SATELLITE INSAR TECHNIQUE FOR URBAN TUNNELLING MONITORING: THE CROSSRAIL PROJECT CASE STUDY

Nuria Devanthery, SIXENSE SATELLITE, *Av. Carrilet 219, 08907 L'Hospitalet de Llobregat, Barcelona, +34 (93) 263 29 69, nuria.devantheryarasa@sixense-group.com*

Javier González Martí, *CRL, Location 5A – 7, Crossrail 1-14 Liverpool Street, London, EC2M 7NH, 02031975460, javiergonzalez-marti@crossrail.co.uk*

Blanca Payas, SIXENSE SATELLITE, *Av. Carrilet 219, 08907 L'Hospitalet de Llobregat, Barcelona +34 (93) 263 29 69, blanca.payas@sixense-group.com*

Eric Audigé, SIXENSE OCEANIA, *22 St Kilda Road, St Kilda, VIC 3182 , +61 (0)3 9510 0582, eric.audige@sixense-group.com*

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 uses a stack of synthetic aperture radar images (SAR) to measure millimetric deformations of terrain structures over wide areas. This technique allows a comprehensive and periodic vision, without any need to access site, with the same accuracy as manual levelling in cities for a fraction of the cost of traditional systems.

Sixense has been using its interferometric processing chain, ATLAS, with the aim of monitoring geotechnical and structural deformations linked to urban construction, specially aimed at tunnelling monitoring, using the experiences in geotechnical and automatic surveying.

ATLAS processing chain was successfully applied to Crossrail I, The Elisabeth Line, in London. In this context InSAR has proved to be a fundamental tool to: (i) present the historical ground/structure behaviour before the start of any construction was presented, (ii) monitor the movements during the construction works covering a huge extension for just a fraction of the cost and resources of what should be expended in order to be done by more traditional approaches, and (iii) keep a monitoring system in place for the long term movement performance of ground and structures, even years after the end of the construction phase.

In this paper, the technique will be briefly detailed and the application case of the monitoring of the different phases of the project will be shown.

1 INTRODUCTION

In urban tunnelling projects, one of the major challenges is to guarantee that the different infrastructure assets crossing or adjacent to the tunnel alignment and other new build elements are not affected by the construction activity (in the short or long term). This can be difficult because for traditional monitoring a good deal of installation and preparation is required, often not allowing much time between the time the instrumentation is installed and commissioned and the start of the construction works, which might not give enough background data to determine and properly understand each assets' natural movement behaviour.

Satellite remote sensing techniques can overcome these limitations and bring some new advantages to tunnelling monitoring due to the availability of historical data, the wider area imaging that allow monitoring over extended areas (and not only locally), and no need to access site. Radar satellite interferometry (InSAR) is a non-invasive surveying remote sensing technique based on the exploitation of synthetic aperture radar images (SAR), which is able to measure millimetric motion of terrain structures over wide areas in both urban and non-urban environments. Moreover, the large size of satellite images provides detailed information about areas outside the area of interest. For any point, satellite time series enable the follow-up of phenomena every few days during the monitoring period.

InSAR comes with no (or very limited) installation costs, minimal health and safety risks, and of course maintains a similar monitoring accuracy to other manual systems. The use of InSAR techniques provides huge cost saving whilst maintaining all the technical/design requirements, since in terms of technical capabilities InSAR is entirely comparable with precise levelling. However, where the precise levelling is carried out in one specific area, and will only provide information in that area at a rate of around 100 points monitored per day, InSAR can provide more than 20,000 measurements points per km^2 in urbanised environments.

ATLAS Interferometry chain, has been developed with the aim of monitoring geotechnical and structural deformations linked to urban construction activities, specially aimed at tunnelling monitoring, using the experiences in geotechnical and automatic surveying. ATLAS has been used for measuring vertical ground and structure movements, specially to monitor ground settlement due to volume loss. Volume loss control is one of the main objectives in big tunnelling and excavation works on densely urbanized cities, where InSAR advantages complement more conventional approaches. ATLAS results can be integrated with other ground monitoring systems for global analysis.

