Radar interferometry as an innovative solution for monitoring the construction of the Grand Paris Express metro network – First results

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ABSTRACT

The Grand Paris Express (GPE) is an unprecedented urban development project centred on a major expansion of the existing public transport network for the whole Paris metropolitan area. Overall, 68 new stations and 200 km of metro lines will be gradually put into service. Among numerous aspects, the project is driven by risk management and neighbourhood disturbance reduction. These considerations play a key role in the design and the construction process and monitoring is a major part of the contractors' missions.

Among the monitoring methods implemented in the framework of the project, there is an innovative technology, Synthetic Aperture Radar Interferometry or InSAR. This technique, deployed over the 200 km of metro line during the construction, is based on the use of SqueeSAR™, a processing chain and proprietary multi-interferogram technique developed and patented by TRE ALTAMIRA.

Key Words: Grand Paris Express, SAR Interferometry, satellite, monitoring, Line 15 South.

1. THE GRAND PARIS EXPRESS PROJECT FRAMEWORK

Grand Paris Express is arguably the largest transport project in Europe. It consists of a fundamental rethink and redesign of the public transport network for the entire Paris metropolitan area.

With 68 new stations and 200 kilometres of additional tracks, the Grand Paris Express network includes of a ring route around Paris (Line 15) and lines connecting developing neighbourhoods (Lines 16, 17 and 18). The routes of the project are shown in Figure 1; the plan also involves the extension of existing metro lines.

Construction work began mid-June 2016 and is intended to last almost until 2030. As a development project on the scale of the whole metropolis, GPE involves the creation of numerous construction sites. Most of the work is carried out in dense urban areas and is based on the use of complex underground drilling techniques. Among numerous aspects, the project is driven by risk management and mitigation; and those aspects play a key role in the design and the construction process.

The Société du Grand Paris (SGP) is the public agency set up by the French government in 2010 to deliver the vision of Grand Paris Express. It leads operations related to the construction of the new lines, stations, structures and facilities, acquisition of rolling stock for the infrastructure and development within and around the stations.

From project conception to the execution of the Grand Paris Express, the SGP relies on specialized companies that support it in its role of project owner. In particular TRE ALTAMIRA was commissioned by the Société du Grand Paris to monitor the impact of the civil engineering operations along its track and the adjacent areas. This is done from space with a precision to the nearest millimetre. The methodology, which is based on the use of the SqueeSAR™ algorithm, the proprietary multi-interferogram technique patented by TRE ALTAMIRA, is used to monitor, without any in-situ instrumentation, the slightest movement of the ground within a kilometre buffer zone centred on the tunnelling routes.

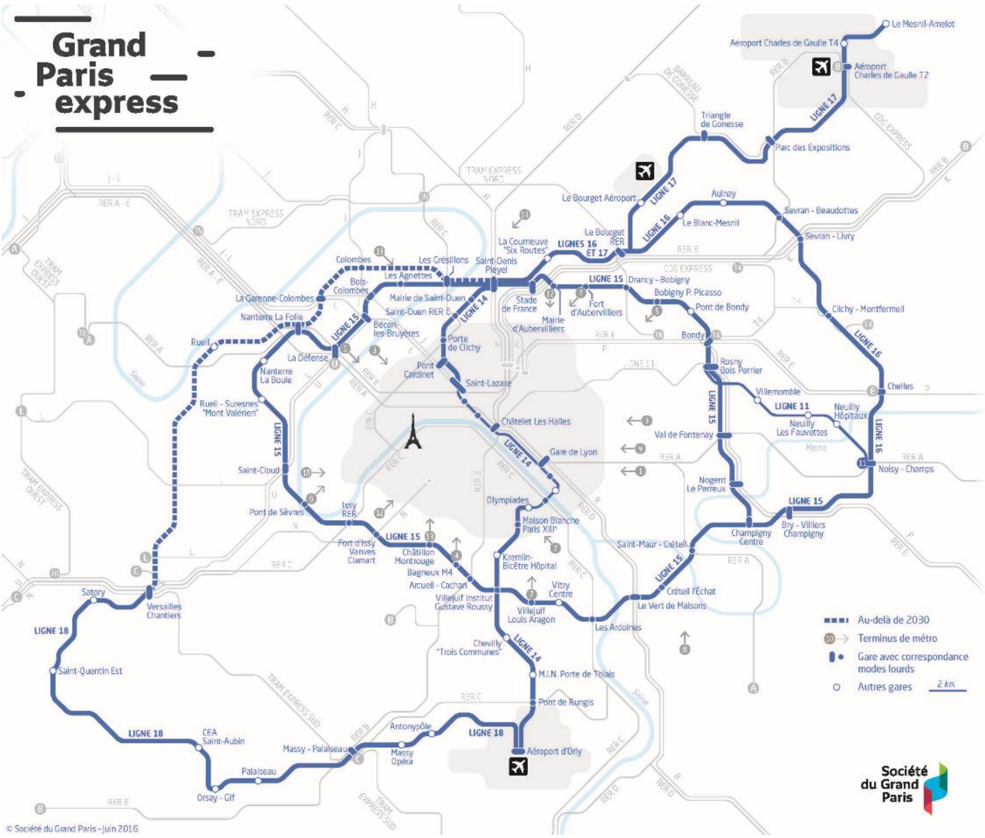


Figure 1. Grand Paris Express routes (Source : Société du Grand Paris)

