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Monitoring of Tunnels in Urban Environments Complementing InSAR with in-situ Ground Instrumentation

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ABSTRACT

One of the challenges in urban tunnelling projects is to guarantee that the infrastructure assets crossing or adjacent to the tunnel alignment and other new build elements are not affected by the construction activity. Radar Satellite Interferometry (InSAR) is a non-invasive surveying technique which provides millimetric deformation measurements of terrain structures over wide areas without any need to access site. This technique allows a comprehensive and periodic vision, with the same accuracy as manual levelling in cities for a fraction of the cost of traditional systems. ATLAS is the Sixense's InSAR processing chain, aimed to monitor the different tunnelling activities phases: access shaft excavation, tunnel construction and settlement. This study focuses on real data obtained by Sixense during the monitoring of urban tunnel construction work in three major projects in London (UK) and Porto (Portugal), using a combination of technologies: InSAR for remote monitoring and two topographic instrumentation methods: Topographic Control Prisms through measurements with Robotic Total Station and Topographic Levelling. The methodology employed integrated InSAR to obtain surface deformation data across the tunnel influence zone and on-site instrumentation for detailed and precise measurements. Its implementation enabled continuous monitoring, revealing accurate and real-time deformation patterns near the tunnels. The results demonstrated a significant correlation between InSAR data and on-site measurements, validating the effectiveness of this combination.

Keywords: tunnel; deformation; InSAR; total station; levelling.

1. Introduction

With rapid urban developments and dense populations settlements in the major cities are leading to underground developments like tunnelling. Urban tunnelling projects often pose significant challenges in terms of ground stability and monitoring. One of the challenges is to ensure the deformation of buildings adjacent to tunnel alignment during the construction activities in urban areas. A wide range of geophysical techniques are employed to measure the ground deformation. Levelling is one of the in-situ instrumentation technique which is more accurate and broadly used for detecting millimetre scale deformations (Karila et al. 2013; Serrano-Juan et al. 2017).

It is essential to obtain precise and frequent measurements of ground deformation during three phases of urban tunnelling projects: planning, construction and operations phases. During the pre-construction phase, historical ground deformation that can affect the future tunnelling project can be provided by InSAR technology. In the course of construction phase, InSAR is integrated with on-site instrumentations to monitor the deformation along the tunnel alignment, that may be associated with tunnel construction (Ge et al. 2016). Post-construction of tunnel projects, InSAR technology can be useful for periodical monitoring to detect accelerations in the settlement over the tunnelling influence zone which is helpful in preventing structural damages to the infrastructures (Milillo et al. 2018).

ATLAS Interferometric Synthetic Aperture Radar (InSAR) is a fully remote sensing monitoring technique to determine the relative ground movement using satellite SAR images (N. et al. 2022). Satellite InSAR provides precise and frequent measurements of ground deformation during the planning, construction, and operation phases, making it an invaluable tool for assessing the impact of tunnel construction on urban environments.

In this study, we present the advancements of InSAR technology in monitoring urban tunnelling activities as a complement of in-situ instrumentation methods. We focus on the real data obtained by Sixense during the monitoring of urban tunnel construction work, using a combination of technologies: Spaceborne InSAR for remote monitoring and two instrumentation methods namely, Topographic Control Prisms through measurements with Robotic Total station and Topographic Levelling. In this paper, we present three case studies and discusses how these two methods are used for monitoring the ground deformation along the tunnel alignment and limitations of the technique. The methodology employed integrated InSAR to obtain surface deformation data across the tunnel influence zone and on-site instrumentation for detailed and precise measurements. Its implementation enabled continuous monitoring, revealing accurate and real-time deformation patterns near the tunnels. This paper demonstrates a significant correlation between InSAR data and in-situ measurements, validating the effectiveness of this combination for tunnel deformation monitoring.