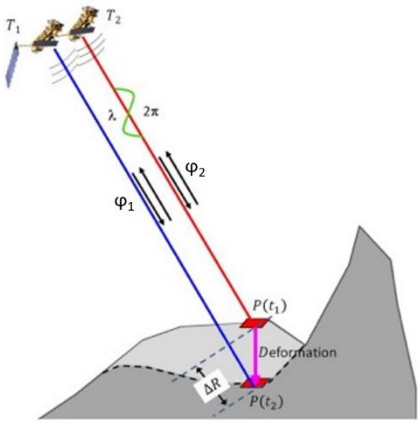
ATLAS InSAR processing chain has been successfully applied in the ground settlement monitoring of CROSSRAIL C704 in UK, one of the largest infrastructures construction projects in Europe. This project comprises the construction of a new railway line which crosses Greater London from east to west, with five tunnelled sections totalling up to 42 km in length. Crossrail area of interest has been monitored with ATLAS using a set of high-resolution TerraSAR-X images (radar interferometry satellite constellation), acquired over London from 01/08/2013. ATLAS provided the accumulated deformation maps and the displacement time series for a dense net of points over the area of interest, during the extended observation time period.

2 TUNNELING MONITORING FROM SPACE: ATLAS PROCESSING CHAIN

2.1 RADAR SATELLITE INTERFEROMETRY

Radar Satellite Interferometry (InSAR) is a non-invasive surveying technique which uses a stack of synthetic aperture radar images (SAR) to measure millimetric deformations of terrain structures over wide areas (Bamler and Hartl, 1998 and Rosen et al., 2000).

Satellite monitoring techniques are based on the exploitation of synthetic aperture radar images (SAR). A SAR image is a complex picture in the mathematical sense. It contains amplitude and phase information. Solutions based on radar interferometry (InSAR) use this phase information to compare two SAR images acquired over the same area at different dates, and compute ground displacements information on the radar waves travel time, as described in figure 1, by means of the interferometric phase (Φ_{int}).



$$\emptyset_{int} = \Delta\varphi = \varphi_2 - \varphi_1$$

$$\emptyset_{int} = \emptyset_{Displacement} + \emptyset_{Topography} + \emptyset_{Orbital} + \emptyset_{Atmosphere} + \emptyset_{Noise}$$

Figure 1: Working principle of InSAR technique

Persistent scatterer interferometry (PSI) technique (Ferretti, 2001 and 2001) takes conventional InSAR a step further to get millimetric precision on the ground motion readings, that is done by correcting atmospheric, orbital and topographic components of the interferometric phase (see figure 1). 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, called persistent scatterers (PS), are permanent highly 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. In fact, their position and density depend strongly on the characteristics of the studied area. The number of natural permanent scatterers is usually around 20,000 points per km^2 in urban areas and up to thousands of points per km^2 in rural areas when using high resolution images from the last generation of sensors.

2.2 ATLAS PROCESSING CHAIN

Sixense has developed its own treatment processing chain, ATLAS, around the core software GAMMA (Werner et al., 2003). ATLAS allows for measuring vertical ground and structure movements, with special attention to urban works and critical non-linear movements, on permanent scatterers with millimetric accuracy.

For each measurement point, the Atlas solution provides: maps of accumulated displacement along the study period; time series of deformation for each point monitored; mean deformation velocity of deformation, and quality indexes of the measurements.

ATLAS PSI uses more than 15/20 SAR images with atmospheric compensation to derive highly accurate elevation and average displacement rate values for each stable point. The high-level of error compensation allows the generation of time series charts, visualizing the evolution of the displacement of each stable point. Urban, semi-urban or rural areas can be studied in detail (both in terms of high spatial resolution and the historical variation of the displacement) over long time periods.

The processing steps (figure 2) are summarized as follows:

Image extraction: SAR data is read from the original media and all the auxiliary parameters are retrieved from the product annotations into ASCII auxiliary files.

Image selection: Analyse the set of available images, quality control is done at this stage to detect images with acquisition defects (images altered by satellite manoeuvres, erroneous annotation file parameters and severe weather conditions during the acquisition, etc.).

