Advanced monitoring system from space for long linear transport infrastructure

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Abstract

Interferometric Synthetic Aperture Radar (InSAR) is a remote sensing technique that successfully detects and monitors ground and surface infrastructure motion with millimetric precision using SAR satellite imagery. ATLAS InSAR processing chain is applied in geotechnical and structural monitoring projects linked to infrastructure design, construction, and maintenance activities. This paper will describe in depth the benefits of InSAR when monitoring transport infrastructure with a focus on long linear assets; both highways and railways will be addressed. This remote sensing technique brings an advanced, sustainable, environmentally friendly, and cost-effective solution for long term monitoring programs on linear infrastructures, enabling detailed analysis of these assets and surrounding terrain on kilometres of motorways and railways. The combination of InSAR results and advanced data analytics provides comprehensive inventories of risk areas. These inventories can be updated at any desired frequency, not only identifying active 'hotspots', but also identifying vulnerable areas, detecting precursory movements, and therefore enabling the implementation of mitigating actions to protect assets and their traffic. The paper will present different case studies where InSAR is being applied to ensure high-quality surveys of both railway and highway networks. The first case study will correspond to a monitoring of a 200 km road on the north of the Peloponnese peninsula in Greece (Olympia Odos); the second case study will present the application of an InSAR monitoring system to a 90 km high speed railway in the West Midlands in UK (HS2). Each monitoring project has been addressed with a different innovative technical approach applying combinations of different Satellite constellations, different orbits, and data science techniques to facilitate the interpretation of the results.

Keywords: Interferometry, InSAR, Structural Health Monitoring, Linear Infrastructure, Civil Engineering

1. Introduction

The application of earth observation techniques plays an increasingly important role when planning the monitoring package of a construction project. Remote sensing applications provide useful background data which is essential to properly understand the actual behaviour of the assets. Some of their unique advantages to large monitoring projects are the availability of historical data, the large size of the images that allow measurements over wide areas and the possibility of monitoring without accessing site. Radar satellite interferometry is a well-known remote sensing technique which allows to derive millimetric measurements of individual terrain structures over wide areas in both urban and non-urban environments. InSAR technique is based on the exploitation of a set of SAR acquisitions from space. For any measurement point, satellite time series allow the follow-up of the observed behaviour every few days during the monitoring period.

ATLAS InSAR processing chain has been developed with the aim of monitoring geotechnical and structural deformations linked to construction activities. It is particularly suitable for monitoring surface movements generated by works that can affect the existing infrastructures next to the construction sites.

In the following sections, an overview of the interferometry technique is presented together with the technical specifications of SAR images demonstrating their value for remote monitoring. ATLAS technology will be presented from its basis in InSAR PSI technique to the analysis of results using data analytics techniques at the last stage. In addition, this paper includes two different case studies of linear infrastructure monitoring where InSAR is being used as an operational monitoring system.

2. Satellite Based Interferometry

2.1 General Basis

Radar satellite interferometry is a widely used technique to monitor terrain deformation over wide areas [Bamler et al. (1998)]. It is a non-invasive technique which requires two or more Synthetic Aperture Radar (SAR) images acquired over the same area at different dates. SAR images are complex images: they consist in the amplitude and the phase component. SAR interferometry uses the phase difference between different acquisitions, the so-call interferometric phase (Φ_{int}), to compute ground displacement measurements based on differences between the radar waves travel time. The working principle is illustrated in Figure 1.

