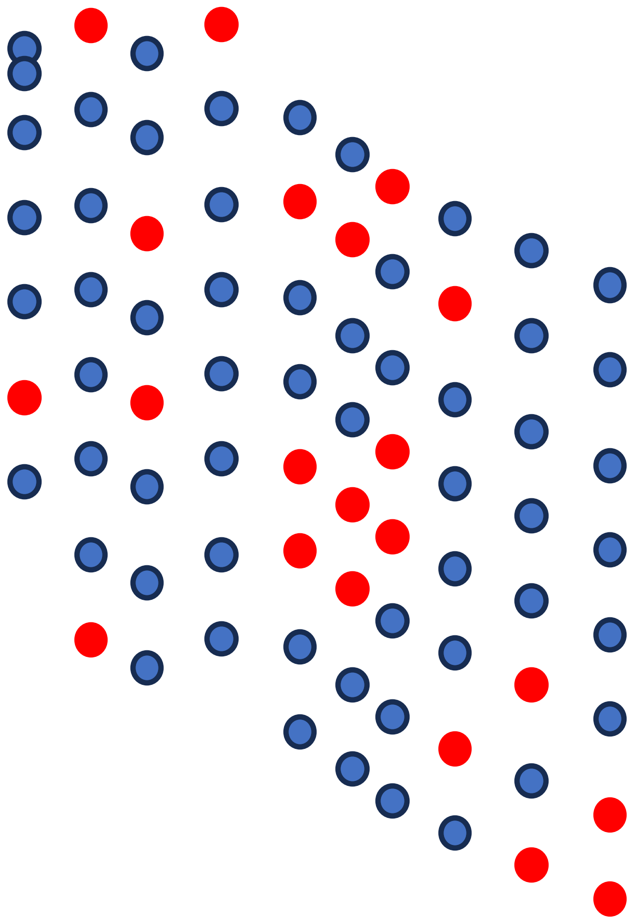
$$\Gamma(\epsilon_p) + \Gamma(\epsilon_{p'}) = \Gamma(\delta_a)$$

Overdetermined linear equation system -> reliable and efficient solution by L1 or L2 norm solvers

If ϵ_p has Gaussian distribution: $|\gamma(\epsilon_p)|^2 = e^{-\sigma^2(\epsilon_p)}$