Image co-registration: A stack of images must be co-registered to a geometry. One image is selected as master and then all the other data is aligned to have a common geometry. Every pixel in all the images must contain the radar response coming from the same ground resolution cell.

Generation of differential interferograms: Selection and generation of interferometric pairs based on the acquisition time, perpendicular baseline and Doppler centroid difference of every image.

PS selection: Selection of the initial stable points (PS like pixels). That is to choose the pixels with low noise level to retrieve reliable measurements of phase. This initial selection is based on the analysis of the radiometric and the phase stability of each pixel in all dataset/stack.

Ground motion estimation: This procedure assesses the ground motion, the vertical height, the atmospheric contribution and the quality index, based on the model coherence performed during the model adjustment, for each pixel selected as PS.

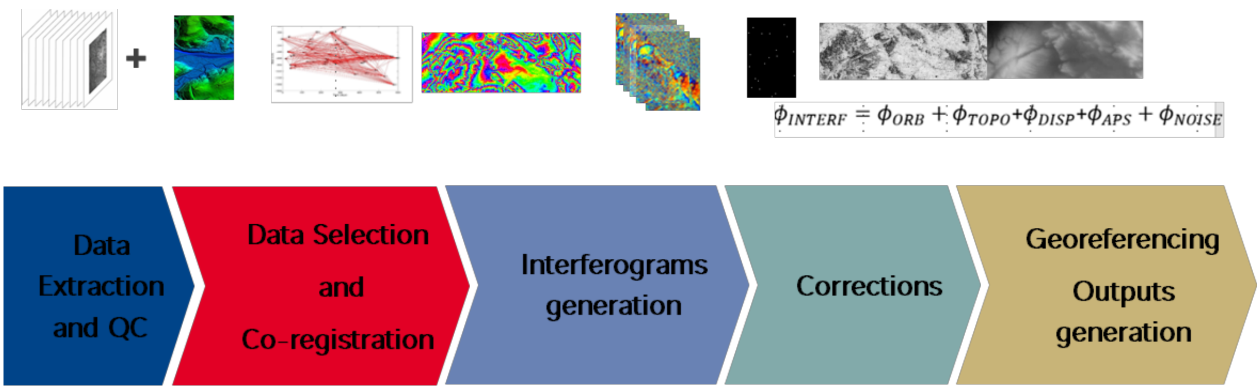


Figure 2: ATLAS processing steps scheme

3 CROSSRAIL MONITORING WITH ATLAS

CROSSRAIL C704, as one of the major tunnelling projects done in terms of impact in a heavily urbanised area consisting in the construction of a new railway line which crosses Greater London from east to west, with five tunnelled sections totalling up to 42 km in length, was the first one in implementing the InSAR technology as a non-intrusive technique to monitor the long-term movement in within the entire project extension. This came with a significant saving, but what is more important, it allowed the decommissioning of the physical instrument to be done in time while still monitoring the assets, and it prevented potential injures by using a monitoring system that was comparable to manual monitoring in terms of repetitivity, without having to have tenths of surveyor teams on site.

ATLAS was successfully applied to CROSSRAIL C704 using a set of high-resolution TerraSAR-X images (radar interferometry satellite constellation), acquired over London from 01/08/2013. The main uses of InSAR in CROSSRAIL have been: (a) a source of information for the ground/structure behaviour before the start of the construction activity; (b) a complementary source of settlement data, which could be considered as 'absolute' and in the same grid for the entire project, especially in big extension projects; (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 provided the accumulated deformation maps and the displacement time series for a dense net of points over the area of interest, during the extended observation time period, detecting: (i) the movements identified on the different ZOI and on tunnel sections, (ii) different seasonal effects on the area of interest, and (iii) subsidence and heave related to dewatering in different areas. In the following subsections, we will show the results of points (i) and (ii).

3.1 DEWATERING AROUND LIMMO/ CANARY WHARF AREA

Dewatering usually results in settlement as porewater pressures in the soil reduce. In this area historic pumping for the Canary Wharf development and the jubilee Line Extension suggested that approximately 1mm of settlement occurred for every 2 mm drawdown. 30m drawdown at Limmo (Figure 3) should therefore result in about 15mm of settlement at ground surface.