2. Material and Methods

2.1.1. Satellite InSAR technique

Synthetic Aperture Radar Interferometry (InSAR) is a non-invasive remote sensing technique capable to monitor wide areas of terrain with millimetric precision, making it ideal for the monitoring of infrastructures. InSAR is based on the exploitation of Satellite aperture radar (SAR) images, which are complex radar images containing phase and amplitude information over a very large area, usually few hundreds square km (Bamler et al. 2009). The InSAR technique consists in analyzing the same two SAR images at different date and computing the ground displacement information based on the differences of the phase components (Figure 1).

Persistent Scatterer Interferometry technique (PSI) takes conventional InSAR a step further to get millimetric precision on the ground motion readings, that is done by correcting atmospheric, orbital, and topographic errors (Ferretti, Prati, and Rocca 2001). This technique requires a database composed of more than fifteen images. The PSI algorithm identifies common points (geographical locations) in each image that reflect persistently the radar signal back to the sensor. These locations are permanent reflective targets, whose reflections remain constant over the whole image stack during the duration of a project. They are generally man-made structures or rocks but can also be arid terrains and other ground features whose orientation and surface characteristics allow a perfect reflection of radar waves.

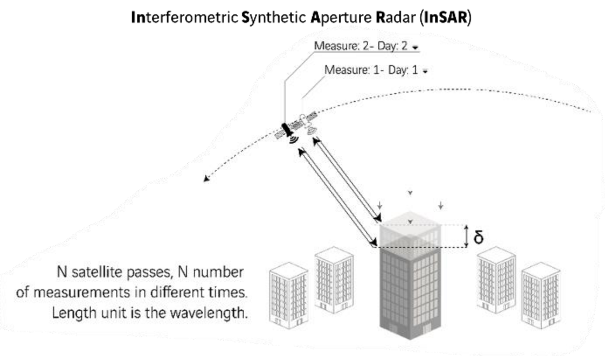


Figure 1. SAR Interferometry principle

The processing steps involved in ATLAS InSAR processing chain:

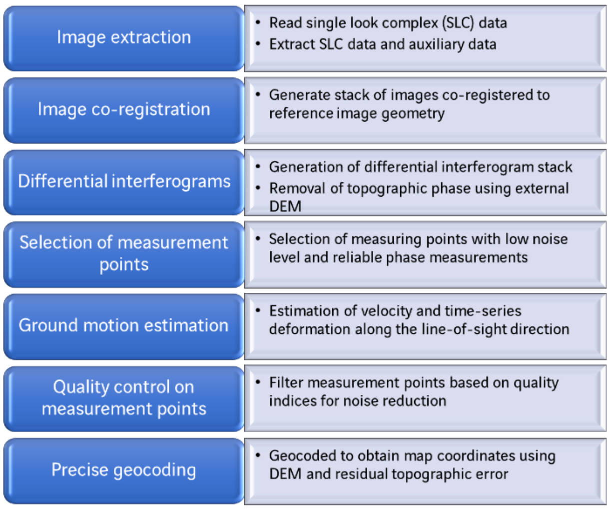


Figure 2. Workflow in SAR Interferometry

Figure 2 shows the InSAR methodology applied in this study. The processing is made with SAR images from the TerraSAR-X satellite on StripMap mode. StripMap mode offers a spatial resolution of only 3x3 meters. This is very important to monitor deformation on assets and infrastructures and to provide large density of measurement points. TerraSAR-X acquires at X-band signal, which allows us to obtain very high sensitivity to ground movement, compared with other satellites that use longer wavelengths (C-band or L-band).

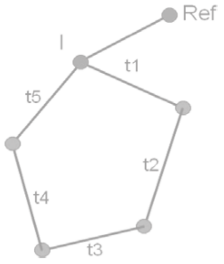
2.1.2. In-situ Method

In the construction of underground works, it is necessary to implement a system to contrast the projected with the reality of the terrain, for which it is necessary to have the help of topographic instrumentation to check whether the hypotheses made in the numerical calculations are reasonably in line with what is actually obtained.

