

Integrating Spaceborne InSAR into Operational Monitoring of Critical Gas Infrastructure

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1 INTRODUCTION & SCOPE OF WORK

The advancements in geodetic imaging, particularly the evolution and refinement of Interferometric SAR (InSAR) technique along with its thorough validation, have facilitated the acceptance of the technique for operational applications. These advancements are particularly relevant and valuable for the monitoring of large-scale critical engineering infrastructures.

In the context of gas pipeline surveying, spaceborne InSAR has become an essential tool for mapping and monitoring surface motion. Pipelines, as massive constructions extending over large areas, pose difficulties for conventional ground-based monitoring methods. Satellite-based InSAR provides an effective solution, enabling the early identification of pipeline segments that require closer inspection and detecting surface motion indicators that could lead to hazardous conditions, allowing for timely information and preventive actions.

A prominent example of such an application is the monitoring of the DESFA pipeline network, the principal natural gas transportation system in Greece, and its associated above ground installations. Spanning a total length of approximately 1630 km, DESFA's high pressure steel pipeline network passes mainly over flat terrains but also includes significant segments in more rugged areas and challenging terrain. The pipeline, buried at a shallow depth of approximately 1.20 m, is systematically monitored using ground-based methods, optical satellite imagery, and aerial surveys. These traditional approaches focus primarily on detecting signs of unauthorized human intervention or other ground deformation issues. However, ground-based geodetic techniques like GNSS and leveling or other surface displacement monitoring techniques face limitations in providing coverage of the entire network, making them more suitable for localized areas of known activity or with pronounced deformation signals.

In the current work, we demonstrate the contribution of spaceborne InSAR to the operational monitoring of the DESFA pipeline network, highlighting its capability to provide spatially continuous information along extensive linear infrastructure. Emphasis is placed on the added value of integrating InSAR with existing surveillance practices, enabling wide-area deformation screening, identification of potentially critical pipeline segments, and informed prioritization of targeted field inspections along the pipeline corridor.

2 METHODOLOGY

A monitoring system based on Copernicus Sentinel-1 mission data and the Persistent Scatterers Interferometry (PSI) technology (Hooper et al., 2012; Foumelis et al., 2021; Foumelis et al., 2022; Hooper et al., 2024) has been established to address these challenges. The first phase of this activity focused on examining historical surface motion data starting in April 2015, utilizing the entire Sentinel-1 archive, including both ascending and descending orbital tracks. Prior to the actual interferometric processing, a feasibility analysis was conducted to investigate and anticipate areas with potential limitations, enabling the development of a strategically tailored and targeted plan. Based on an automated processing chain, a dedicated workflow was then designed to generate surface motion rates and corresponding time series at sensor resolution. Measurements extend several kilometers on either side of the pipeline, enabling the detection of deformation signals even beyond direct vicinity that could potentially propagate and impact the pipeline.

To ensure robustness and proper compensation of different error sources, the area of interest was divided into several overlapping tiles processed independently. Post-processing included the geometric decomposition of Line-of-Sight (LoS) motion into vertical and East-West components and the separation of temporal trends from seasonal motion facilitating easier interpretation by expert domain engineers. Several statistical properties of the measurements, quality indicators and obtained uncertainties, geographic locations showing significant motion or demonstrating proper performance, and their corresponding time series visualizations were among the key findings summarized in a structured document format by an automated reporting mechanism. Finally, a layer of human interpretation and validation is incorporated to ensure the reliability, and consistency of measurements and deliverables.

3 RESEARCH OUTCOMES

The historical surface motion analysis was conducted for both Sentinel-1 SAR acquisition geometries over the period from April 2015 to September 2023, covering approximately 8.6 years, while annual updates of the solution were subsequently performed up to 2026. The analysis extended across a 2.5 km buffer zone around the pipeline, allowing the investigation of deformation patterns both in the vicinity of the pipeline and in more distant areas where ground motion phenomena could potentially propagate towards the infrastructure.

InSAR monitoring provided approximately 4.74 million PS targets from ascending tracks and 3.78 million targets from descending tracks, corresponding to an average density of about 500 points per km² (Figure 1). As expected, the spatial density of measurement points was strongly influenced by land cover, with reduced coverage observed where the pipeline crosses highly vegetated areas and agricultural land.