$$\sigma^2(\epsilon_p) + \sigma^2(\epsilon_{p'}) = \sigma^2(\delta_a)$$

Very well-known relation for combination of **independent** noise realizations



Tests on real datasets

Dataset 1

Sensor: Sentinel-1

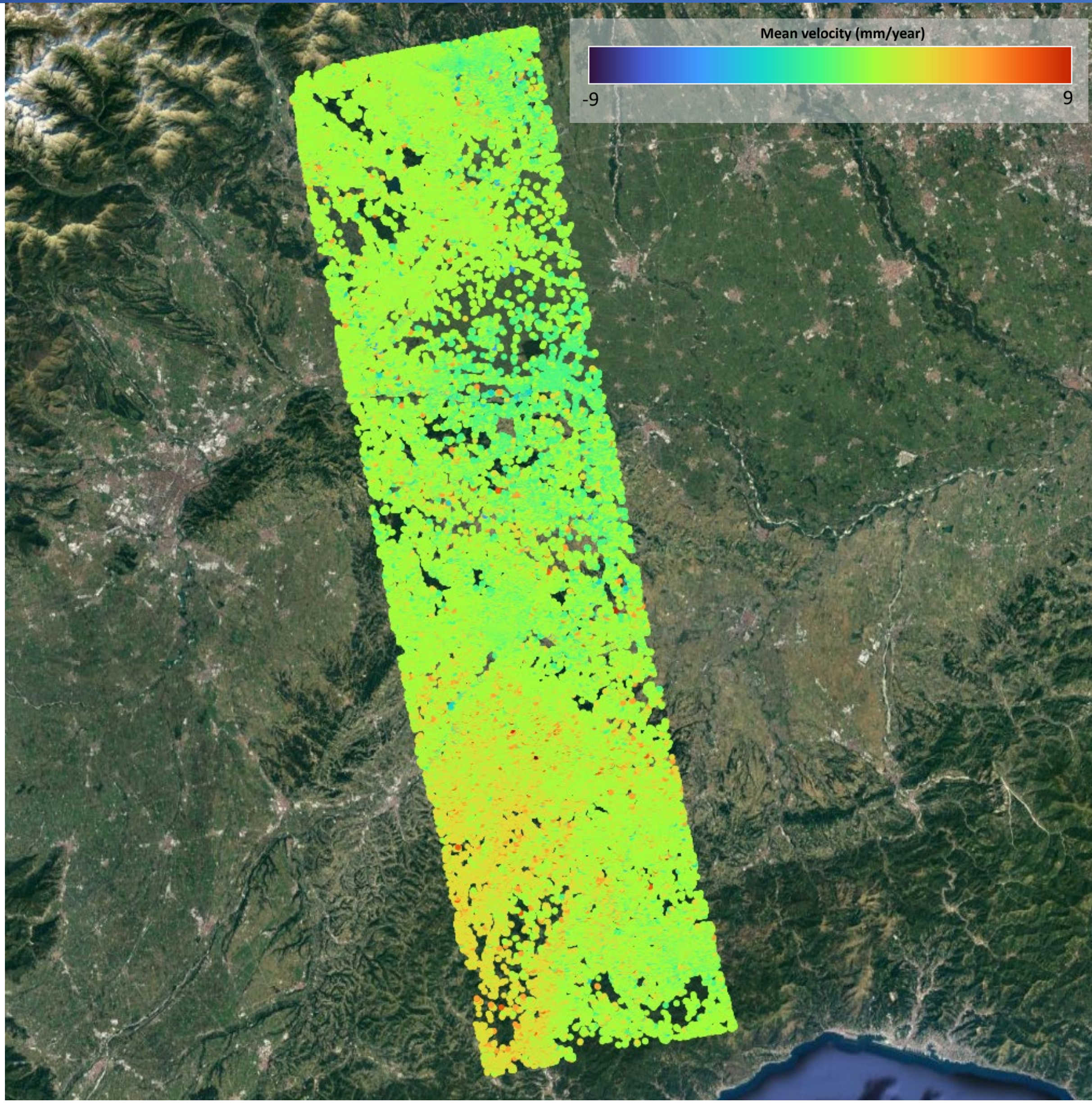
Number of images: 86

Track: 015

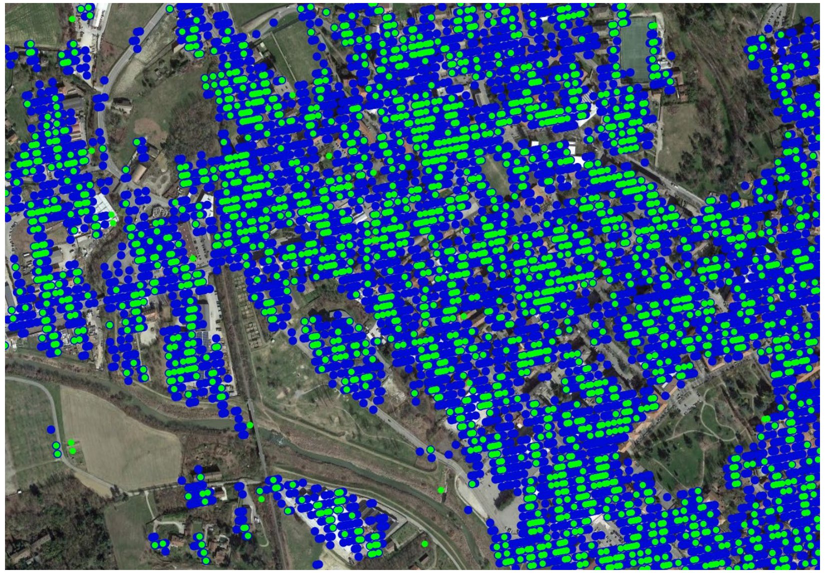
Period: January 2020 – October 2022

Area: Piemonte, Italy

Land use: urban areas, rural areas, bare soil, mountains



Point Coherent Estimation vs standard selection methods



Blue dots and green dots circled by blue: PSs identified with the proposed PCE method