On the other hand, the measurements obtained can allow the detection of possible instabilities that could affect both excavations and structures as well as nearby buildings. Topographic methods measure angles, distances and slopes, all with highly accurate equipment. It is basically a question of monitoring movements of structures (Δx, Δy, Δz) using Topographic Control Prisms and seating (movements exclusively in Z) through measurements with Topographic Levelling (Z) both on structures and on the ground through the installation of Levelling Milestones.

It is essential to have initial readings and data, prior to any action of the project (reading "0") that will allow the comparison of the successive data obtained in the reading campaigns (which can be manual or automated) and thus observe the evolution of these over time and the influence of the progress of the excavation on the surface and the structures. It is also necessary to have immovable reference points that must be located in stable areas.

Topographic (Z) levelling measurements, accurate to 0.01 mm. Itinerary or polygonal method. An itinerary or polygonal is carried out, which is nothing more than a chained succession of radiations. In this case, it is carried out by means of closed routes, starting and ending in an immovable Levelling Base of known coordinates in the vertical and which will serve as a reference (Ref) for the successive coordinates obtained from the points. At the end of the route, the coordinates obtained at the Base must be the same as those at the start.



For the data collection with Total Station a 1" (0.3 mgon),0.01" (0.01 mgon) precision equipment is used. The prisms are installed on structures and are used to measure horizontal and vertical displacements (seating and angular distortions). The prisms reflect the light sent by a measuring instrument and the variations in the position of the reflecting point are recorded over time. This makes it possible to evaluate the displacements and deformations of the structures on which they are installed. The Total Station has the function of measuring the set of prisms distributed over the area to be auscultated according to a previously established cycle of observations. Once each of the readings has been recorded, it sends the measurements, via the monitoring device, to a management center which processes and analyses the data, modifying, if necessary, the reading cycles and sending the new instructions to the Total Station via the same monitoring device. The results are compared according to previously established tolerances. In the event of movements greater than expected, the system generates a warning signal classifying the movement, according to the threshold reached, in green zone (expected movement), amber zone (movement increase alert) and red zone (alarm due to instability).

Table 1. SAR dataset used in this study.

Study Area	Satellite	Sensor	Orbit	Resolution	Study Period	No. of Images
Crossrail (London), UK	TerraSAR-X	StripMap	Descending	3 x 3 m	08/2013 ~ 11/2019	126
Thames tideway (London), UK	TerraSAR-X	StripMap	Descending	3 x 3 m	01/2014 ~ 12/2017	83
Porto Metro, Portugal	TerraSAR-X	StripMap	Ascending	3 x 3 m	07/2021 ~ 07/2022	19

3. Urban Tunnelling

Ground movements caused by major construction projects, such as tunneling have the potential of causing damage to overlying structures. This is even more probable when the project is done under or around heavily urbanized areas. In order for this to be measured it is necessary to understand not only the ground behavior before the start of the construction activity, but as well the structural behavior. The way that we will have this control is through monitoring techniques, and it should be carried out while the construction is being done, and after it’s finished until ground settlement due to construction activity has faced out. InSAR technique can overcome the limitations of traditional monitoring techniques by means of providing historical data measurements, wide area measurements without losing resolution over single structures, and providing measurements regularly after the end of the project.

ATLAS has been demonstrated to be useful in numerous construction work activities, in different work phase:

1) During the access shaft excavation phase, including potential dewatering. The satellite measurements cover a very large area of interest, much larger than the officially planned ZOI (Zone of Influence, outside which there should be no movement according to design, and outside which references are chosen for ground instruments). Dewatering activities have shown on different occasion, an impact over long distances, sometimes very unexpectedly. ATLAS measurements easily cover such large areas and can overcome the potential problem of loss of references for the ground instruments.
2) During tunneling, where satellite measurements are used again to check any widening of the settlement trough over and outside the planned ZOI, as a backup and verification of the ground instruments.
3) For litigation mitigation, by proving that areas outside the ZOI are not impacted, they are an extremely efficient tools against unjustified claims.

