

# Deep Learning for Measuring Surface Deformations Using Radar Interferometry (InSAR) - Application to the Monitoring of Gravitational Instabilities in High Mountains

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### Collaborations

- EDYTEM, Morphodynamics team: Xavier Bodin, Florence Magnin, Ludovic Ravanel
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## 3. PhD Title

Deep Learning for Measuring Surface Deformations Using Radar Interferometry (InSAR) - Application to the Monitoring of Gravitational Instabilities in High Mountains

## 4. Abstract

The aim of this thesis is to exploit the potential of satellite synthetic aperture radar interferometry (InSAR) and deep learning methods to detect, measure and monitor slow gravitational movements in high mountains. Every six days, Sentinel-1 satellites acquire complex radar images whose phase difference can be used to measure ground surface movements with centimeter or even millimeter precision by exploiting time series of interferograms. The volume of data generated and the artefacts affecting these images necessitate the development of automated methods to extract fringe patterns indicative of ground movement and convert them into velocity measurements characterizing the dynamics of the observed phenomenon. Deep learning methods dedicated to natural, medical or remote sensing images (optical, radar amplitude) are hampered by the specificity of InSAR data (wrapped phase, loss of coherence, atmospheric fringes, etc.) and the lack of labelled data to train the models. To address these challenges, previous work established a database using Sentinel-1 interferograms on the French Alps, which enabled the testing of convolutional neural networks (CNNs). This thesis will extend and generalize this work with the following objectives: i/ taking time series of interferograms into account by constructing models that are capable of analyzing information from coherence matrices; ii/ focusing on ‘transformer’ type models to take spatial relationships within interferograms into account and to integrate topographical information from digital terrain models; iii/ developing networks that perform both semantic segmentation to detect the moving area and regression to estimate the speed of that area. The models developed will be tested on known gravitational movements monitored by researchers from the EDYTEM and ISTerre laboratories, in particular the inventory of rock glaciers, which will be enriched by the velocity measurements obtained from this work.

## 5. Context and Objectives

The use of satellite radar imagery has become widespread through the European Copernicus program, which provides free, regular images thanks to systematic acquisitions by the Sentinel-1A and 1B satellites, launched in 2014 and 2015 and replaced in 2024 and 2025 (Sentinel-1C and 1D) to ensure the continuity of observations. With a resolution of around 10 meters and acquisitions every 6 or 12 days, these data enable the creation of Satellite Image Time Series (SITS), which are extremely rich in both spatial and temporal detail for monitoring phenomena such as landslides [Nati-2022], volcanic activity [Bigg-2026] or seismic movements [Funn-2019]. These synthetic aperture radar (SAR) images are acquired regardless of weather conditions and sunlight, a valuable advantage at high latitudes and in mountainous areas where cloud cover regularly disrupts optical imagery. Furthermore, SAR sensors provide complex images, and the phase difference between two acquisitions makes it possible to detect surface movements on the order of the wavelength, i.e. a few centimeters in C-band. This method, known as SAR interferometry (InSAR) [Mass-1998], is widely used in the field of geophysics and increasingly for the monitoring of gravitational natural hazards.

InSAR relies on relatively complex processing workflows. Software such as SNAP, distributed by the European Space Agency (ESA), enables the initial stages (generation of interferograms, orthorectification, etc.) to be carried out almost automatically and produces a colossal amount of data by forming pairs at different time intervals covering entire mountain ranges, or even entire regions. Extracting the desired information then requires developing or adapting certain processing steps to the specific application context: prior information, available supplementary data and in-situ measurements, the nature and precision of the information sought, etc. These steps increasingly rely on machine learning methods to detect the presence of movements masked by various sources of disturbance: loss of temporal consistency due to surface changes, errors in the digital elevation model (DEM) and geometric distortions that are particularly pronounced in mountainous terrain, and finally atmospheric effects that hide the deformation signal.