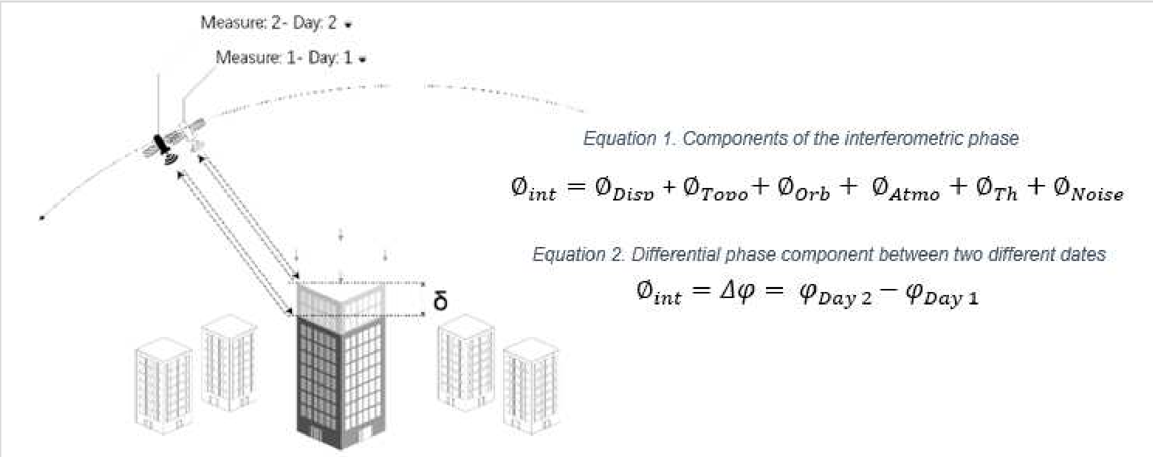

Figure 1: SAR interferometry working principle.

The interferometric phase consists in different components: the component due to the displacement, the topography, orbital errors, atmospheric effects, and noise. To obtain millimetric precision on deformation measurements, the interferometric phase component due to movements must be isolated. This process is performed using InSAR advanced techniques.

2.2 Satellite Images

The first satellite-based radar sensors for research and commercial purposes dates to the early 90s. Their main goal was to collect information across the Earth to monitor natural disasters. With the arrival of more satellites, multiple microwave bands of the electromagnetic spectrum are covered which implies the availability of retrieving more information and at different resolutions (Table 1) and, as a result, a growth of SAR applications in the frame of surface deformation monitoring.

Band	Wavelength (cm)	Relative penetration	Typical Spatial Resolution (m)	Geolocation precisions (m)	Measurement precisions (mm)	Footprint (km)
X	3.8 – 2.4	Low	High (1 – 3)	1	High (2 – 3)	From 4 x 4 to 30 x 50
C	7.5 – 3.8	Medium	Medium (5 –30)	5 – 10	Medium (4 – 5)	From 20 x 20 to 250 x 170
L	30 – 15	High	Low (30 – 40)	5 – 40	Low (10 – 20)	From 25 x 25 to 350 x 350

Table 1: SAR satellite bands and general characteristics of their associated datasets [Devanthéry et al. (2022)].

Nowadays, the mostly used mid-resolution data is the Sentinel-1 imagery from the European Space Agency (ESA), which is acquired from a two-satellite constellation: Sentinel-1A & Sentinel-1B. It acquires mid-resolution C-band images with a pixel size of about 20 x 5 m in surface and it covers approximately 250 x 180 km on the ground within a single image footprint. The main operational high-resolution constellations are the Cosmo-SkyMed from the Italian Space Agency, and the TerraSAR-X from the German Aerospace Centre, that recently has been enlarged with the new PAZ satellite from the Spanish Ministry of Defence and operated by Hisdesat. The high-resolution imagery, acquired with the so-called StripMap mode, offers a spatial resolution of 3 x 3 meters. Its image frames cover about 60 x 30 km on the ground.

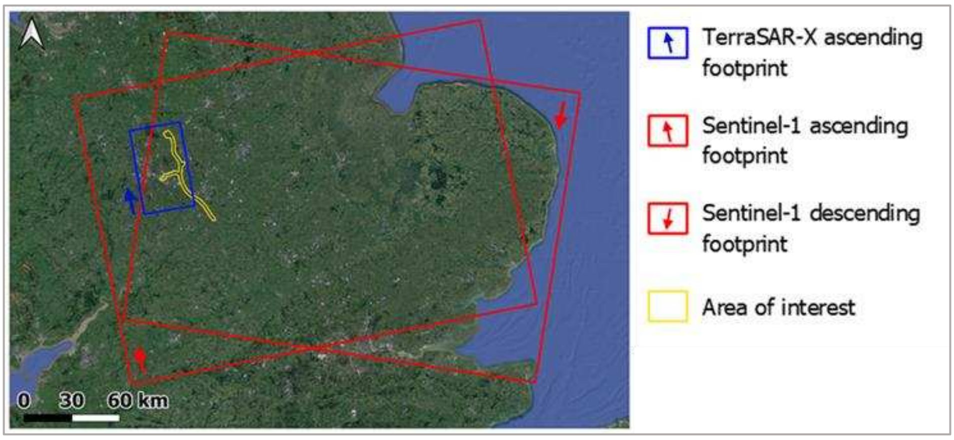

Figure 2. Spatial coverage of different satellite images over an area of study.