4) Upon termination of civil works, where satellite measurements provide a technically and financially efficient way of controlling long term stabilization of movements.

3.1. Crossrail UK

Crossrail is one of the major tunnelling projects done in a heavily urbanized area. It consisted in the construction of a new railway line which crosses Greater London from east to west, with five tunneled sections totaling up to 42 km in length (Figure 3). We acquired 126 scenes of TerraSAR-X images (Table 1) and the ATLAS processing chain were successfully applied to the project ATLAS InSAR applied to the Crossrail project have the following benefits: (a) a source of information for the ground/structure behavior before the start of the construction activity; (b) a complementary source of settlement data during construction; (c) a check for the long term movements, right after the end of the construction activity, or after many years if claims are raised in a later stage.

ATLAS InSAR measurements allowed to study the effects of dewatering activities, which usually result in settlement of the ground. Satellite measurements cover a very large area, which allowed to study a larger extent than the one initially planned, including zones in which there were no ground instruments results. This advantage of the InSAR technology was crucial to determine the total extension of the settlement due to dewatering activities, which reached a much wider extension than the area estimated at the design phase.

Additionally, InSAR results were used to check any widening of the settlement on the planned zone of interest, since tunnelling usually results in settlement movements associated to the loss of volume during the perforation phase. Figure 4 shows the deformation related to the tunnelling activities of the Crossrail project. The image shows deformations of more than 15 mm of subsidence during the period from August 2013 to November 2019.

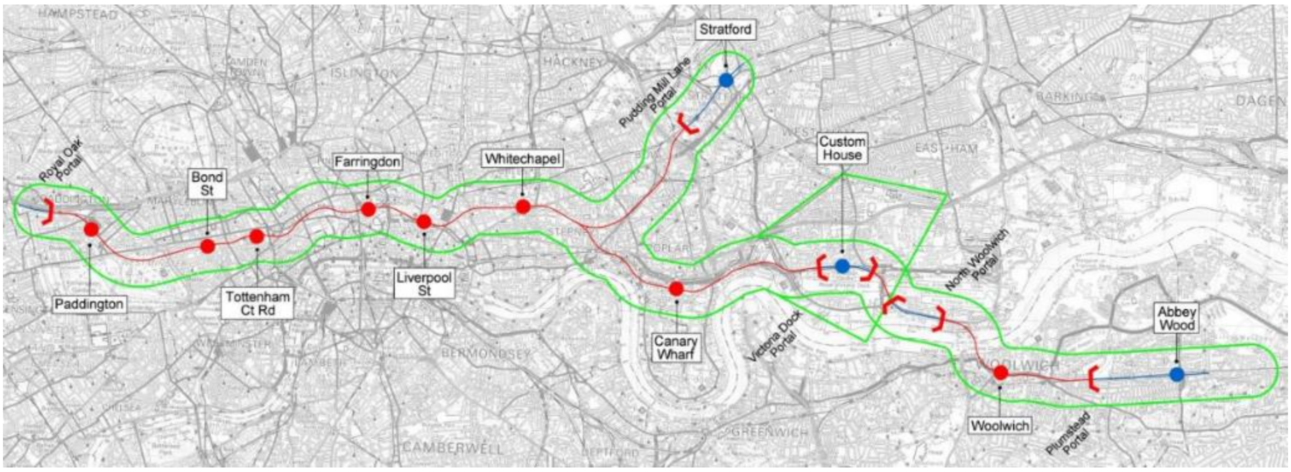


Figure 3. Crossrail Project, UK and the area of interest illustrated in green polygon.