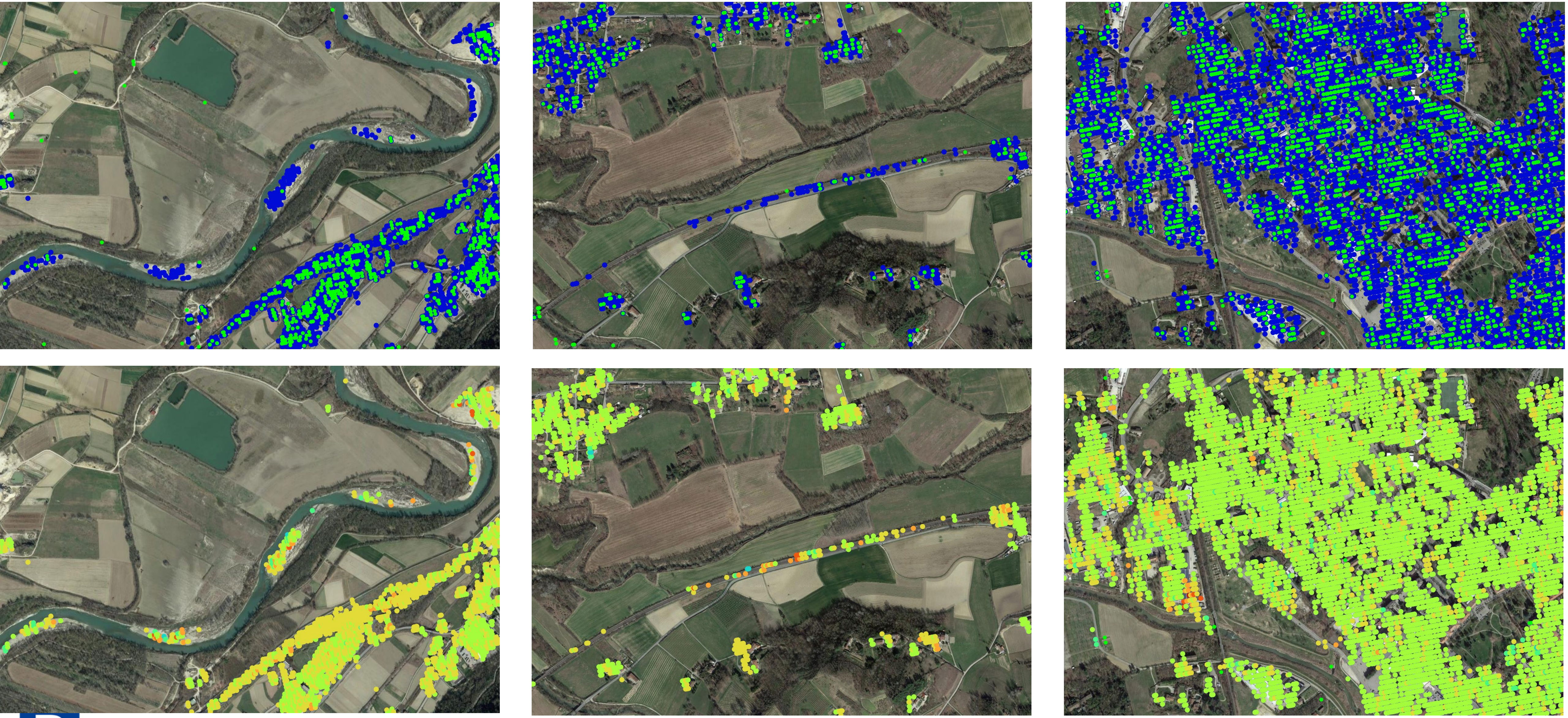
Green dots without blue circle: PSs selected by the joint use (logical OR) of the signal-to-clutter ratio (SCR) and the amplitude dispersion (AD) methods

The thresholds for PS identification were chosen in order to have about the same false detection rates for the three methods.

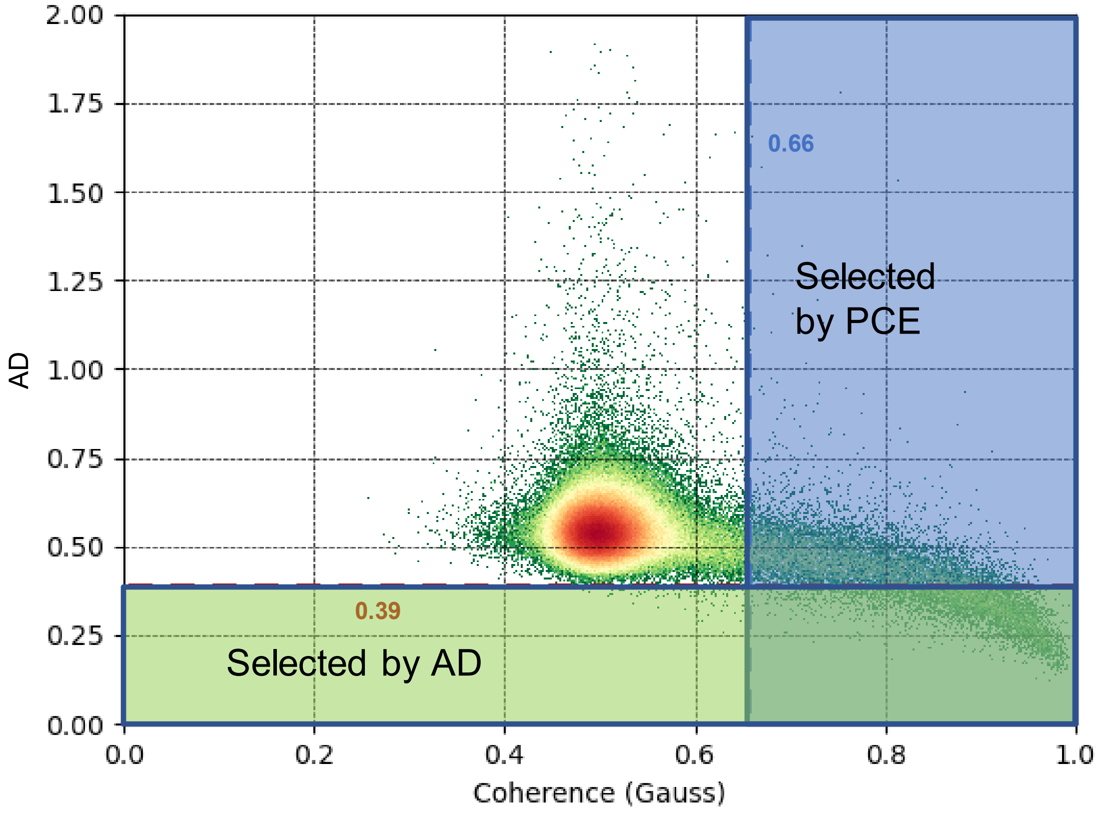
Three areas with different types of ground cover, recognizable from the background very-high-resolution optical image.