2. SAR INTERFEROMETRY FOR GROUND MOTION MEASUREMENTS

2.1 SqueeSAR™, an advanced InSAR chain

InSAR technology (Interferometric Synthetic Aperture Radar) detects ground motion with millimetric precision. Synthetic Aperture Radars are high resolution radar satellite systems and “Interferometric” refers to the superimposition of radar waves to detect differences through time. Radar satellite images record the precise distance travelled by the radar signal between emission and reception. Therefore, when the ground-to-satellite distance is compared through time, InSAR technology can provide highly accurate ground deformation measurements.

TRE ALTAMIRA, the largest InSAR group worldwide and part of the Collecte Localisation Satellite (CLS) Group, has developed an advanced interferometric chain which is able to process radar images to obtain millimetric measurements. The technique has been refined throughout the last decade and has become the industry standard in InSAR deformation monitoring services.

SqueeSAR™ provides highly precise measurements of ground displacement by processing multi-temporal radar satellite images acquired over the same area. Since its introduction in 2010, SqueeSAR™ has challenged the industry standard by identifying many more reliable measurement points, hence increasing the overall understanding of ground displacement occurring in an area of interest. The technique requires a dataset of at least 15-20 SAR images, acquired over the same area with the same acquisition mode and geometry. By statistically exploiting the imagery, SqueeSAR™ singles out measurement points on the ground that display stable amplitude and coherent phases throughout every image of the dataset (Ferretti et al., 2011). The measurement points mainly belong to two different families, as illustrated in Figure 2 :

- Permanent Scatterers (PS): discrete radar targets characterized by highly stable radar signal return (e.g. buildings, rocky outcrops, linear structures, etc.),
- Distributed Scatterers (DS): patches of ground exhibiting a lower but homogenous radar signal return (e.g. uncultivated land, debris, desert areas, etc.).

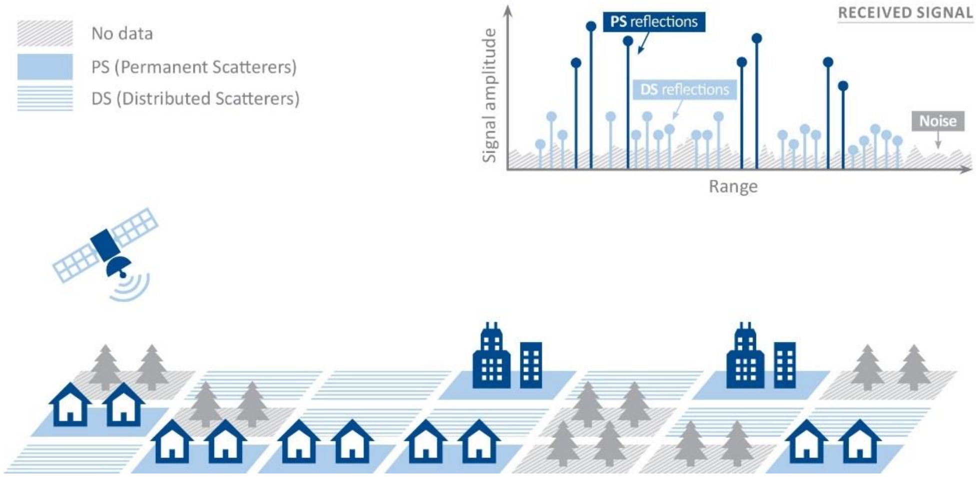


Figure 2. SqueeSAR™ analysis sketch

Radar satellites view the ground at an off-nadir angle that can vary between 20 - 50 degrees. Any ground deformation is therefore represented as 1-D movement either away from the satellite or towards it. The results are displayed in the form of a deformation map showing the magnitude of the measured movement. Information on deformation velocity is given in mm per year from the scale varying from red to blue, depending on the orientation and intensity of the movement. Each measurement point also contains a time dimension, in the form of a time series of deformation, which makes the investigation of localized deformation trends possible. Some examples will be shown below, mainly in the following section.

2.2 Results of the SqueeSAR^{TM} analyses of the GPE network

2.2.1 Historical ground motion study (1992-2015)

As part of the Grand Paris Express project, TRE ALTAMIRA carried out, as a first step, a retrospective study of the ground motion over the 200 km of the Grand Paris Express network. InSAR was applied to map historical ground motion and provide an extensive inventory of the soil surface behaviour from April 1992 to March 2015 (date of contract notification to TRE ALTAMIRA) and the identification of vulnerable structures before the start of any construction work.