In order to harness the potential of deep learning methods, work began at LISTIC in 2021 as part of Antoine Bralet’s PhD thesis. This led to the development of an initial dataset (ISSLIDE), published on IEEE-dataport, which primarily contains data on rock glacier movements of around one meter per year [Tama-2026]. Tests carried out using ‘off-the-shelf’ neural networks [Bral-2024] and the results obtained with the ECSPLAIN approach developed during the PhD [Bral-2025] have demonstrated the full potential of AI methods for extracting fringe patterns linked to gravitational movements. This promising work and the rapid advances in deep learning methods pave the way for new methodological developments to improve the detection of gravitational instabilities and estimate their velocity, thereby enabling the measurement and monitoring of the dynamics of the observed phenomena.

The work proposed in this thesis will focus on the following research objectives. The first objective is to incorporate the temporal dimension into the process of detecting and measuring displacement. This involves developing models that exploit the relative continuity of motion and the redundancy of information in time series of interferograms spanning a period ranging from a few weeks to the entire ‘snow-free’ season. The second objective is the integration of ‘transformer’-type models [Doso-2021] to account for spatial relationships within the interferograms and to incorporate contextual information, particularly from digital elevation models. As these networks are more computationally intensive and require more labelled data, the integration of new InSAR databases dedicated to machine learning [Reye-2026] or the simulation of deformation in real interferograms may prove necessary. The final objective is to estimate the velocity of movements detected using machine learning regression methods. The development of multi-task networks should enable both semantic segmentation to locate moving areas and regression to determine the average velocity and any accelerations or decelerations in these areas.

The models developed will be tested on known gravitational movements monitored by researchers from the EDYTEM and ISTerre laboratories. In particular, we will draw on field data from the inventory of rock glaciers compiled over several years by Xavier Bodin and the Morphodynamics team at EDYTEM. The results obtained using the methods developed may

contribute to updating this inventory, notably by providing velocity measurements that enable these rock glaciers to be classified according to their dynamics.

## 6. Methodology and Expected Results

### Methodological developments

The initial stages of InSAR data processing are now relatively automated and can be carried out using open-source software such as the Sentinel Application Platform (SNAP), distributed by the European Space Agency (ESA). The successful candidate will be able to use these tools to generate time series of interferograms for two regions. The first will cover the Western Alps, where a significant number of moving sites have been identified, some of which are monitored by various instruments capable of providing ground truth data. A second region will be selected in the High Mountains of Asia and will enable to test the transferability of the developed methods on large mountain ranges with very different topographical and meteorological characteristics.

The thesis will focus primarily on the methodological challenges associated with incorporating temporal information into transformer-based networks [Doso-2021]. Three methodological approaches will be explored to analyse time series of InSAR interferograms, by varying the level of processing and the nature of the representations used. The first approach will involve processing the interferograms directly — in wrapped phase (modulo  $2\pi$ ) or unwrapped, depending on the constraints associated with the observed phenomena — as image sequences, feeding a transformer model designed to analyze both the spatial and temporal dimensions simultaneously. To make this processing computationally feasible, the interferograms will be divided into georeferenced patches, each of which will constitute an input token in the manner of a ViT (Vision Transformer). These tokens will be augmented with positional embeddings encoding the acquisition date and geomorphological information (location, altitude, aspect, slope, etc.), enabling the self-attention mechanism to identify deformation patterns by incorporating their temporal evolution. This method tests the hypothesis that a purely data-driven model, without explicit physical bias, can extract the characteristic signatures of slow gravitational movements directly from raw phase and coherence information supplemented with contextual elements, provided that sufficiently dense and varied time series are available.

A second approach will be based on a representation using complex coherence matrices estimated from co-registered Single Look Complex (SLC) image stacks, as utilized in phase-linking algorithms [Vu-2025]. These matrices, which encapsulate the second-order statistics of the radar signal within a circular complex Gaussian model (phase variability, spatial and temporal correlations between acquisitions), provide a physically grounded description of the observed dynamics, which is more robust than the raw phase in the face of decorrelation effects. The transformer will then operate on these matrices, combining their statistical content with topographical information derived from the digital elevation model. This approach aims to reconcile the descriptive richness of representations derived from signal processing with the

ability of attentional neural architectures to model complex long-range dependencies, both spatial and temporal.

