CRUSTAL DEFORMATION MONITORING

ESA NoR ID 67274

Carolina Pagli
Department of Earth Sciences, University of Pisa

1. INTRODUCTION

InSAR has been successfully applied to measure a variety of processes that pose significant hazards to our society, such as fluid-induced deformation in urban areas and at active volcanoes. Yet in Italy pathways for PhD students to gain hand-on skills in SAR data processing and InSAR time-series analyses are limited, mainly due to lack of the required processing infrastructure in many Earth Science departments.

My overall aim is to foster new advances in science and help the new generations InSAR analysts to gain processing skills and experience in monitoring our hazardous planet. I studied physical processes associated with fluid extraction in urban areas, and hydrothermal fluids and magma motions in active volcanoes.

A first paper lead by my PhD student, Diana Orlandi, was recently published (Orlandi et al., 2022). The paper combines InSAR and AI to study the subsidence of cities in Northern Italy due to sub-surface fluid extractions. A second paper lead by my PhD student, Birhan Abera Kebede, and my post-doc, Alessandro La Rosa, is currently under preparation and it focuses on understanding whether the InSAR measured deformation in the Tullu Moye volcanic complex is caused by magma and/or hydrothermal fluids.

2. INSAR AND AI TO STUDY THE IMPACT OF FLUID EXTRACTION IN SINKING CITIES

Subsidence in urban areas can have a significant and irreversible impact on ecosystems and the infrastructures (i.e. Cigna and Tapete, 2021).

Monitoring of subsidence with InSAR is well established given that the majority of the surface motion occurs in the vertical component which is the best-resolved by InSAR (i.e. Béjar-Pizarro et al., 2016). Nevertheless, even with the most recent Sentinel1a/b missions, one of the main limitations is the signal loss of coherence, largely due to changes in the surface conditions between the acquisitions.

A novel approach was used to overcome incoherence and enhance the spatial density of InSAR-derived surface displacement time-series (Orlandi et al., 2022). The approach is based on a deep learning model known as Transformers (Vaswani et al., 2017), which compared to conventional deep learning models for sequential data, process sequential input according to a self-attention mechanism, i.e., a weighting of the significance of an input of the sequence. As a result, parallelization during training is facilitated and made efficient for large dataset.

Sentinel-1a/b SAR data from Ascending path 117 and Descending path 168 during 2017-2021 were processed to produce 592 and 740 interferograms for the Ascending and Descending path, respectively (Table 1). The interferogram processing and subsequent time-series analysis was performed on the ESA's Geohazards Exploitation Platform (GEP), using the P-SBAS (Parallel Small BAseline Subset) Interferometry module (Casu et al., 2014; De Luca et al., 2015). The threshold of the coherence was set to 0.75, VV (Vertical, Vertical) mode for the polarization was chosen and a Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission at 1 arcsec spatial resolution (30 m/pixel) was used.

Region	*Period of time*	*Geometry*	*Path*
Emilia-Romagna	04/2017-11/2021	Ascending	117
Emilia-Romagna	06/2017-12/2021	Descending	168
Tuscany	04/2017-06/2021	Ascending	117
Tuscany	06/2017-12/2021	Descending	168

Table 1. Sentinel1a/b SAR data used in the study.

InSAR velocity maps are shown in figure 1 and 2. The maps show deformation in some of the main cities in Northern Italy, such as Bologna, Modena, Reggio-Emilia and Pistoia. In both tracks the main deformation patterns are sub-circular range increases (ground motion away from the satellite in the Line Of Sight (LOS)) consistent with subsidence. Generally, the level of coherence is good in urban areas but at some locations, like the city of Carpi, significant loss of coherence still occur (Fig. 3).

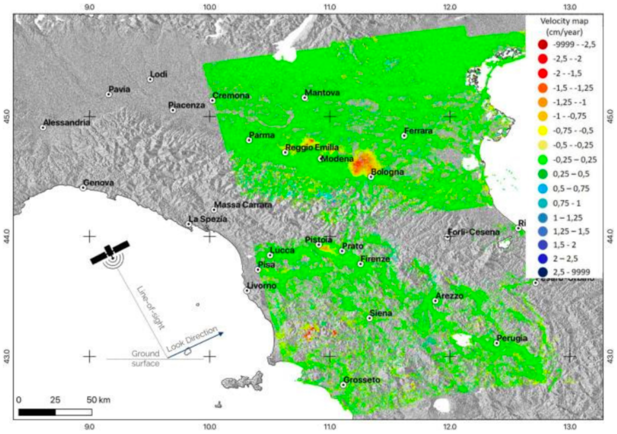


Figure 1. Average velocity map derived from Sentinel1a/b data in Ascending path 117 during 04/2017-11/2021.