The historical ground motion analysis was generated from the processing of satellite images acquired, on one hand, since the early 1990s to 2010 by the medium-resolution satellites missions (ERS and ENVISAT of the European Space Agency with 20 m resolution), and on the other hand, by high resolution satellites (COSMO-SkyMed of the Italian Space Agency and TerraSAR-X of the German Space Agency with 3 m resolution) over the more recent period 2011-2015.

In order to cover the entire Grand Paris Express network which extends over 38 km from West to East, the high-resolution satellite frames were spatially combined in order to exploit all available image archives. Figure 3 illustrates this coverage strategy; COSMO-SkyMed and TerraSAR-X frames are joined to image the entire GPE network extent.

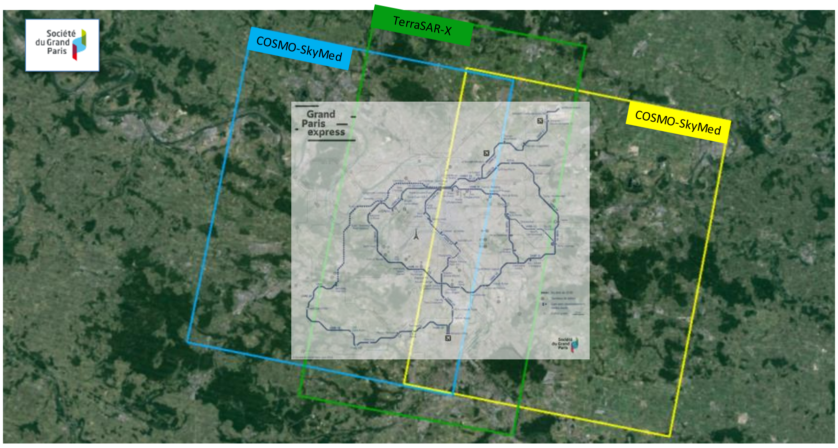


Figure 3. Coverage of the Grand Paris Express routes for the historical InSAR study

Thanks to the size of the satellite image, a buffer zone of 1 Km centred on the network route was analysed providing an exhaustive information of soil surface motion before and during works beyond the zone of geotechnical impact considered for the project. Figure 4 and Figure 5 show the ground motion rates computed from the analysis of ENVISAT and TerraSAR-X data over the Eastern section of Line 15 of the Grand Paris Express, respectively. The figures show that the use of high-resolution imagery has provided an important increase in measurement point density. The 3-metre resolution of the high-resolution data provided the possibility to conduct an analysis at the infrastructure level, while medium-resolution data provided an overview of regional deformation trends.

Figure 4. Ground motion study generated from the Envisat data SqueeSAR^{TM} analysis (2003-2010)

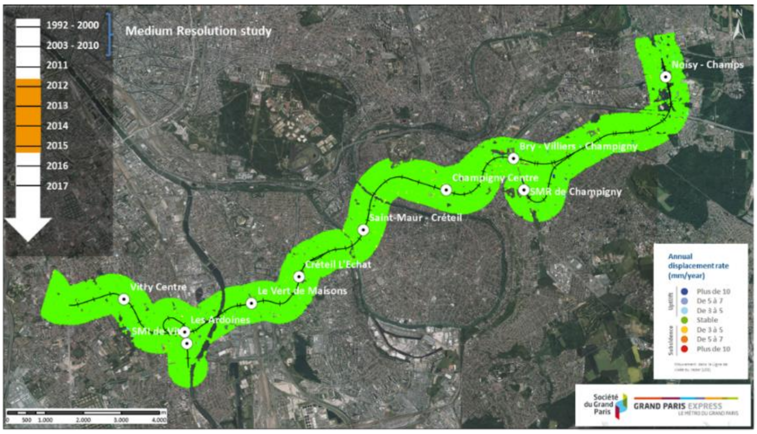


Figure 5. Ground motion study generated
from the TerraSAR-X data SqueeSAR^{TM} analysis (2011-2015)

This historical analysis has made it possible to create an inventory of the ground surface behaviour from April 1992 to March 2015, before the start of any construction work. In key areas where surface movements were detected, additional ground surveys have been or will be carried out if required to complement geological and geotechnical data.

2.2.2 Monitoring of the construction phase

As the first groundworks started in 2016 with the commencement of the construction Line 15 South, systematic satellite monitoring was initiated. The coverage of the area of interest is provided by the TerraSAR-X high-resolution satellite with an unrivalled measurement point density in an urban context (> 10,000 points/km²). This satellite offers measurements that are accurate to the millimetre, and is thus particularly suitable for detecting and measuring surface deformations related to the progression of the tunnel boring machine. Figure 6 shows the satellite frame coverage; data are also acquired since January 2017 with a new frame to cover the Eastern section of the GPE.

Monthly InSAR measurement updates based on 11-day image acquisitions complement in-situ real time auscultation by remotely monitoring a larger area.