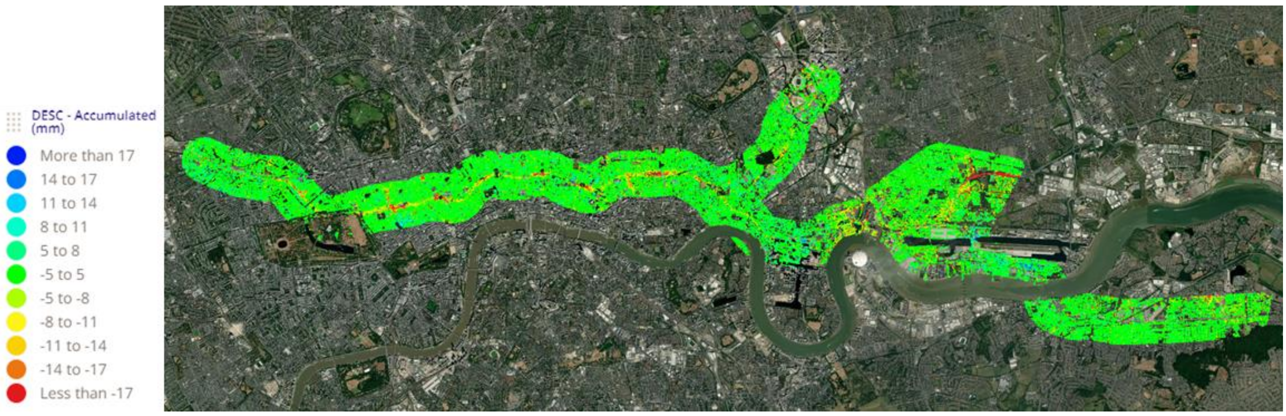


Figure 4. Displacement rate map along the Cross rail tunnel layout

3.2. Thames tideway Tunnel

The area of interest (AOI) to be monitored for this project covers the east section of Thames tideway tunnel project (Figure 5). The InSAR monitoring area covers approximately 11 km tunnel layout.

ATLAS InSAR monitoring was applied over the East tunnel alignment including a “corridor” of 500m on either side of the tunnel. The area of interest for this study covered the East section of the Thames Tideway Tunnel alignment over a distance of more than 5.5km, covering 2 separate tunnel drives between Bermondsey and Stratford, and Bermondsey and Greenwich (Scoular et al. 2020).

The ATLAS InSAR monitoring solution was successfully applied in the Thames Tideway East section. The baseline study has been derived by using 83 high-resolution TerraSAR-X images acquired in descending mode which have provided up to 147,126 measurement points (Figure 5).

The results were delivered through the Sixense’s Beyond Satellite web-based platform that enables the integration between ATLAS InSAR data and classic monitoring methods.

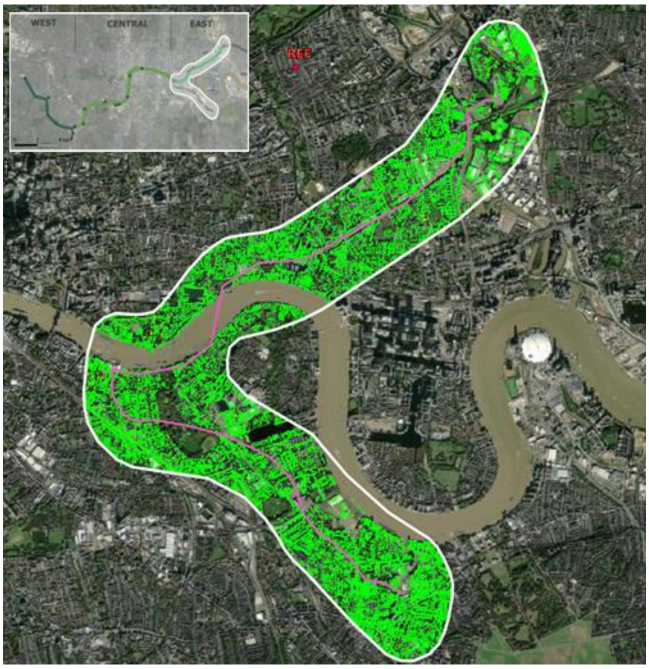


Figure 5. Thames Tideway Project and the area of interest in the East section.