The proposed algorithm largely outperforms the classical, although basic, SCR and AD methods, both in density and coverage of the identified PSs.

Point Coherent Estimation vs standard selection methods



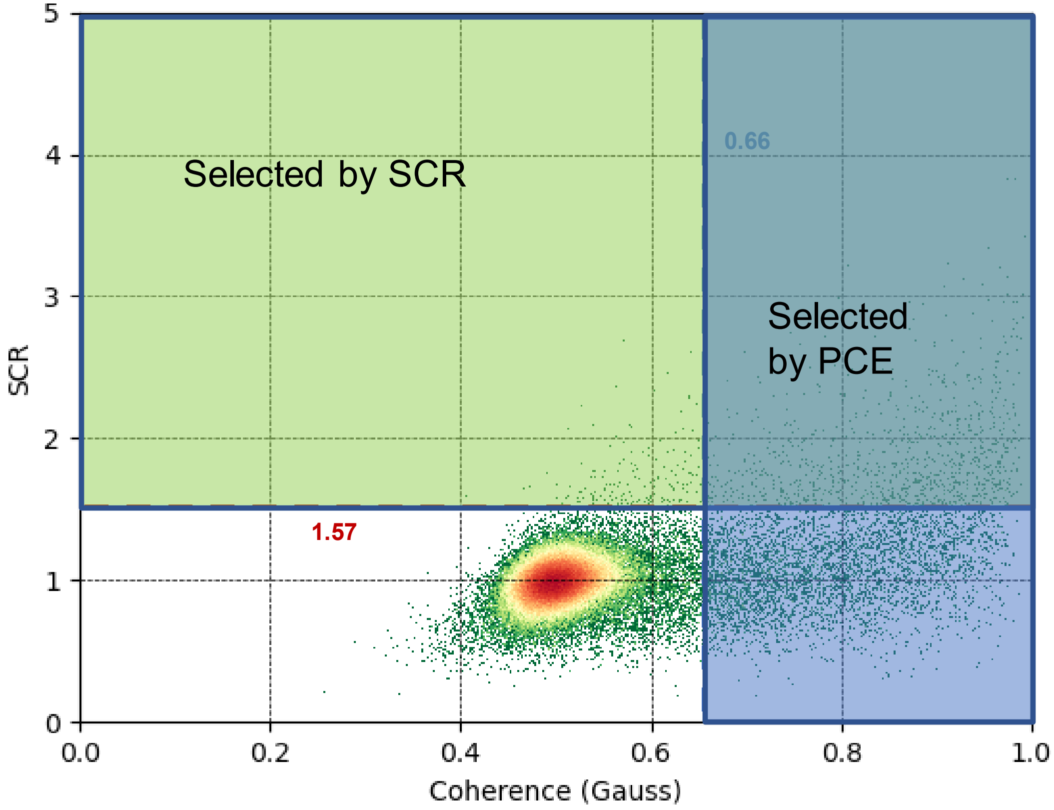
PCE vs amplitude dispersion (AD) method



2-D histogram
(based on all processed pixels)
of the AD vs the point temporal
coherence estimated by PCE.