Figure 3: Limmo area while construction activity was taking place

For the Limmo shaft construction the lower aquifer level needed to be lowered by approximately 30m, later this pumping effort was reduced and other smaller pumping schemes were commissioned. The peak CROSSRAIL dewatering flow was 620l/sec from 37 wells in Jan 2014, and a peak flow radius to the 2m drawdown contour was 3.5 km. Figure 3 shows one of the active shafts at Limmo area, while the pumping was on-going. The shaft was necessary in order to access and build the SCL (Spray Concrete Lining) Tunnels.

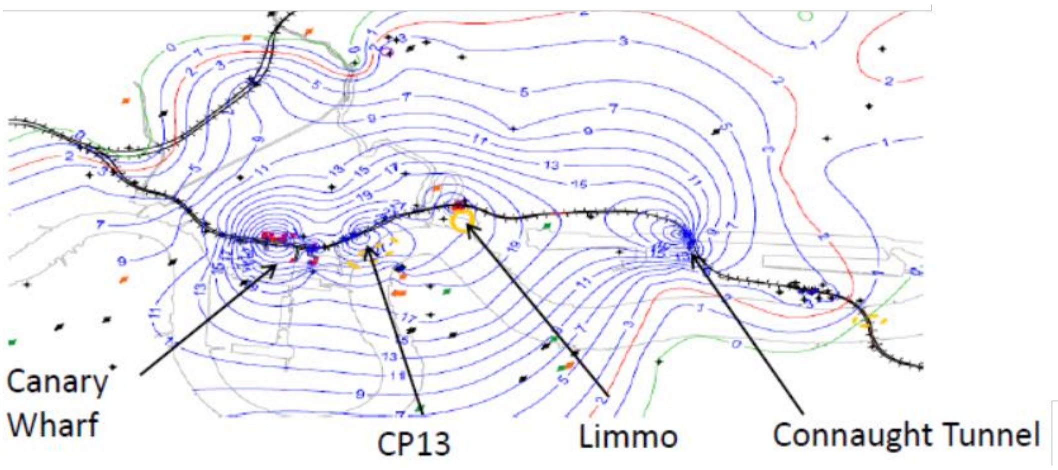


Figure 4: Ground settlement prediction due to dewatering

ATLAS was able to monitor the entire area exhaustively, much further away than originally predicted, and for a reasonable cost in a very unreliable ground were many other parties were working at the same time. The results were published internally in several papers, presentations, and even shared with other projects such as Lee Tunnel, which was affected by the dewatering.

Figure 4 shows the accumulated displacement map over Limmo area and its surroundings from August 2013 to March 2015. Yellow points show the shaft locations (CP13, CP14 and Limmo). The map is showing a big subsidence (in red and dark violet) reaching more than 30 mm since August 2013.

The tunnel alignment is highlighted and the map shows subsidence (in red and yellow) over it, related to the tunnelling activities. Moreover, the high density of measurement points available using InSAR, made possible the detection of a geological fault in the area that affected drastically the dewatering regime on either side of the fault (see dotted line in Figure 4).