3.3. Porto Metro, Portugal

The expansion of the Porto metro in Portugal is a real urban development project and will bring the various cities of Greater Porto closer together. Sixense deployed rigorous in-situ monitoring and conducted InSAR monitoring of infrastructures in this metro line. We applied ATLAS InSAR technology to this metro line project using 19 scenes of TerraSAR-X satellite during the period of 07/2021 – 07/2022 (Table 1).

The total area monitored in this study is about 3.7km^2 and we have obtained good density of measurement points which are identified as PS points (57.115 PS/Km^2).

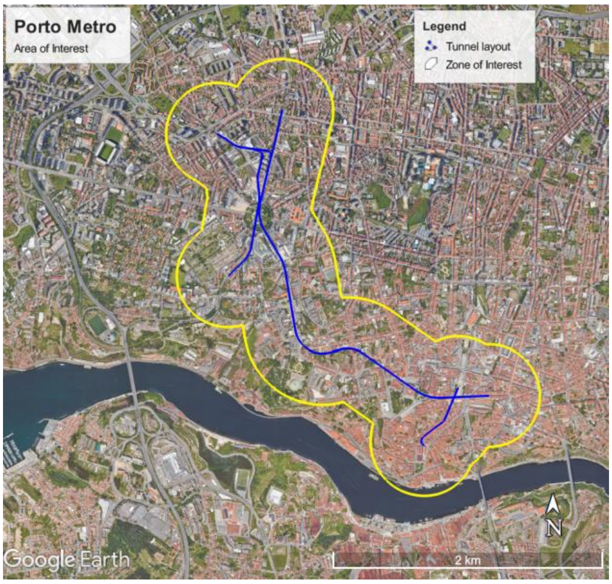


Figure 6. Study area: Porto Metro, Portugal

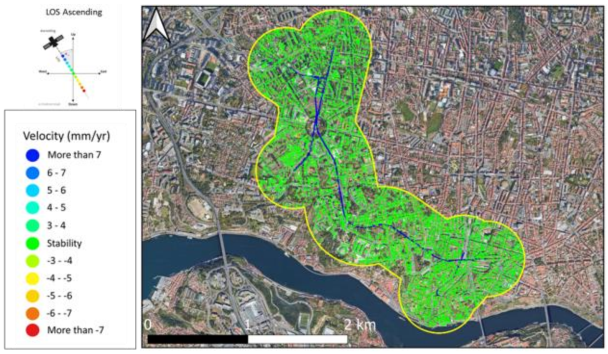


Figure 7. Displacement rate map along the Porto metro tunnel layout

The results generally show stability. There are areas of subsidence near the tunnel layout, and some of these having been detected by in situ instrumentation. The deformation results from InSAR and in-situ leveling are presented in Figure 8 and Figure 9. The area showed stability for a period and the subsidence was detected near Sant Antonio station hospital and Liberty station. ATLAS InSAR has proven to be an effective tool in the detection and measurement of deformation zones, capable of providing valuable information for decision making. Also, it is found that X-band images have been shown to be appropriate for monitoring the PORTO circular Metro extension project.