Colors, from green to red,
indicate histogram frequency

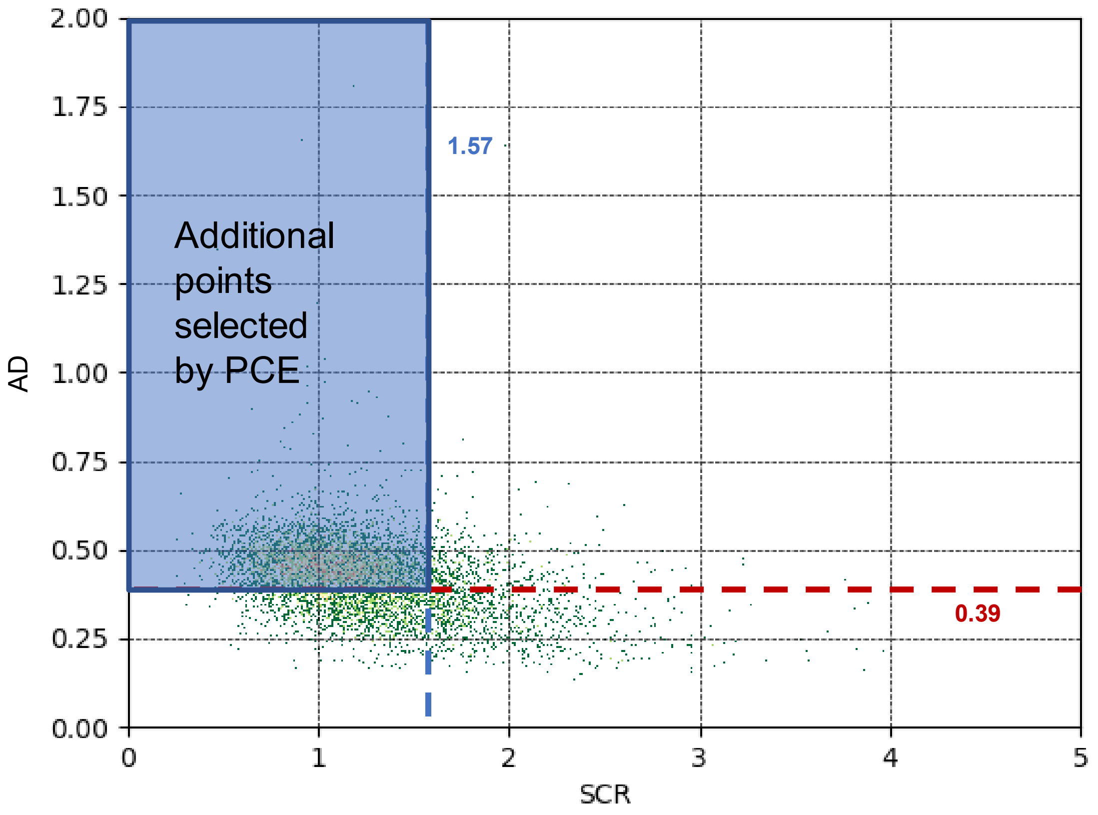
PCE vs Signal to clutter ratio (SCR) method



2-D histogram
(based on all processed pixels)
of the SCR vs the point
temporal coherence estimated
by PCE.

Colors, from green to red,
indicate histogram frequency

Selected points 2D histogram



2-D histogram
(based on the points selected by PCE)
of SCR and AD.