The precision of measurements obtained using the InSAR PSI technique are related, among other factors, to the use of the band selected for the image acquisition (see Table 1). Another factor that must be considered is the behaviour of the different wavelengths with the type of surface to be studied, which will directly affect the density of measurement points obtained in the different types of land cover.

2.3 ATLAS InSAR Processing Chain

The ATLAS processing chain has been developed around the core software GAMMA [Werner et al. (2003)]. It provides vertical ground and structural movements with millimetric precision, and it is specially focused on the monitoring of construction works in urban environments and critical non-linear movements.

ATLAS PSI uses a stack of 15/20 or more SAR images to estimate the velocity of deformation, the accumulated deformation for each date and the historical time series over a set of measurements points, called Persistent Scatterers (PS) [Ferretti et al. (2000)]. These PS are points with low level of noise and with phase stability along the period of study. They usually are located over man-made structures, rocks, or arid regions, i.e., structures with better radar reflection properties. The first step of the ATLAS InSAR processing chain starts with the definition of a study area and the period of interest, so the most suitable stack of satellite images is chosen. The general workflow of the processing chain is shown in Figure 3.

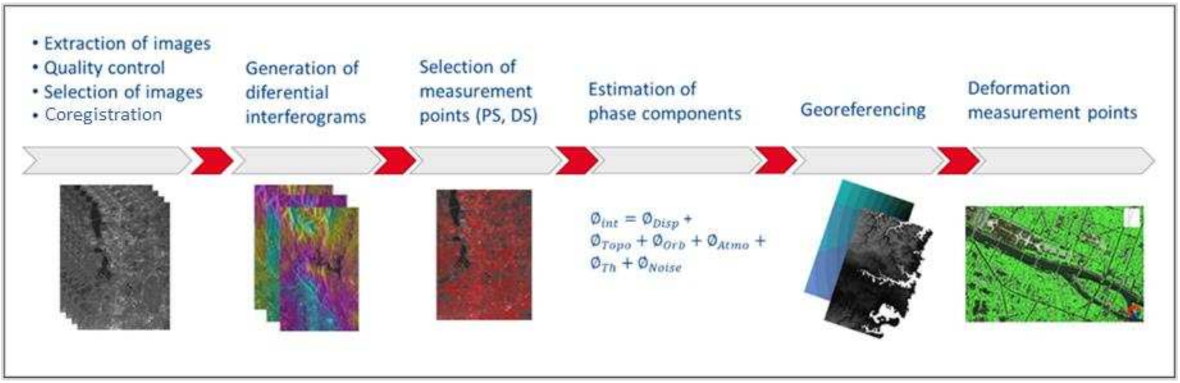

Figure 3: ATLAS InSAR processing workflow.

3. SAR Interferometry Applied to Linear Infrastructure Monitoring

3.1 Application

In the construction sector, an InSAR monitoring system becomes the perfect choice for a cost-effective long-term surveying program in large-scale monitoring projects. It works as a global monitoring system, covering wide terrain areas within one image frame. The derived information from an InSAR study helps to optimized available resources and redirect them towards critical areas. It can be implemented at different stages of a project [Ibarrola et al. (2021)]: During designing and planning phase, during construction phase and during post-construction or maintenance phase:

During **designing phase**, to gather information that helps plan the project. Even when preliminary works have already started, InSAR provides historical information using archive images. It is one of the few techniques that allow to retrieve information from the past. During the **construction phase**, InSAR monitoring provides a common benchmark for different work teams and different sites from the same project. In many cases, the high-precision standards of civil engineering projects include an InSAR monitoring system as a complementary information to the in-situ monitoring instrumentation, and it works as a common reference for different traditional surveying techniques. An implemented InSAR monitoring system allows a faster decommissioning of in-situ instrumentation, thus leading to saving time and costs for the instrumentation monitoring. In the **last stage of the construction project**, when the construction works have been finished and most of the instrumentation are being decommissioned, InSAR monitoring system becomes the perfect choice for a cost-effective long-term monitoring system. The **maintenance period** of an infrastructure may last over several years.