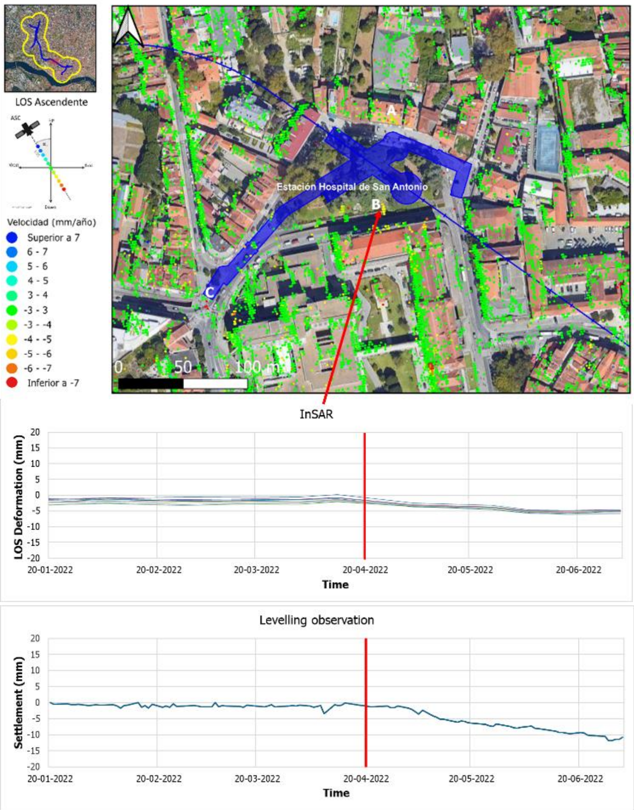


Figure 8. Deformation due to dewatering at Sant Antonio station hospital: InSAR vs Leveling.

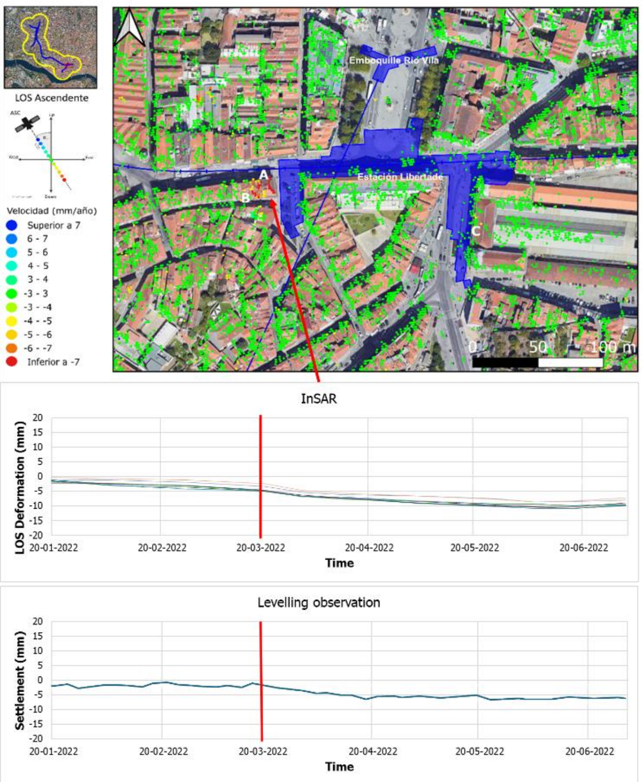


Figure 9. Deformation due to dewatering at Liberty station: InSAR vs Leveling.

4. Conclusions

In conclusion, this study highlights the importance of using a combination of technologies for tunnel monitoring in urban environments. The findings have significant implications for the planning and management of underground construction projects, contributing to enhancing the safety and efficiency of these vital urban infrastructures.

ATLAS Synthetic Aperture Radar Interferometry (InSAR) is a remote sensing technique, which uses radar satellite-acquired images, which has proven to be a suitable monitoring technique in the field of civil engineering. In this paper, ATLAS processing chain has been presented and three different case applications in two major cities London and Portugal, have been shown. In Portugal, it has been monitored the metro tunnel with high-resolution TerraSAR-X imagery from July 2021 to July 2022 using ATLAS InSAR. Velocity of deformation maps and deformation time series have been shown for infrastructure monitoring, more precisely road monitoring. The maps exposed above illustrate the advantages provided by the InSAR technique. In the Crossrail tunnelling activities, in London, 42 km of tunnel alignment have been monitored with ATLAS InSAR using high-resolution TerraSAR-X imagery from August 2013 to November 2019. Velocity of deformation maps and deformation time series showing settlement in the tunnel length and dewatering areas show how the technique was used for monitoring while the construction activities were ongoing and is still used during the post-construction stage.

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