Colors, from green to red, indicate histogram frequency

Dataset 2

Sensor: Sentinel-1

Number of images: 120

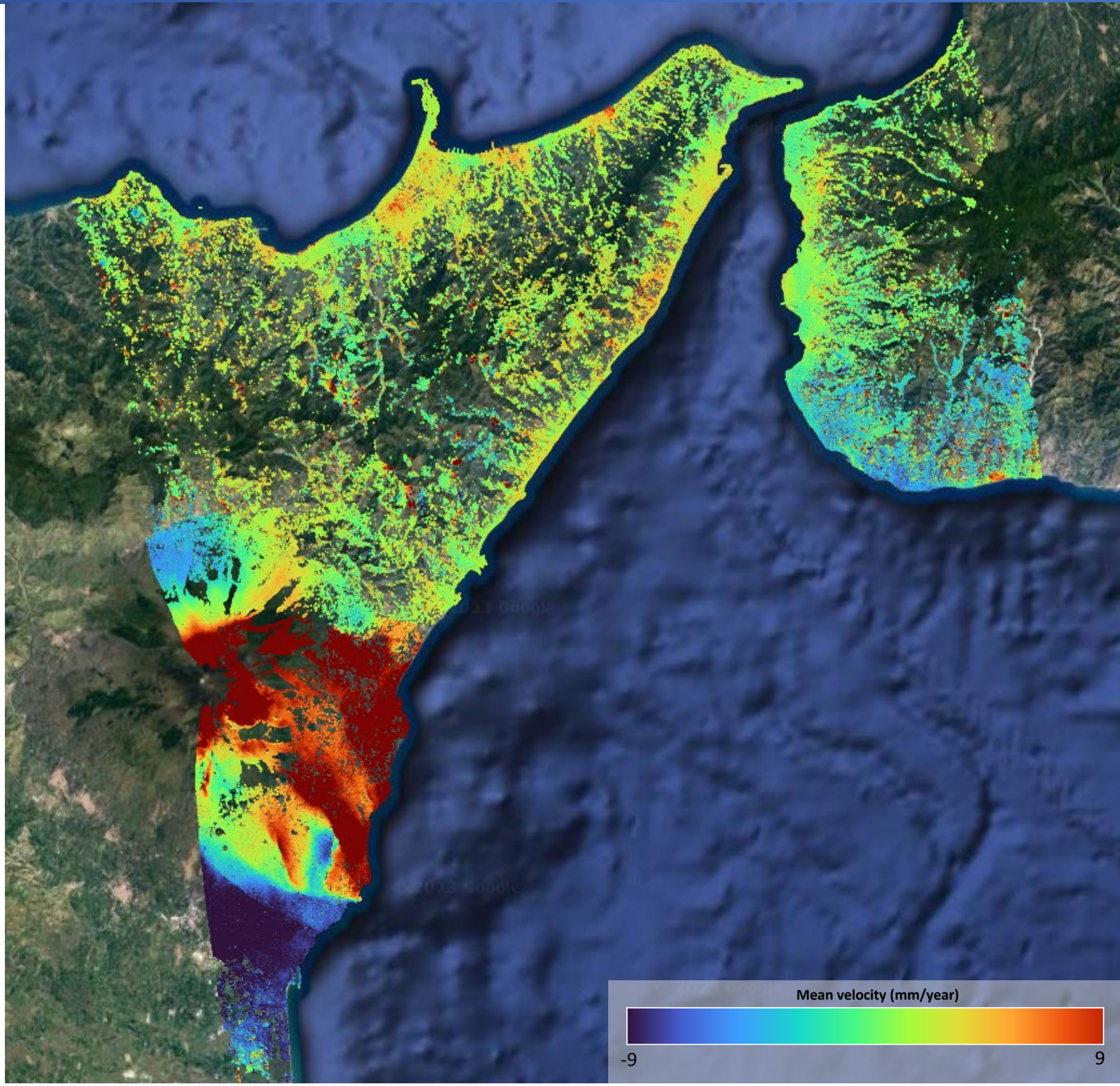
Track: 044

Period: January 2020 – December 2022

Area: Sicily and Calabria

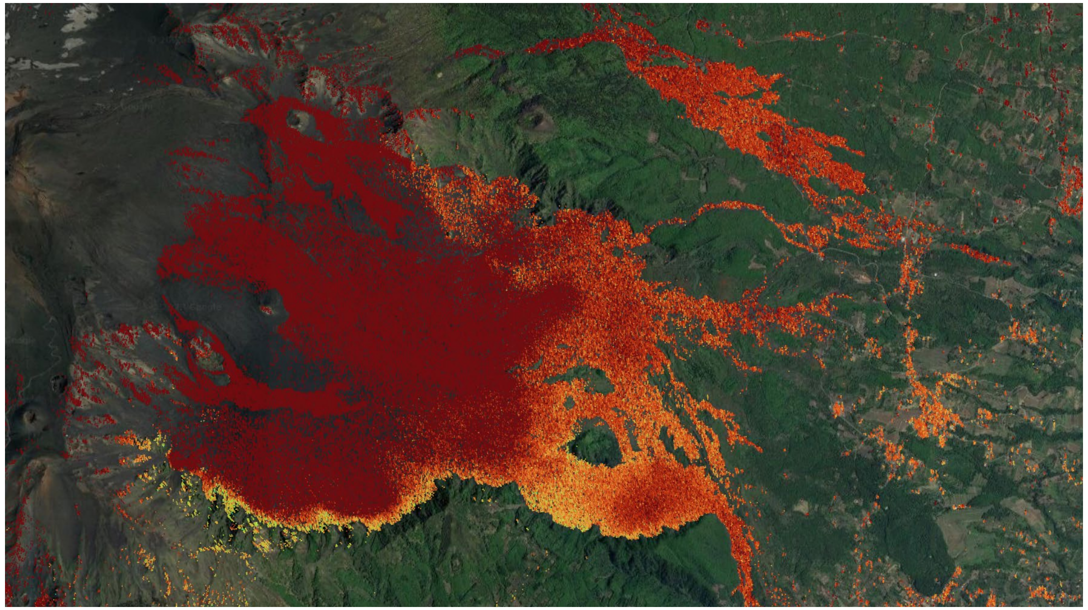
Critical areas: several fault lines around Etna volcano

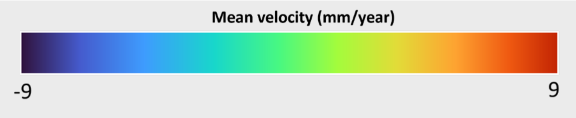
Land use: urban areas, rural areas, bare soil, vegetation