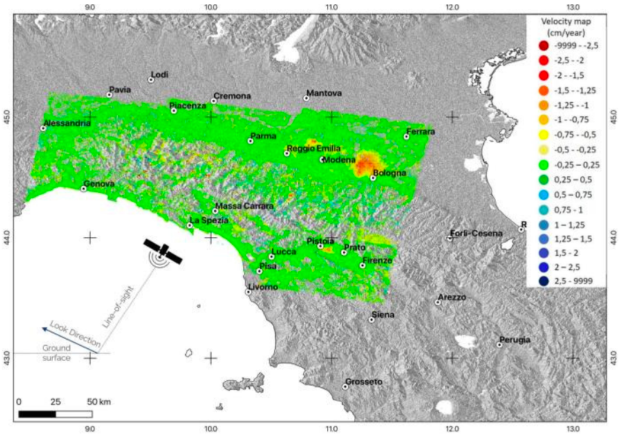
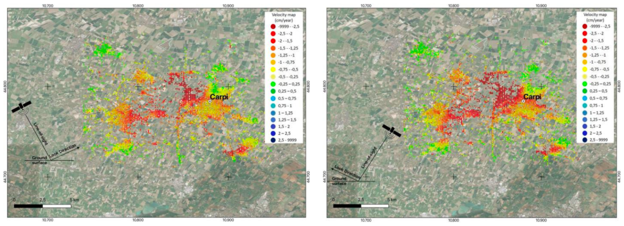


Figure 2. Average velocity map derived from Sentinel1a/b data in Descending path 168 during 06/2017-12/2021.

We used Transformers to predict the velocity in the missing incoherent areas (Orlandi et al., 2022). In particular, in Fig. 3 the example of the subsidence of the city of Carpi is shown (Emilia Romagna region). Here the coherence of the velocity maps is relatively low in both Ascending (a) and Descending (b) paths. Our results show that using our approach it is possible to predict velocity at the missing data points, in incoherent areas, leading to detecting the full extent of the subsidence field (Fig. 4).



(a) (b)

Figure 3. Average velocity map derived from Sentinel1a/b for the city of Carpi in Ascending (a) and Descending (b)

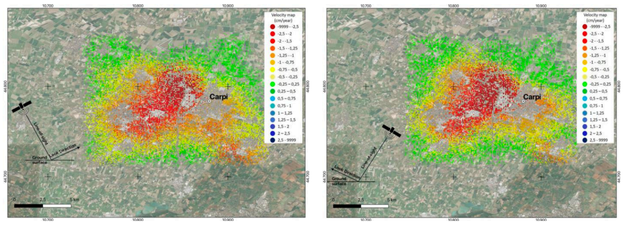


Figure 4. Additional data predicted by Transformers in the incoherent areas.

3. INSAR OF GEOTHERMAL SYSTEMS IN THE EAST AFRICAN RIFT

In this work InSAR was applied to studying the Tulu Moye volcanic complex in the East African Rift System (EARS) of Ethiopia to identify the locus, intensity, and style of deformation, to constraint the magmatic plumbing system and ultimately to understand the causes of deformation, whether magmatic and/or hydrothermal.

The East African rift system (EARS) is a divergent continental rift system that extends from Afar in the north to Mozambique in the south (Fig. 5a). It consists of a several sectors with contrasting magma poor and magma rich rifting. The northern EARS is magma rich and displays a series of volcanic centres that have potential for geothermal energy.

Tulu Moye is located in the central the Ethiopian sector of the rift (Fig. 5b). It is volcano-tectonically active with intense geothermal indications. The area is covered by Pliocene-Holocene volcanic products.

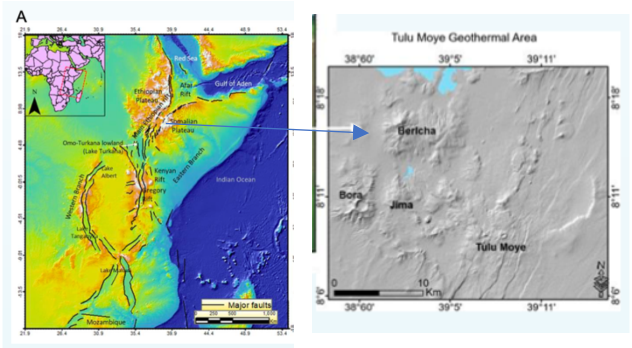


Figure 5. Map of the East African rift System (A) and the Ethiopian rift system (B). C) Location map of Tulu Moye geothermal area.

Two SAR paths from ESA's Sentinel 1a/b satellite during 2014-2017 were used to form interferograms of Tullu Moye in both ascending and descending geometry. The interferogram processing and subsequent time-series analysis was performed on the ESA's Geohazards Exploitation Platform (GEP), using the P-SBAS (Parallel Small BAseline Subset) Interferometry module (Casu et al., 2014; De Luca et al., 2015) to derive velocity maps of Tulu Moye in the satellite Line of Sight (LOS) (Fig 6).

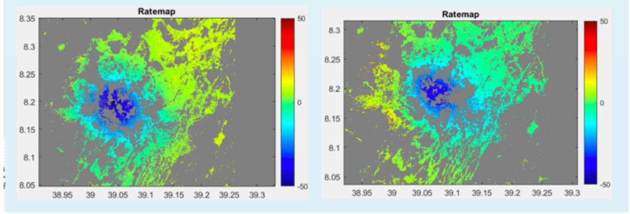


Figure 6. InSAR velocity maps (mm/yr) of ascending path 087 (left hand side) and descending path 079 (the right hand side).