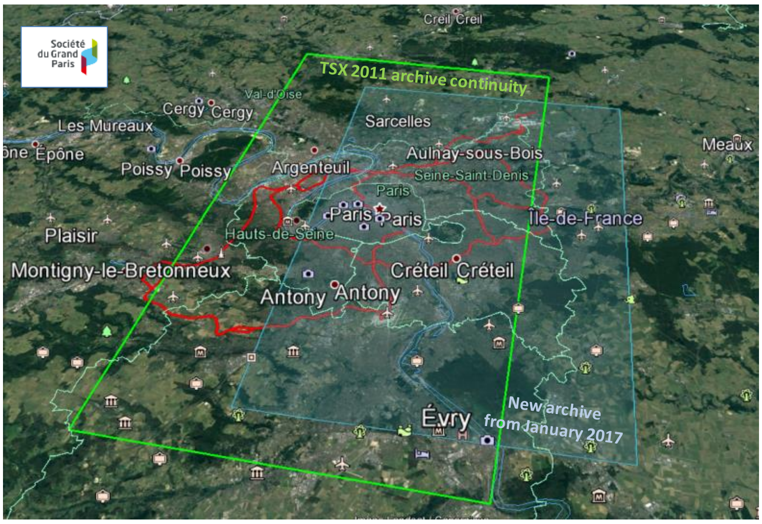


Figure 6. Grand Paris Express network satellite coverage for monitoring

Within the SqueeSAR^{TM} chain, TRE ALTAMIRA has developed methodologies that allow the evolution of nonlinear motion to be accurately monitored in space and time in urban areas. The methodology is based on the use of a sufficient acquisition sampling rate to be able to retrieve the different events in the evolution of the measurement point displacement (Ferretti et al., 2000) (Garcia et al., 2015). The time series of two measurement points located in a construction yard are shown in Figure 7. The strong settlement that occurred in September 2016 was successfully detected.

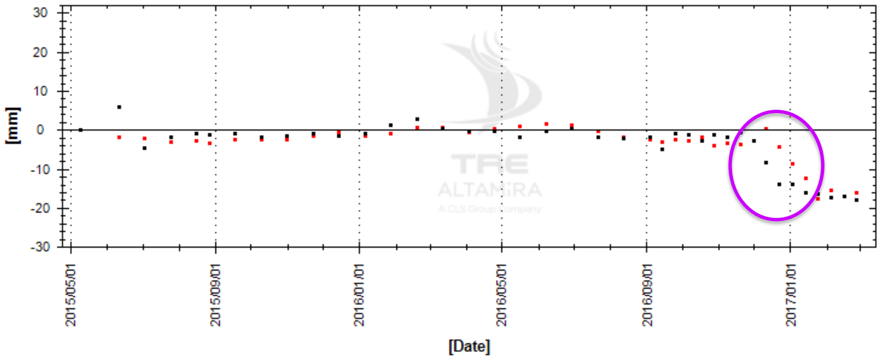


Figure 7. Time series of measurement points located in a construction zone

Furthermore, it is possible to combine the interferometric measurements with data provided by on-site auscultation (precision levelling measurements, inclinometers, etc.). The satellite-based information can be used to validate the stability of in-situ instrumentation reference points, to perform cross-calibrations by representing the data in the same system or even to simply compare the measurements. The two following sections present examples of how InSAR data can be further exploited by the project actors. Subsection 3.1 presents the use of historical data while monthly update data are considered in subsection 3.2 and compared with in-situ measurements.

It is furthermore worth mentioning that in the InSAR project framework, a turnkey tool for visualization and exploitation of the data is made available in order to facilitate access to the results to all the actors of the GPE project, e.g. contractor, prime contractors and civil engineering companies.

3. EXAMPLE OF EXPLOITATION OF THE RESULTS

3.1 Exploitation of the InSAR Historical results

Setec (www.setec.fr) is a leading provider of engineering services. The Company participating as the designer and construction manager of the western section of Line 15 of the Grand Paris Express project. The construction of this section of the GPE project started at the beginning of 2017 and is led by the CAP Consortium managed by Vinci. As part of their activities, Setec has analysed the historical results achieved by InSAR in order to better understand historical ground displacements in the project area.

3.1.1 Geologic context

The Line 15 project, and in particular the south-west section for which Setec is the main contractor, includes a tunnel of more than 12 kilometres in length (10 metres in diameter), 8 railway stations and a dozen ancillary ventilation / rescue access structures. Located in a highly urbanized area, works must be carried out while limiting disturbances to nearby areas.