The third approach will adopt a hybrid architecture, combining a convolutional backbone with attention heads. A ResNet-type or 3D CNN encoder [Abda-2025] will first extract local features at different scales, capturing the basic patterns in the interferograms (fringes, artefacts, areas of coherence loss). These representations will then serve as input tokens for the transformer, which will analyze their global interactions. This configuration allows us to capitalize on the complementary strengths of convolutional networks — effective for low-level signal processing — and transformers, which are particularly well-suited to modelling complex contextual relationships. The backbone can be pre-trained in a self-supervised manner, for example via a masked patch reconstruction task (Masked Autoencoder) on a large corpus of unannotated interferograms, in order to reduce dependence on annotated data, a major constraint in this field.

The three approaches will be systematically evaluated for their ability to detect unstable areas and estimate their movement speed, using appropriate metrics (IoU for segmentation, RMSE for regression) and independent test datasets provided by partner laboratories. The evaluation will include a comparison with operational reference methods (SBAS, PS-InSAR) [Huss-2025] in order to quantify the actual contribution of the proposed approaches. A comparative analysis will assess the impact of the level of feature processing on performance, whilst attention map visualization techniques will shed light on the models' decision-making mechanisms.

## **Expected results**

From a methodological perspective, the findings of this thesis will address the challenge of incorporating temporal information into transformer-based neural networks for the detection and estimation of slow gravitational movements in radar interferometry. The methods developed will be published in international conferences and journals such as the IEEE International Conference on Image Processing (ICIP) and IEEE Transactions on Geosciences and Remote Sensing (TGRS). In line with the principles of reproducible science, the code and models developed will be distributed via a GitHub repository, and the data used for training may form the basis of a new database accessible through the French space agency (CNES) research infrastructure 'Data-Terra'.

From an applied perspective, the most effective methods will be applied to real-world cases of Alpine rock glaciers, with the aim of integrating them into the operational monitoring tools developed by the 'Permafrost' community, in particular by contributing to the work of the 'Rock Glacier Inventories and Kinematics' (RGIK) group. In conjunction with the work of the IGE, ISTERre and EDYTEM laboratories, the results obtained in the Alps could form a useful knowledge base for natural risk managers such as the Mountain Land Restoration Service (RTM), and help meet the objectives of the National Action Plan for the Prevention of Glacial and Periglacial Risks (PAPROG). Finally, depending on the progress of the work, tests of the

developed methods on interferograms covering the High Mountain of Asia may be carried out in collaboration with the Indian Institute of Remote Sensing (IIRS), with whom LISTIC has been developing exchanges for several years.

## **7. Candidate Sought**

The successful candidate must have an excellent academic background specializing in artificial intelligence for image analysis and hold an engineering degree or a master's degree.

A solid grounding in mathematics, machine learning and programming is required, as well as strong writing skills.

Knowledge or experience in the field of remote sensing for Earth observation would be an advantage.

A minimum B2 level of English is required.

## **8. Funding for the Thesis**

*The doctoral contract sets a basic salary, indexed to changes in civil service pay. Order of 26 December 2022 amending the Order of 29 August 2016 setting the amount of remuneration for doctoral students on contract NOR: ESRH2235820A - Article 1 - Article 1 of the aforementioned Decree of 29 August 2016 is replaced by the following provisions: "Art. 1. - The minimum monthly remuneration for doctoral students on contract is set as follows, subject to the provisions of Article 2 of this Decree:" - from 1 January 2026: €2,300 gross.*

*Teaching hours may be undertaken up to a limit of 64 tutorial-equivalent hours per academic year, subject to authorization by the university president, and shall be remunerated at the rate set for tutorials currently in force. Other activities supplementary to the doctoral contract are provided for in Article 5 of Decree No. 2009-464 of 23 April 2009, as amended. The total duration of activities supplementary to the research activities entrusted to the doctoral student under the doctoral contract may not exceed one-sixth of the annual working time.*

## **9. Contact**

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