To evaluate the effective coverage of the PSI results along the pipeline, the network was divided into 100 m segments, resulting in a total of 1,607 segments. PS targets were present in 1,566 segments. Of these, 1,219 segments were considered fully exploitable, defined as segments containing at least 10 targets, while 347 segments were considered partly exploitable. Only 41 segments contained no PS targets and therefore could not support surface motion assessment. Overall, approximately 60–70% of the pipeline was effectively monitored using C-band Sentinel-1 SAR data, which can be considered satisfactory given the known limitations of C-band interferometry over vegetated and agricultural areas.

The combination of ascending and descending LoS measurements was performed using both the commonly applied gridding approach, based on a regular 100 m grid, and the Nearest-Neighbour Vector (NNV) decomposition approach proposed by Foumelis (2018). The latter enabled a higher spatial density of decomposed vertical and east-west horizontal motion components, resulting in approximately 7.5 million point targets.

The analysis enabled the identification of areas characterized by motion stability (Figure 2), as well as pipeline segments exhibiting relatively higher deformation rates. In addition, the availability of displacement time series supported the detection of sites with seasonal motion components, as well as locations where short-term ground motion accelerations occurred, related to different underlying processes.

In conclusion, the monitoring system is built to offer continuous updates, incorporating new satellite acquisitions at defined time intervals that are suited to the unique surface motion properties of the pipeline. It serves as a complementary tool for proactive monitoring or wide-scale emergency inspections, particularly for assessing the impact of natural hazards, adverse anthropogenic activity or weather-related phenomena that are expected to intensify.

This approach complements existing monitoring activities, offering a solid and scalable solution for enhancing the safety and strengthening the resilience of critical energy infrastructure, while also being applicable across all aspects of the pipeline network lifecycle.