In addition, half of the project’s path is located in a coarse limestone (construction stone) underground exploitation area (Figure 8). Those quarries, located at about 20- to 30-metre in depth and organised into different levels with an approximate thickness of 1 to 2 metres, were dug much before the start of urbanization using the "*hagues et bourrage*" technique. It consists of exploiting almost all the noble stone’s layers, filling the empty spaces (the “*bourrage*”) with earth or low-cost extraction wastes that will be held by walls of interlocked stones: the “hagues” (Figure 9). Over time, those retaining structures have deteriorated, often causing generalized settlements, or even in some cases collapses (sinkholes), which sometimes reach the surface. Since the 1960s, the Inspection Générale des Carrières (IGC, www.igc.fr), a department of the City of Paris, has been inspecting accessible quarries, keeping up-to-date maps of the historical exploitations; a portion of one of them is displayed in Figure 10.

Constrained by the presence of the exploitation and filling structures, the Grand Paris Express tunnel depth is about 40 m in order to avoid past quarries and prevent ground settlements. Moreover as shown in the Figure 8 profile, the tunnel passes under two fairly steep hillsides, usually covered with slopeslides.

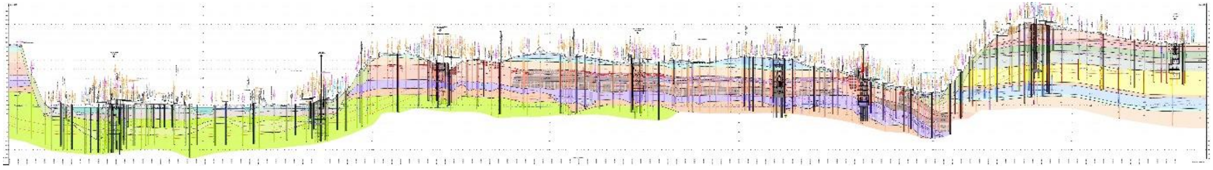


Figure 8. Geotechnical longitudinal profile of the project

Figure 9. Example of an accessible ceiling supported by pillars, walls and filling backfill

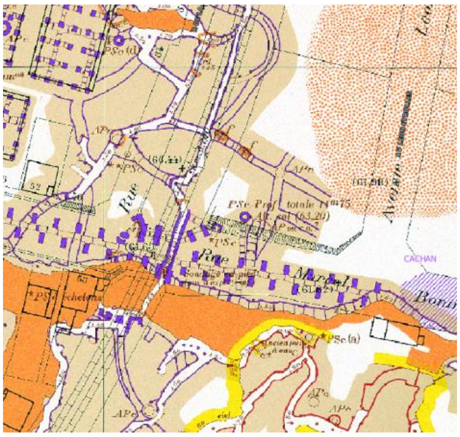


Figure 10. Quarries map of Paris

3.1.2 Analysis of historical InSAR results

Setec engineers set up some methodologies to take advantage of the interferometry results during the design phase. It was proposed that this "historical" data be considered in the same way that conventional geotechnical surveys provide input during the pre-project phases. The SqueeSAR^{TM} data were thus combined with historical maps and conventional geotechnical surveys to detect ground movements due to the evolution of quarry conditions or possible slope instability to provide an analysis of the state of pre-existing motion prior to the commencement of construction.

The study focused on the amplitude of the accumulated motion over time. For each measurement point, the analysis of time series shows during which period the displacement started, and identifies if and when these deformations stabilized. These observations were analysed along with existing geological and geotechnical knowledge in order to explain the cause of the motion, and to estimate their potential impact on the Line 15 project once the tunneling activities started.

A displacement map created by interpolating data between 1992 and 2010 is presented in Figure 11. Estimated displacements are colour-coded: from red for settlements (up to 100 millimeters over the 18-year study period) to dark blue for uplift (maximum 40 millimeters in 18 years). Figure 11 shows an area of significant settlements in the vicinity of the Line 15 tunnel route (zone 6). This settlement zone is superimposed on the quarry map at the level of a 19th and 20th century exploitation of Fontainebleau sand (Figure 12). Time series are drawn in Figure 13; the curves show that these settlements might not be stabilized. This is an example of an area of the project where special attention will be paid during the construction stage.

Figure 11. Interpretation by zones of interferometric results

Figure 12. Detail of area 6 of Figure 11 overlain on the quarry map

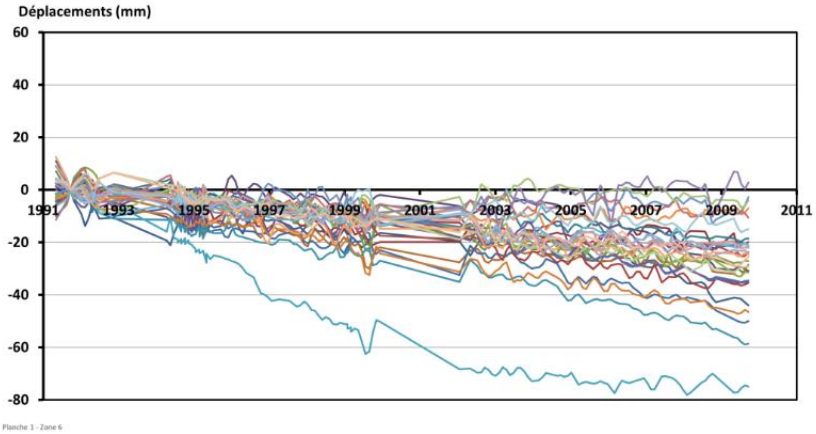


Figure 13. Cumulative displacements measured by interferometry, non-stabilized points