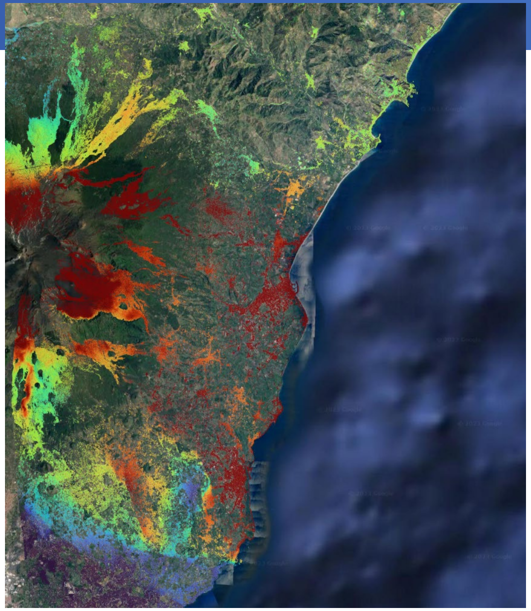


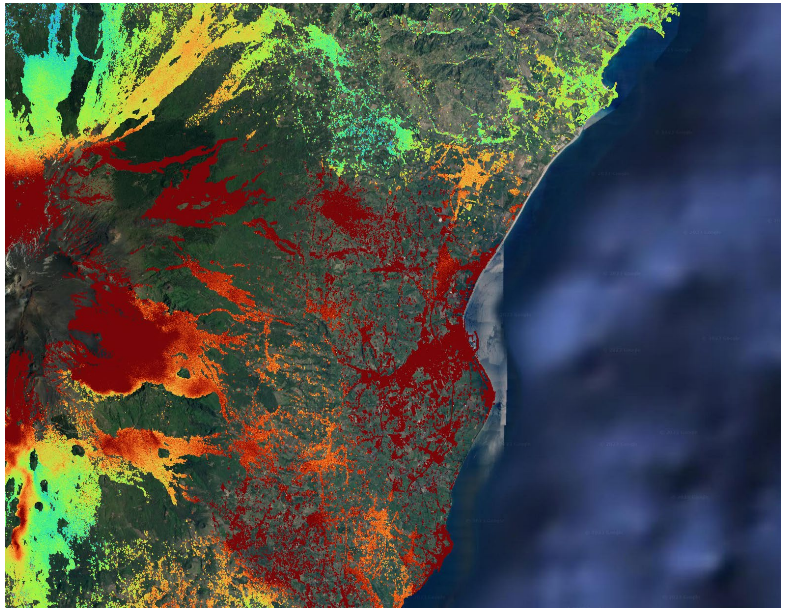
Etna Volcano

Mean velocities Jan. 2020 – Dec. 2022



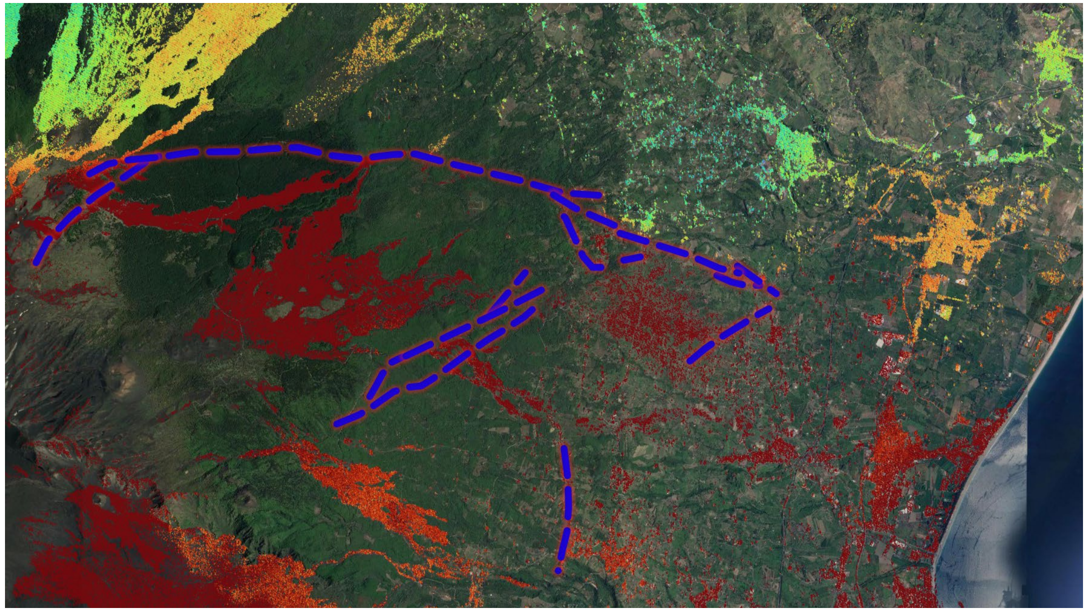


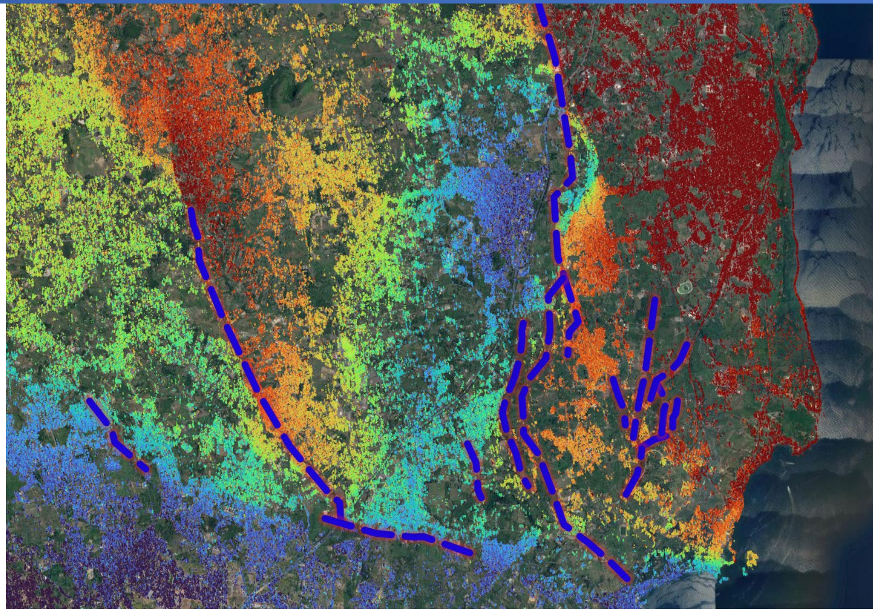


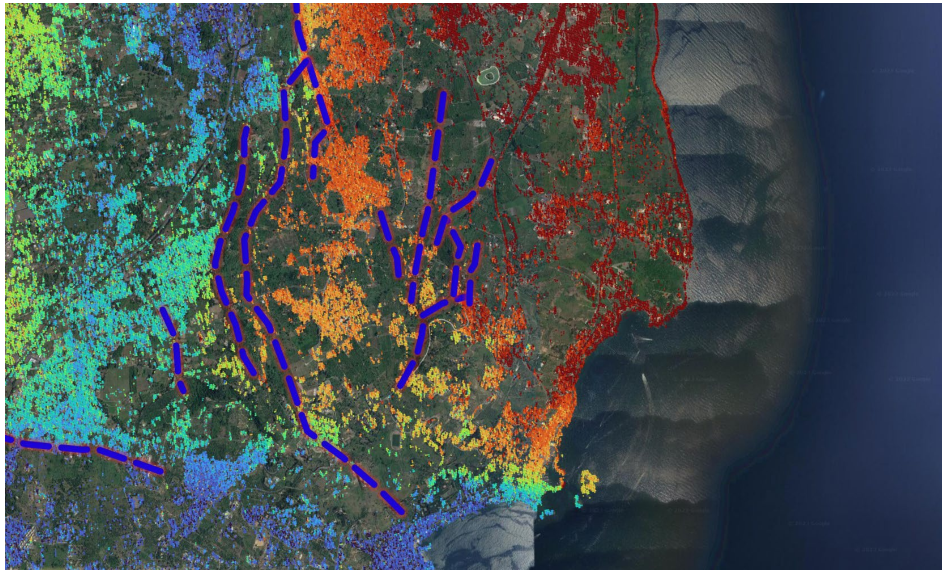


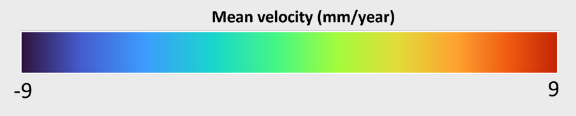
Fault lines

Mean velocities Jan. 2020 – Dec. 2022







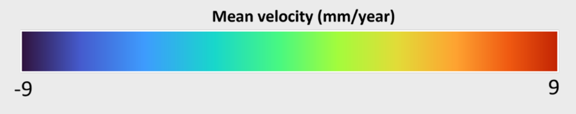


Other areas including urban, coasts, …

Mean velocities Jan. 2020 – Dec. 2022

Taormina

Messina - Reggio Calabria



Conclusions

- We presented a method for Point Coherence Estimation (PCE) in InSAR:
  - Theoretically very simple and clean, without critical assumption or articulated processing
  - Reliable and accurate
  - Computationally fast
- The PCE technique bases on:
  - Linking with a (linear) equation the relative temporal coherence between two independent close points (which can be directly calculated because large artifacts cancel out in the phase difference) with the temporal coherences of each of the two single points
  - Solving an overdetermined system of these equations corresponding to a set of pairs of independent points within a certain distance, to obtain a robust estimation of the coherences of each considered single point
- The PCE method provides:
  - Very dense set of measurements
  - Good coverage (also in areas characterized by weak distributed scattering)
  - Coherent points or PSs are selected based on their estimated coherence or noise level
  - (The method works with full-resolution points but can be also applied to points with degraded resolution for a multi-look or distributed scatterer processing)
- The PCE method (patented) is part (together with other innovative solutions) of a novel InSAR processing chain we at B-Open have developed (currently in Beta version) and that will be made available as SW as a service

Thank you

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