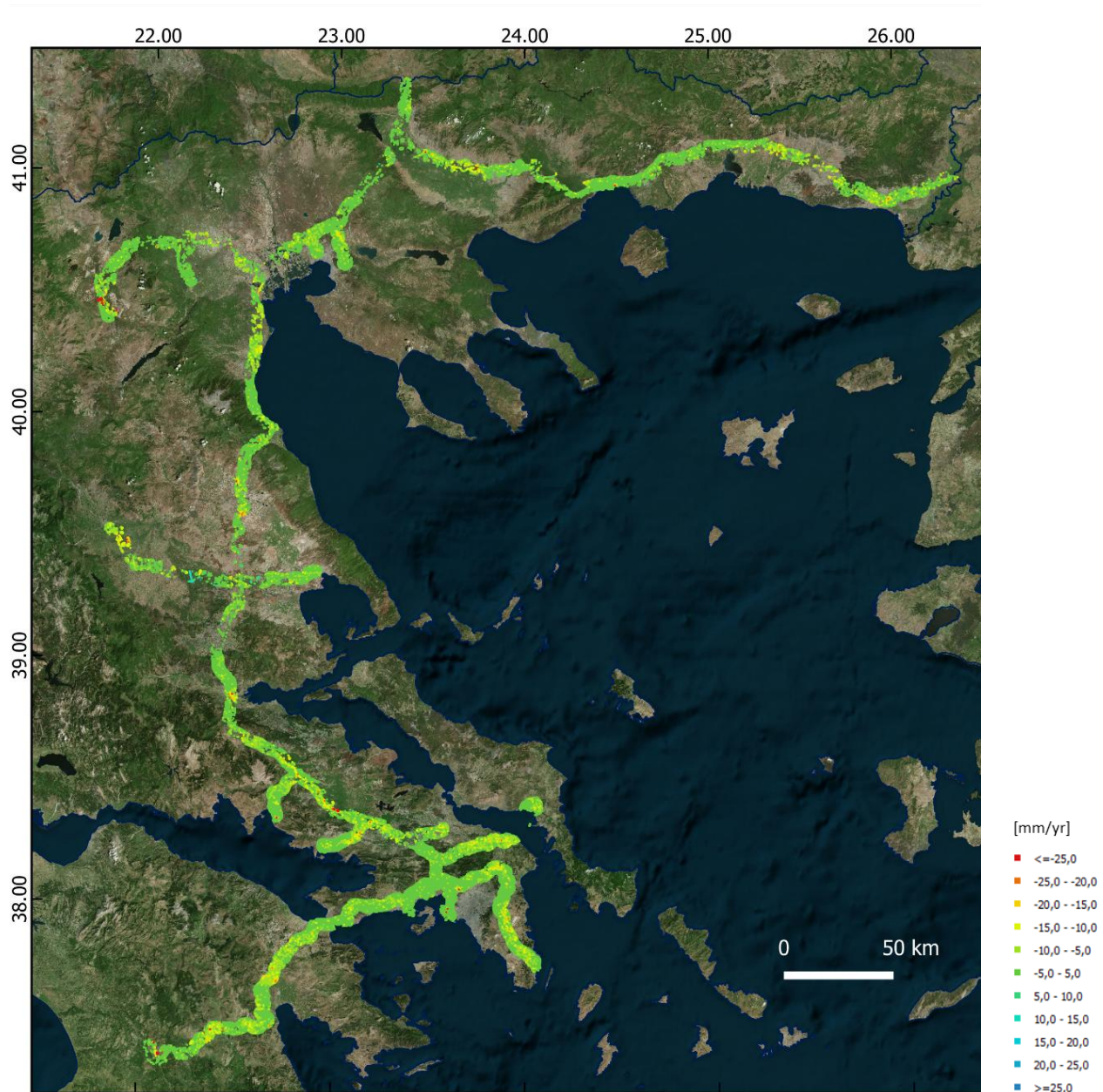


Figure 1. PSI-derived vertical surface motion along the DESFA pipeline corridor within a 5 km buffer, based on Copernicus Sentinel-1 data.

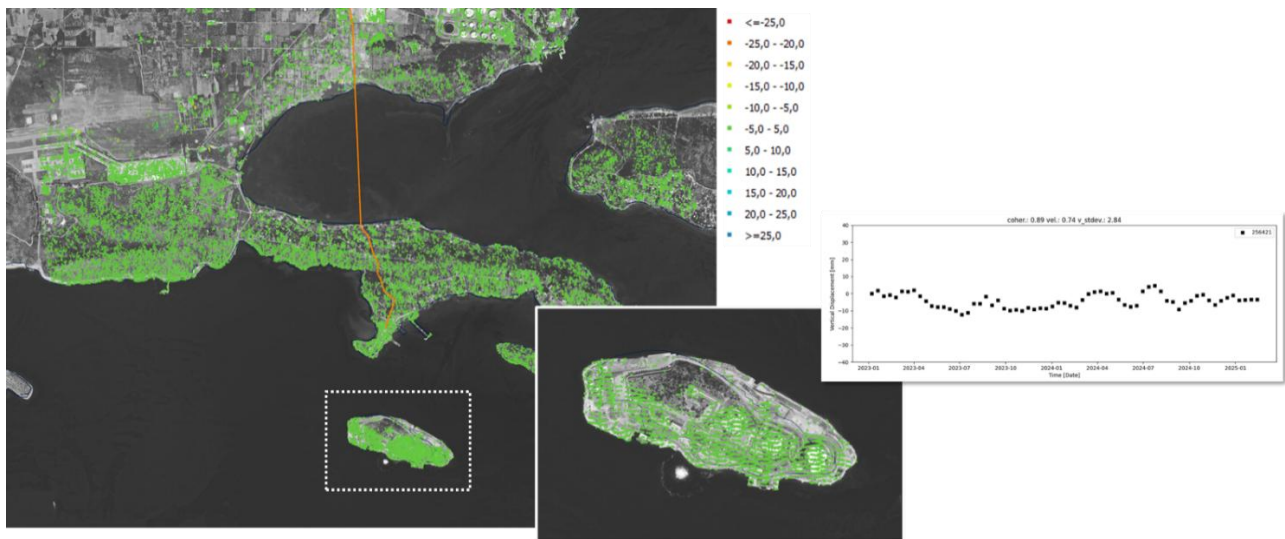


Figure 2. PSI vertical surface motion rates over the Revithoussa LNG Terminal, indicating overall ground and structural stability. The displacement time series show negligible temporal variability.

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