Interferometric monitoring is continuing during the construction phase, which in this section started with the backfilling injection of the quarries above the tunnel path, and with the construction of the retaining structures for the stations and works. These works can cause uplift or settlement under different structures or sensitive networks. For this reason all potentially impacted buildings are also subject to conventional surveying surveillance: topographic targets, tiltmeters, inclinometers etc. Interferometry provides additional consideration of the monitoring results.

3.2 Complementarity of InSAR and topography: survey of a sensitive building during civil works

In this section, the cross-correlation between topographic measurement and InSAR is illustrated. Civil work activities that have started in the vicinity of future stations may cause displacements of buildings or facilities; the most sensitive ones are selected during preliminary studies of risk analysis. These buildings are further monitored for the duration of the project to ensure that potential displacements do not surpass the defined tolerance limits.

The case of a historical building that has been identified by the design studies as potentially impacted by civil works is considered in this section. Further monitoring was thus required. GAusS Joint Venture, created by Dynaopt, Structure & Rehabilitation and Hyp-Arc, was appointed to assist the Line 15 South-East contracting owner to further monitor this infrastructure. Gauss led a topographic survey to measure the horizontal and vertical displacement several times throughout the day.

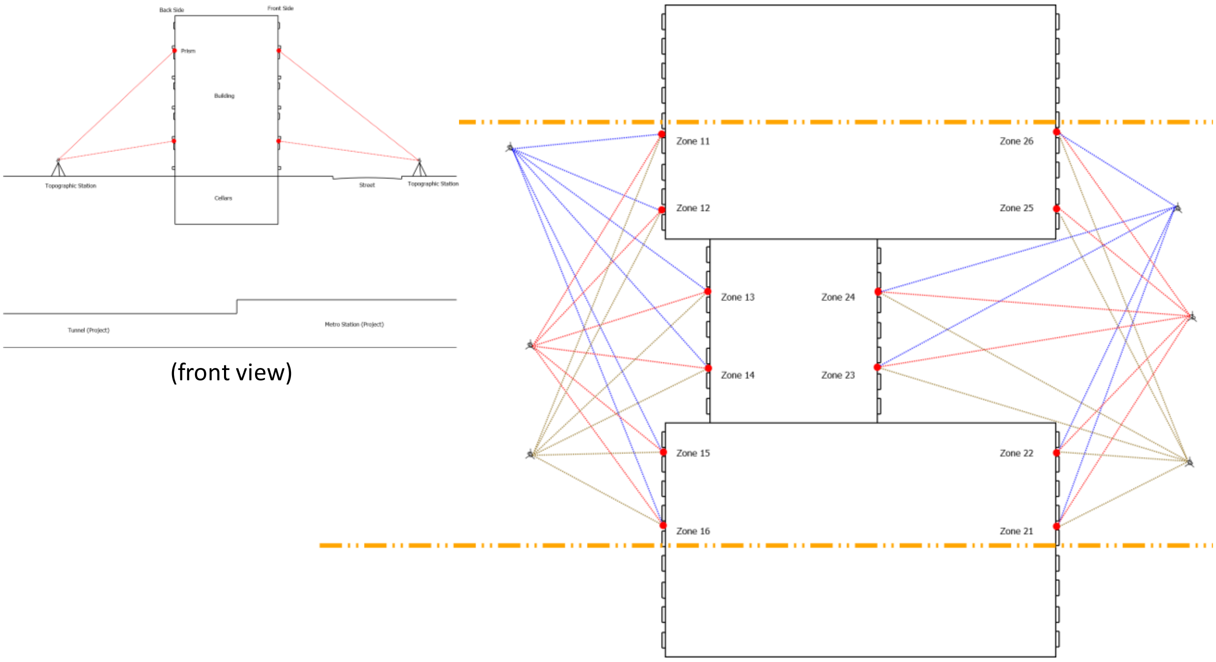
3.2.1 Characteristics of the topographic survey

This case study considers a multilevel masonry building. The preliminary studies revealed that this building was constructed in the 1930's on footing. The structure is built on two-level cellar. Overall, it is over in a good state. During the project preparation phase, some high-pressure injection has been done in order to compensate the previous settlement of the structure. An observational monitoring method is put in place to manage the work in real time. Several parameters are moreover taken into consideration such as the absolute, relative vertical and relative horizontal displacements and the motion velocity. An iterative decision-making process is thus designed and the injection parameters are modulated according to the observations.