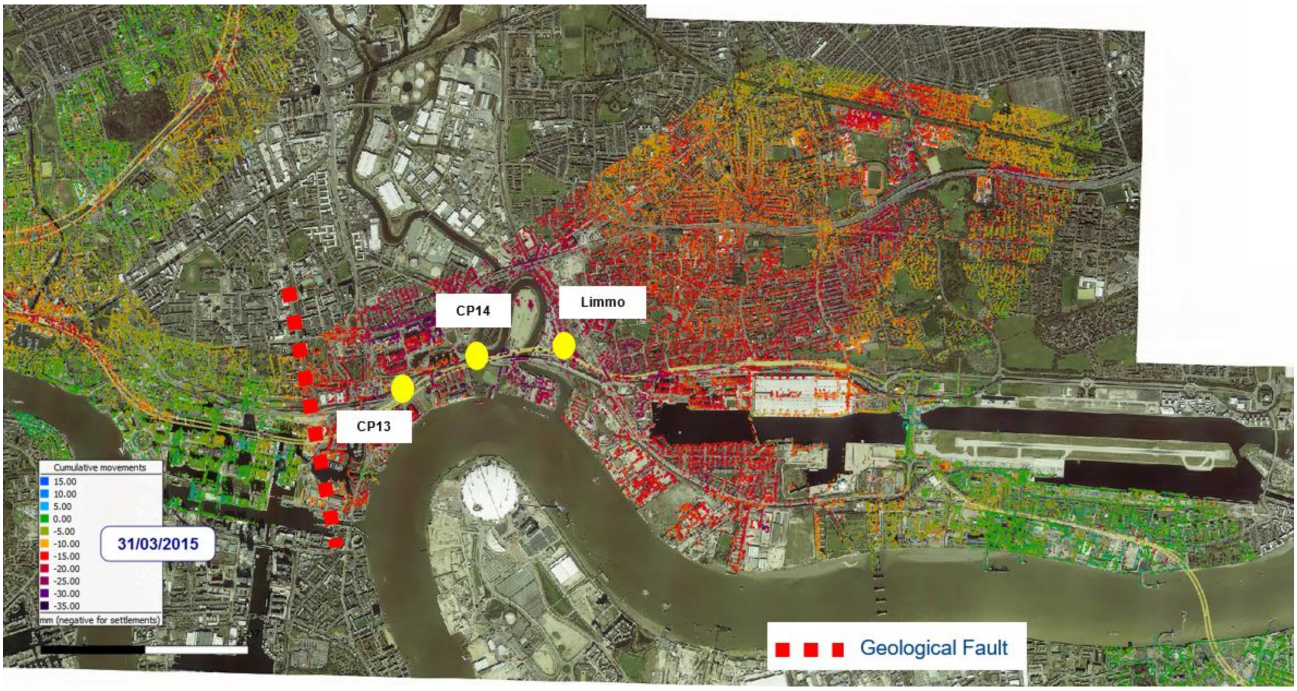


Figure 5: Ground settlement due to dewatering

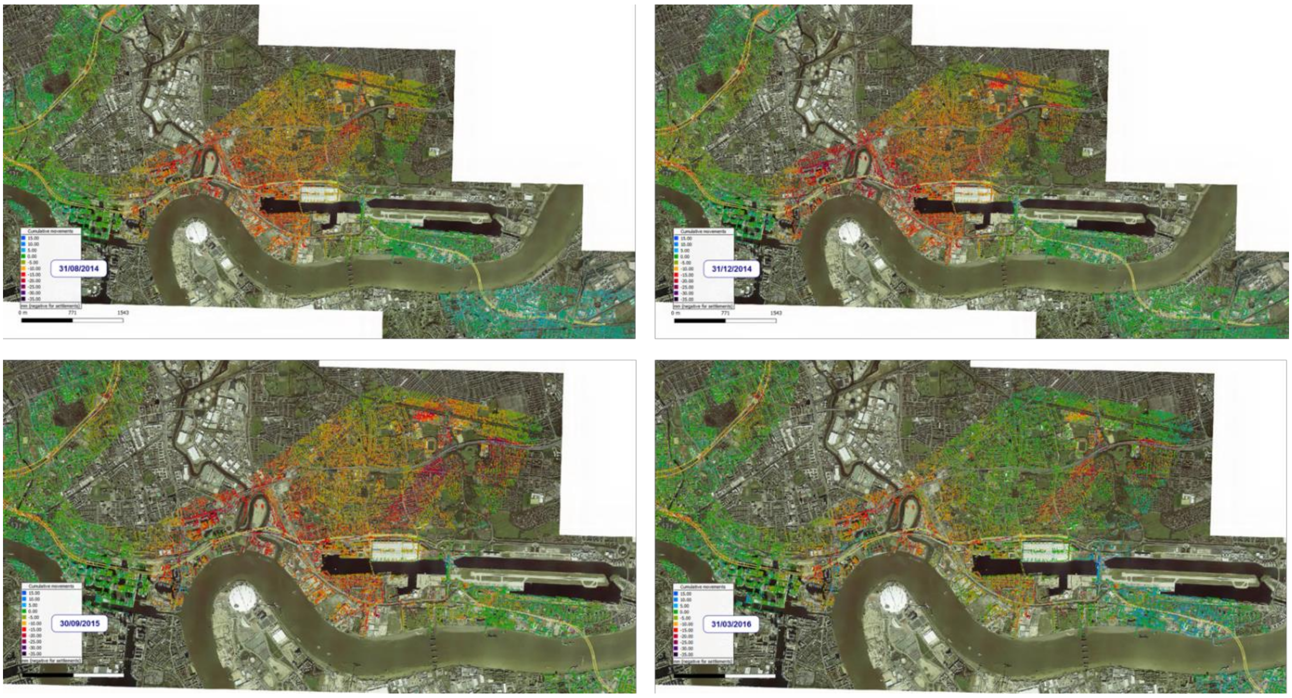


Figure 6: Ground settlement evolution due to dewatering

The evolution of the deformation measured in the area is depicted in Figure 6. The deformation map from August 2013 to August 2014 (upper-left), December 2014 (upper-right), September 2015 (bottom-left) and March 2016 (bottom-right) show the maximum intensity of the subsidence around end of 2014, and a decreasing intensity since this period.

3.2 LONG TERM MOVEMENTS AT LIVERPOOL STREET, FINSBURY CIRCUS

The area around Liverpool Street has been one of the most complicated ones in the project, not only because of the many SCL tunnels and shafts to be fitted, but as well the variable ground conditions, and the massive buildings around the main shaft. Several years of ground treatment and compensation grouting while the excavation was being done were necessary. On the top of this, due to the many necessary works to be done, several projects needed to be working together, each of them with their own design in terms of ground settlement. Figure 7 shows the accumulated deformation map from August 2013 to June 2016 over Finsbury Circus area. The map shows subsidence up to more than 25 mm for 4 years (red to pink areas) coinciding with the tunnel alignment (depicted in yellow).

Figure 7. Recorded settlement at Finsbury Circus after almost 4 years of work

After more than 6 years of work, the tunnels were completed, and the new challenge was to demonstrate the ground stability, more commonly known as long term settlement. The pre-agreed according to the Crossrail Act was that there would not be more than 2mm per year once the construction will been finished. ATLAS gave assistance in several stages of the work:

(i) as a verification system to the more traditional ones, without taking in consideration splits in between the different contracts or contractors.

(ii) as a system to verify structural integrity. The huge properties around Finsbury Circus were divided in different data clusters and the data on those groups was analysed individually, and compared against the other monitoring systems. Figure 8a shows the accumulated deformation map from August 2013 to June 2016 over the area of maximum deformation, and Figure 8c shows the time series corresponding to each group of points (labelled with the number highlighted in the deformation maps from 1 to 8). The measured points show a behaviour tending to stability. InSAR outcome showed that the data coming from InSAR was comparable to the manual or automatic monitoring in place during the construction activity, as demonstrated in Figure 8b. Data coming from the area 1 of Figure 8a are depicted in the pink line, which show complete agreement with manual monitoring data (lines red and orange).