3.2 Data Analytics

An InSAR monitoring study usually provides thousands of geolocated measurement points with millions of deformation values distributed in time. Such a large amount of data makes it necessary to have tools to manage this volume of information. Thus, different data analytics techniques are applied to provide a simplified way of visualizing InSAR results focusing on different assets and allowing a fast and easy analysis:

- **Active Deformation Areas (ADA)** is a geospatial technique that has been developed and tested to statistically aggregate nearby InSAR timeseries with similar behaviour. It allows a quick identification of movement areas with the target pattern.
- **InSAR to Assets (I2A)** is a geospatial technique that has been developed to spatially select InSAR points and timeseries that affect different asset (i.e., buildings, road/streets, or rail/metro sections) and classify those assets based on several statistical criteria.

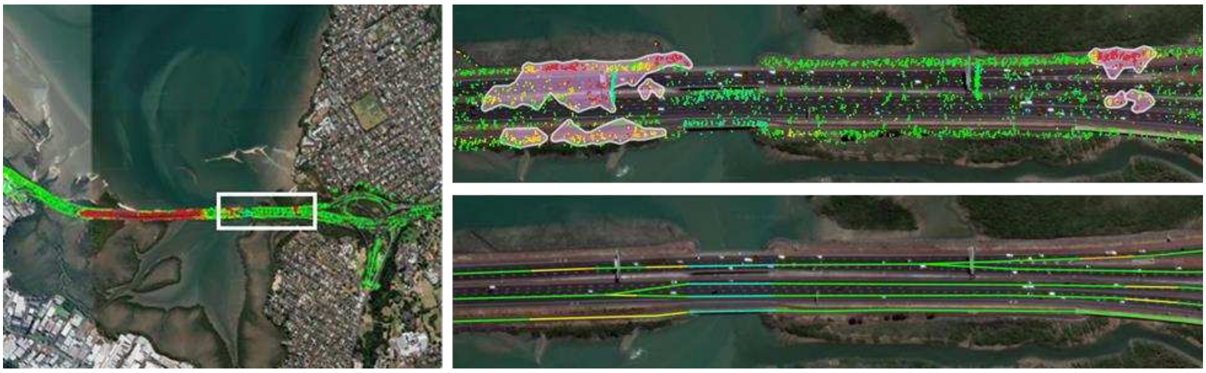

Figure 4: Sample of results obtained by applying data analytics techniques for monitoring of highways.

Figure 4 shows examples of results obtained by using both ADA and I2A analysis techniques focused on a bridge section of a highway monitoring. In this case, the original InSAR dataset contains more than 7 million measurement points obtained after processing 48 high-resolution SAR images distributed in nearly 2 years. The application of geospatial analysis techniques automatically detects areas with similar deformation patterns (i.e., subsidence, uplift, seasonal, …) and classifies several sections of the highway based on InSAR deformation measurements. In addition, geospatial analysis can help to integrate information from different sources at asset level (i.e., road section) leading to a more robust solution.

4. Case Study: Maintenance phase of Olympia Odos Motorway

4.1 Project description

Olympia Odos S.A. is the company that designs, constructs, operates, and maintains the Olympia Odos motorway. This motorway runs from Elefsina (Athens) to Patras along 200 km bordering the Mediterranean Sea. Due to the mountainous orography of the area, the motorway runs next to mountain slopes, it crosses mountains through tunnels and passes by cut and fill sections.

4.2 The needs

Olympia Odos S.A. contracted Sixense's InSAR services as part of an overall optimization of the monitoring system in the frame of the maintenance phase. The recently constructed motorway is located in a complex geotechnical area, so it is necessary to monitor the stability of terrain to ensure how the infrastructure is potentially being affected. InSAR monitoring solution enables the study of great areas, allowing also to carry out historical studies to detect any precursor of recent movements.