An accuracy of 0.3 mm is required for the displacement measurements. The monitoring is based on the prisms installed by Société du Grand Paris that implemented preliminary topographic monitoring to observe natural displacements of the more sensitive buildings during a one-year period before the beginning of the excavations (Figure 14).

Figure 14. Constrained centring magnetic spherical prism and pin point target

A dozen pairs of prisms were installed on the building and located on the first and third floors of the structure as shown in Figure 15. This type of installation allows for the measurement of absolute displacements in the three directions; relative vertical and horizontal displacements can also be deduced.



(front view)

Figure 15. Multi station topometric measurement (Hyp Arc)

Figure 16 shows the measurements carried out from April 10th and July 12th, 2017. The measurements were taken three times per day. An uplift of almost 9 mm is measured for Building 2.

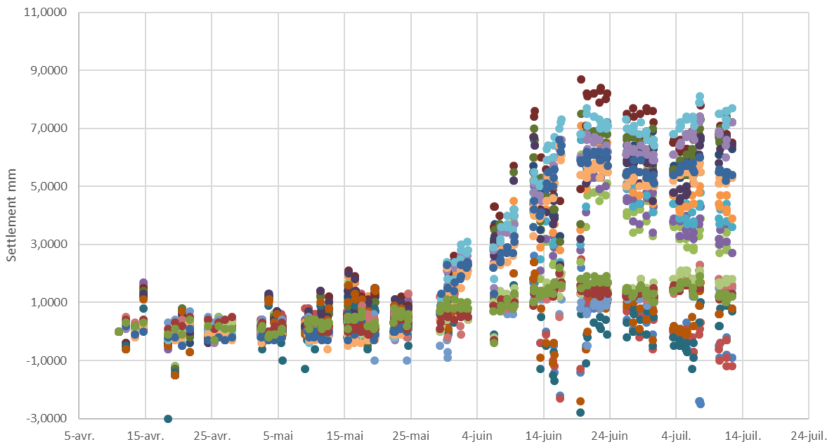


Figure 16. Topographic absolute measurement

3.2.2 *Topography and InSAR survey cross-analysis*

In order to correlate in-situ and InSAR measurements, topographic data has to be projected to the satellite Line of Sight (LOS) direction to have the same referential as the interferometric data. The Line of Sight (LOS) corresponds to the direction in which the satellite “looks” at the Earth’s surface; it is inclined with respect to the vertical direction. As illustrated in Figure 17 and Figure 18, what the satellite is able to detect is the projection of the real motion (see green vector in Figure 18) into the LOS plane.

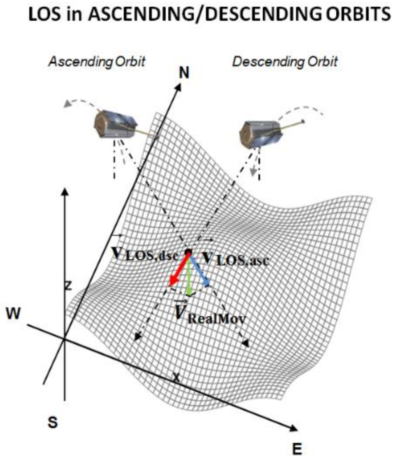
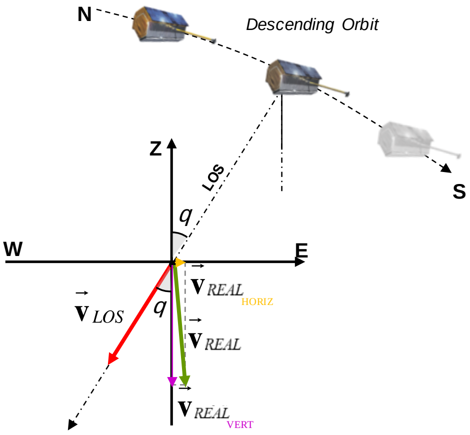


Figure 17. Actual motion (green vector) and geometrical sensibility in LOS of descending and ascending satellite passes (red and blue vectors, respectively)



$$|V_{LOS}| = |V_{REAL_{VERT}}| .\cos\theta$$

Figure 18. Projection of the in-situ data in the satellite geometry

As the slope is almost insignificant and the motion mainly occurs in the vertical dimension, taking into account an incidence angle, the in-situ data in Z has been referenced to put into a common reference and transformed into LOS as illustrated in Figure 18. The result of the comparison is shown in Figure 19 to Figure 21. The trends of both TS closely coincide and the motion induced by the injection is also detected applying interferometry. In Figure 19, the motion measured by topography is about 1 mm. This value is in the level of the precision of InSAR measurements as reflected by the slight variations of the InSAR data in the graph. In Figure 20 and Figure 21, the agreement is more evident as the detected motion is more significant.

Overall, this comparison sets a good reference value in order to demonstrate the agreement and accurate performance of both techniques.