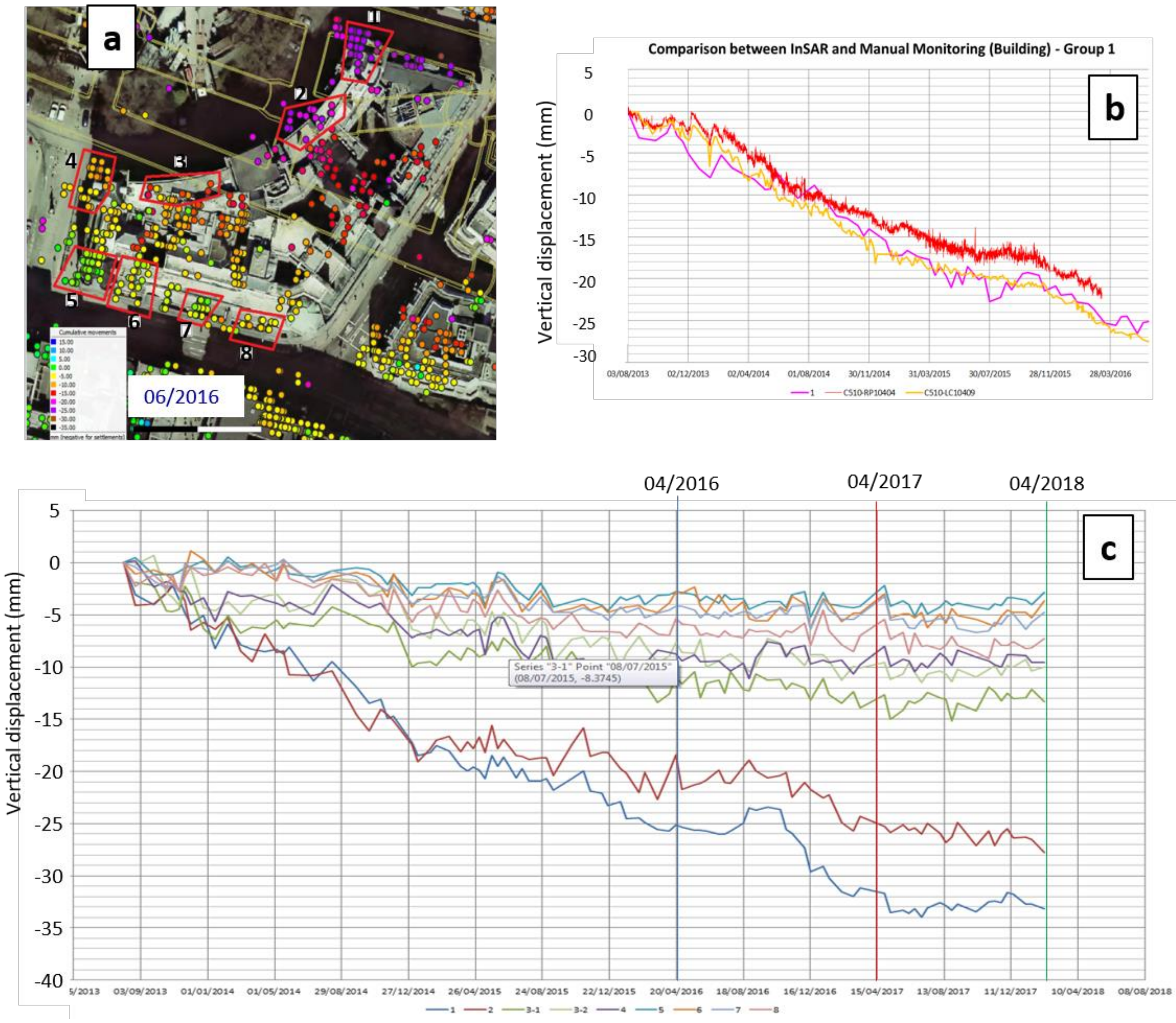


Figure 8. Recorded settlement at Finsbury Circus since August 2013

(iii) To be able to meet the key milestone of decommissioning and re-instatement of the specific equipment installed for the monitoring of the works, InSAR was used to assure the different stake holders that their assets were going to be monitored as long as necessary to prove ground and structure stability. It would provide the possibility of re-process images as well in years to come if an important volume of claims were to arrive.

4 CONCLUSIONS

Ground movements caused by major construction projects, such as tunnelling, have the potential of causing damage to overlying structures. This is even more probable when the project is done under or around heavily urbanised areas.

For this to be measured it is necessary to understand not only the ground behaviour before the start of the construction activity, but as well the structure behaviour. Synthetic Aperture Radar Interferometry (InSAR) has proven to be a suitable monitoring technique to monitor tunnelling activities. ATLAS, the Sixense's InSAR chain, has been and still is successfull to monitoring deformations related to CROSSRAIL activities, while the tunnelling activities were ongoing, and after they were finished until ground settlement will fade out.

In this paper, the results showing deformation maps related to dewatering in Canary Wharf and Limmo areas, and related to the tunnelling activities in Finsbury Circus have been presented, illustrating the advantages provided by the InSAR technique over big areas and a long period of time.

5 REFERENCES

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