4.3 Satellite based Application Solution

The aim of this study is to have a better understanding of the behaviour of infrastructure and terrain at the last periods of construction and after the road construction phase for a long-term operations monitoring. InSAR technology contributes to the maintenance of the Olympia Odos motorway with high-quality ground deformation measurements in the past, present and future. Thus, the ATLAS InSAR analysis includes an InSAR study covering a 7 year-period, and covering two different phases:

- End of construction phase: 4-year Historical Study (Oct. 2014 - Sept. 2018) with mid-resolution Sentinel-1 data.
- After construction phase: 3-year Routine Monitoring (Sept. 2018 - June 2021) using mid-resolution Sentinel-1 imagery with different delivery frequencies.

For the first phase, three sets of 96, 99 and 101 medium-resolution radar images from Sentinel-1 were processed using both ascending and descending orbits. The second phase corresponds to the routing monitoring with interannual deliveries, where the new satellite images acquired every 12 months are included to provide updated deformation measurements. The use of images from both ascending and descending orbits allows to estimate the deformation components in Up-Down (Vertical) and East-West (Horizontal) directions.

Figure 5: InSAR monitoring coverage along the 200 km of the Olympia Odos motorway.

4.4 Results and Benefits

Mid-resolution Sentinel-1 images in ascending and descending orbits were used to analyse both up-down and East-West deformations. The ATLAS InSAR study provides ground deformation values, with a total amount of approximately 300,000 measurement points (PS) considering both ascending and descending results (Table 2). The ground areas where no measurement points could be retrieved mainly correspond to agricultural fields and forests, due to the high temporal decorrelation and loss of coherence.

Dataset		Road Length (km)	Surface (km^2)	Measurement points
Sentinel-1	LOS ASC175	64	> 150	> 50,000
	LOS ASC102	136	> 300	> 100,000
	LOS DESC007	200	> 450	> 140,000
	U-D & E-W	200	> 450	> 125,000

Table 2: Summary of results obtained by InSAR monitoring during the historical study.

ATLAS InSAR is being successfully applied in the Olympia Odos project to monitor the motorway and surrounding areas, during a period of 7 years, and providing precise measurements of ground deformation with very important benefits such as:

- Enabling a global analysis of the behaviour of the terrain along the 200 km motorway.
- Quickly identifying the location of stable and movement-prone areas during the study period.
- Providing precise measurements of the velocity of deformations.
- Providing an inventory and inspection of the motorway´s critical spots to plan regular interventions.
- Allowing an early detection of precursor movements enabling the implementation of mitigative actions to protect the road, assets, and traffic.

The results are delivered through a web-based visualization platform which was specially developed to easily read and analyse ATLAS InSAR measurement results.

5. Case Study: Construction phase of High Speed 2 in the Midlands

5.1 Project description

The HS2 project is a new high-speed railway linking up London, the Midlands, the North, and Scotland, serving over 25 stations. The N1 and N2 sectors cover around 103 km of the railway in length. The N1 links the Long Itchington Wood tunnel to the Delta Junction/Birmingham Spur, while the N2 sector links the Delta Junction to the West Coast Main Line Tie-in. The new railway line in the West Midlands passes mainly by farming areas and a densely build-up area in Birmingham.

5.2 The needs

The InSAR monitoring system implemented in the HS2 N1N2 section is part of the collaborative relationship between Balfour Beatty VINCI (BBV, the contractor) and Sixense (provider) to identify and eliminate cost drivers in the course of the HS2 project. It also serves as global monitoring system common to the different operational teams working in different sectors. InSAR monitoring is meant to be used as a durable monitoring system covering the period prior to the start of the construction and it will remain during the post-construction phase.

5.3 Satellite based Application Solution

Sixense supports BBV in HS2 N1N2 project by providing a continuous monitoring over 6 years after the historical baseline, delivered in June 2021, using an optimized combination of high-resolution TerraSAR-X imagery for urban area, and mid-resolution Sentinel-1 imagery for non-urban area to fully exploit the advantages of both X-band and C-band where they give the best results.