Both ascending and descending rate maps show a concentric, elongated pattern of LOS decrease, consistent with uplift over a 7 km by 10 km region to the west of mt. Tulu Moye, that reaches up to 5 cm/yr. The shape of deformation is elongate NNW-SSE.

To explain the InSAR observations we jointly inverted the ascending and descending velocity maps assuming a horizontal tensile dislocation (Okada sill model) in a conventional elastic half-space. We invert the velocity maps for the best-fit source parameters of the tensile dislocation, using a Monte Carlo simulated annealing followed by a derivative based method, after quad-tree partitioning of the rate maps to reduce the data size (Fig. 7). The best-fit model is at depth 7.45 km, Length 8.80 km, width 1.01 km, Strike -51.8, Opening 894.2 mm/yr, Vol. change 7.94 X10-3 km3/yr.

The parameters of the best-fit model correspond to an opening sill-shaped source striking orthogonal to the rift axis. The source is positioned directly below the seismicity (Greenfield et al., 2019) and at the top of high conductivity anomaly (Samrock et al., 2018). We favor a magmatic source as an interpretation but pressurization from fluids and gas remain possible.

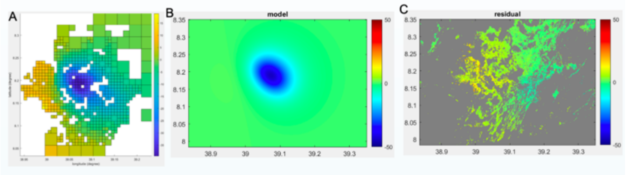


Figure 7. A) Quad-tree partitioning of the descending track, B) predicted model and C) residual assuming Okada tensile dislocation.

The results of this work have been presented to the Summer School on *Geothermal and Magmatic Systems* in Krafla (Iceland, June 2022), organized by the European Training Network IMPROVE and Nordvulk (Nordic Volcanological Centre, University of Iceland).

4. CONCLUSIONS

We used InSAR to study crustal deformation in different hazardous contexts, from fluid-induced urban subsidence to uplift caused by magmatic and hydrothermal sources.

The young researchers, PhD students and post-doc, involved in the InSAR processing and modeling had the opportunity to quickly process data from their areas of interest and to produce results that can be published in international journals and presented at international conferences. One paper was recently published (Orlandi et al., 2022) and a second one on Tulu Moye is in its final stages.

6. REFERENCES

Béjar-Pizarro, M., Guardiola-Albert, C., García-Cárdenas, R.P., Herrera, G., Barra, A., López Molina, A., Tessitore. , S., Staller, A., Ortega-Becerril, J.A., García-García, R.P. Interpolation of GPS and Geological Data Using InSAR Deformation Maps: Method and Application to Land Subsidence in the Alto Guadalentín Aquifer (SE Spain). Remote Sensing. 8(11):965, 2016.

Casu, F., Elefante, E., Imperatore, P., Zinno, I., Manunta, M., De Luca, C., Lanari, R. SBAS-DInSAR Parallel Processing for Deformation Time Series Computation, IEEE JSTARS, 7, pp. 3285-3296, 2014.

De Luca, C., Cuccu, R., Elefante, S., Zinno, I., Manunta, M., Casola, V., Rivolta, G., Lanari, R., Casu, F. An On-Demand Web Tool for the Unsupervised Retrieval of Earth's Surface Deformation from SAR Data: The P-SBAS Service within the ESA G-POD Environment, Remote Sens. 2015, 7(11), 15630-15650, 2015.

Greenfield, T., Keir, D., Kendall, J.-M., & Ayele, A.. Seismicity of the Bora-Tullu Moye volcanic field, 2016–2017. Geochemistry, Geophysics, Geosystems, 20, 548–570, 2019.

Orlandi, D., Galatolo, F.A., Cimino, M.G.C.A., La Rosa A., Pagli, C., Perilli, N. Enhancing land subsidence awareness via InSAR data and Deep Transformers, Proceedings - 2022 IEEE International Conference on Cognitive and Computational Aspects of Situation Management, CogSIMA 2022, pp. 98–103, 2022.

Samrock, F., Grayver, A. V., Eysteinsson, H., & Saar, M. O. Magnetotelluric image of transcrustal magmatic system beneath the Tulu Moye geothermal prospect in the Ethiopian Rift. Geophysical Research Letters, 45, 12847–12855, 2018.

Cigna, F., and Tapete, D. Present-day land subsidence rates, surface faulting hazard and risk in Mexico City with 2014–2020 Sentinel-1 IW InSAR, Remote Sensing of Environment, 253, 112161, 2021.

Vaswani, A., Shazeer, N. et al. Attention is all you need. NIPS - Advances in neural information processing systems, 30, 2017.