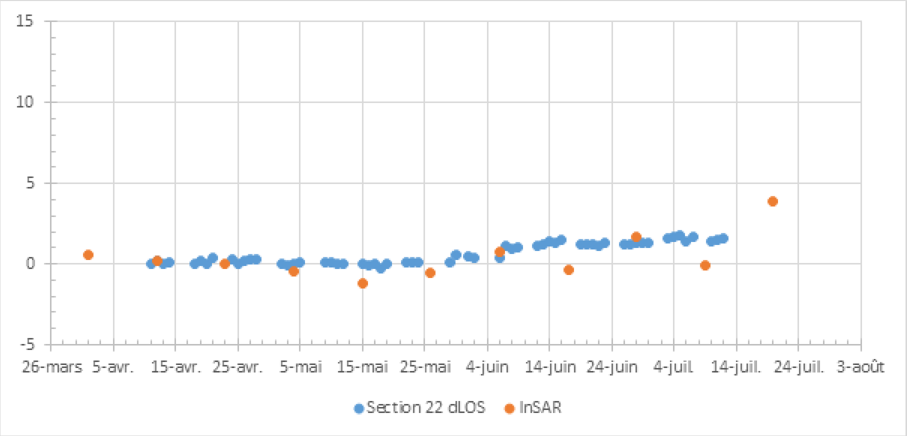


Figure 19. Comparison of topographic data and InSAR measurement in Zone 22 (Figure 15)

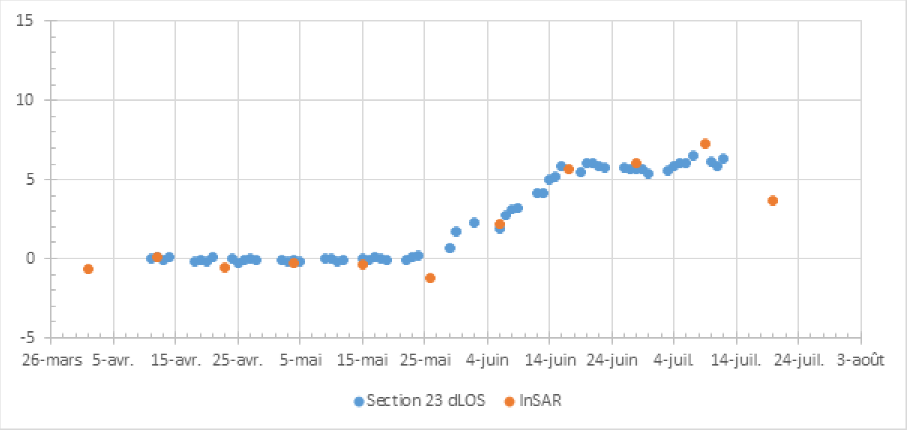


Figure 20. Comparison of topographic data and InSAR measurement in Zone 23 (Figure 15)

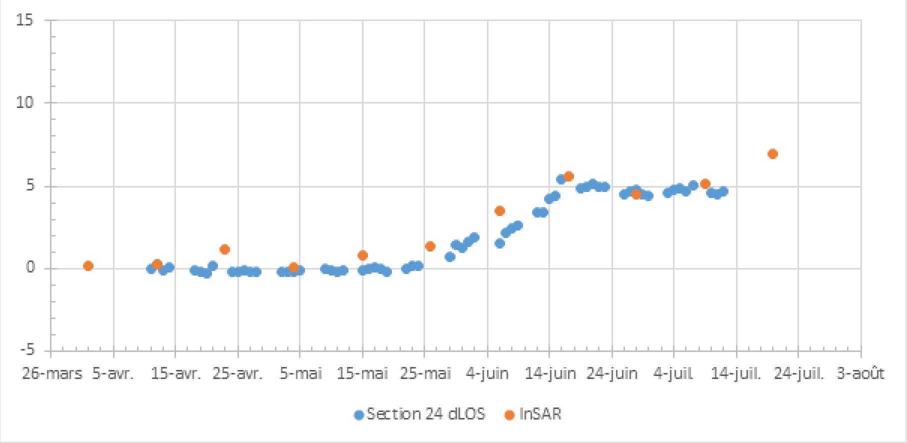


Figure 21. Comparison of topographic data and InSAR measurement in Zone 24 (Figure 15)

4. CONCLUSION

The analyses presented in this paper show the complementarity of the measurements collected by InSAR and in-situ instrumentation. InSAR is a cost-effective solution used to consider a large perimeter beyond the area of settlement induced by tunnelling works. The high density of measurement points obtained by this remote solution offers the possibility to measure surface deformation where in-situ auscultation instrumentation is not installed and is therefore complementary to these real-time alert systems which guarantee the safety of underground works. The temporal and spatial coverage offered by InSAR provides both historical data on the natural movements of buildings and surrounding ground, as well as an ongoing check of the stability of instrumentation reference points, which is fundamentally important information when sub-millimetric accuracy measurements are required. The increasing number of underground infrastructure projects that combine terrestrial and spatial solutions demonstrates that InSAR is now fully operational as a support to challenging tunnelling works.

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