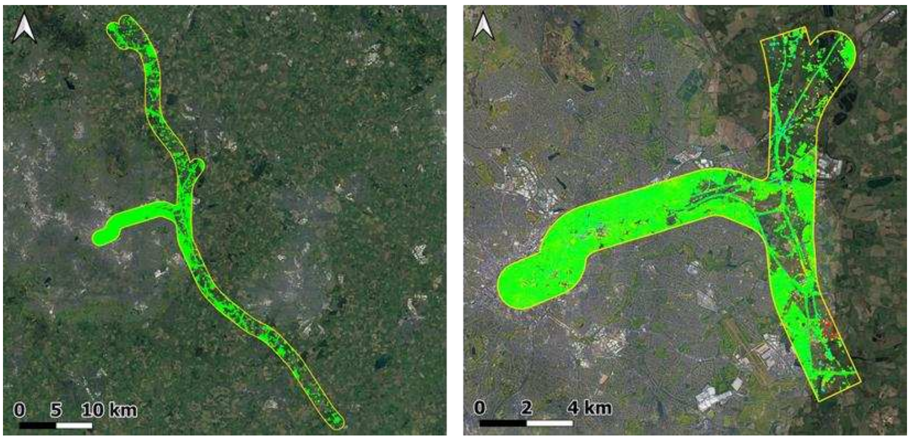

Figure 5: InSAR monitoring coverage for HS2 N1N2 project; (Left) Mid-resolution Sentinel-1 study; (Right) High-resolution TerraSAR-X study.

ATLAS InSAR analysis includes a monitoring covering two different phases: (I) 5-year Historical Study (11/2015 - 05/2021) mid-resolution Sentinel-1 data and 1.5-year Historical Study (12/2019 – 05/2021) high-resolution TerraSAR-X data (II) 6-year Routine Monitoring (starting in 06/2021). As InSAR monitoring must cover the pre-construction, construction and post-construction phases, different delivery frequencies are planned to provide the best option in each of the phases based on project’s activities and needs.

5.4 Results and Benefits

The resulting deformation measurements have been computed using an initial 296 mid-resolution Sentinel-1 images in ascending and descending orbits and a set of 123 high-resolution TerraSAR-X images. Table 3 shows the number of points of each dataset and densities obtained within the area of interest.

<table>
<tr><th colspan="2">Dataset</th><th>Study Area</th><th>Surface (km²)</th><th>Measurement points</th></tr>
<tr><td rowspan="6">Sentinel-1</td><td rowspan="2">LOS ASC</td><td>Full AOI: LIM</td><td>> 170</td><td>> 130,000</td></tr>
<tr><td>Urban Birmingham</td><td>> 15</td><td>> 60,000</td></tr>
<tr><td rowspan="2">LOS DESC</td><td>Full AOI: LIM</td><td>> 170</td><td>> 190,000</td></tr>
<tr><td>Urban Birmingham</td><td>> 15</td><td>> 90,000</td></tr>
<tr><td rowspan="2">U-D & E-W</td><td>Full AOI: LIM</td><td>> 170</td><td>> 130,000</td></tr>
<tr><td>Urban Birmingham</td><td>> 15</td><td>> 60,000</td></tr>
<tr><td rowspan="2">TerraSAR-X</td><td rowspan="2">LOS ASC</td><td>Full AOI: Urban Tunnelling</td><td>> 60</td><td>> 750,000</td></tr>
<tr><td>Urban Birmingham</td><td>> 15</td><td>> 430,000</td></tr>
</table>

Table 3: Density of points in the historical study datasets.

Results from the ATLAS InSAR study allow:

- The global analysis of the behaviour of the terrain along the alignment, assessing the potential long-term ground movement trends and the location of stable zones.
- To obtain precise measurements of velocity of deformation and accumulated deformation.
- To know the precise delimitation of the perimeter of deformations and its evolution in time.

Due to the wide scope of InSAR monitoring and the availability of data though different phases in time, it provides valuable information to handle third parties' requirements and claims.

6. Conclusion

InSAR monitoring is increasingly being implemented as an operational monitoring in many linear infrastructure projects. This remote sensing system has proven to be a cost-effective solution to control ground deformations over wide areas, providing complementary data to traditional ground instrumentation in construction projects, enabling to obtain historical information using archive imagery and an optimal cost-effective long-term monitoring solution.

Acknowledgements

Many thanks to people involved in Olympia Odos and HS2 projects for their helpful insight and their trust in the applications of innovative approaches as monitoring systems. Their feedback about the application of the InSAR solution to the civil engineering world has been very valuable.

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