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Innovative InSAR approach to tackle strong nonlinear time lapse ground motion

J García Robles *Altamira Information, Spain*

O Mora *Altamira Information, Spain*

B Salvá *Altamira Information, Spain*

Abstract

Persistent scatter interferometry (PSI) based algorithms are the conventional tools used to aid in the detection of constant ground motion in a set of radar images within a concrete time span. Despite the fact that slight variations in the ground motion trend exist, the conventional linear PSI technique, used on a regular basis worldwide, is able to retrieve these variations incorporating its contribution to the general linear trend of the time series (TS).

However, when the ground motion does not have linear dependence on time — for instance, in the case of different trends and even strong variations, such as the alternation of periods of heave and subsidence — the linear deformation model to differentiate/isolate the atmosphere is not applicable. This is because the linear method approach of decorrelation of atmosphere over time and its spatial correlation fails to comply. A new approach is therefore needed to be able to retrieve accurate measurements, irrespective of the motion being linear or nonlinear. With this new approach, a valuable, cost-effective technique to monitor motion either in civil engineering projects or in naturally occurring events with a nonlinear deformation pattern is provided.

The objective of this paper is to present a new approach to the conventional methodology in order to tackle the nonlinearity problem, not only for the cases where it is not possible to apply the conventional PSI, but also for those that may benefit from the application of this new nonlinear methodology accuracy of the TS, despite the longer processing time.

The methodology used to achieve this objective involves the use of conventional PSI algorithm techniques, combined with a nonlinear module which is based on the advanced differential Interferometric synthetic aperture radar (InSAR) technique with the aid of lineal-dependent models, such as error residual height (ERH) dependent on the spatial baseline of the satellite orbits and thermal compensation dependent on temperatures.

In this paper, a comparison between both techniques in the same case study and with the same radar acquisitions is presented. The area chosen as a case study is a zone of the City of London, an area where nonlinear motion, triggered by tunnelling works, has been clearly discerned. Lineal processing was shown to possibly underestimate or misestimate the ground motion detected in the TS in a nonlinear scenario, while the new methodology was able to reflect when exactly the area under study was stable and when the period of motion started.

1 Introduction

Satellite InSAR technology is used worldwide for mapping ground motion (Usai 1997; Arnaud et al. 2003). This technology is used for a broad range of projects in civil engineering, particularly for tunnelling projects. This mapping of ground motion is necessary for the monitoring of infrastructures during the different phases of tunnel construction, including planning, dewatering, tunnelling, construction of facilities like shafts, settlement and maintenance. Two examples of such motion mapping are the historical and current monitoring of ground motion on the Crossrail London railway construction project, and the historical and current monitoring of ground motion in Societé Grand Paris (SGP) underground metro project. Crossrail railway is among the most significant infrastructure projects ever undertaken in the UK, serving London and its environs by providing a new east–west route across Greater London. SGP is another ambitious project which aims to rebuild and reinvent the subway infrastructure of the whole city of Paris and outskirts.

PSIs are InSAR-based algorithms (Ferretti et al. 2001; Berardino et al. 2002; Thierry et al. 2005) used to aid in the detection of constant variation of ground motion in a set of radar images within a concrete time span with millimetric precision. When a stack of images is available, PSI algorithms are a very cost-effective way of monitoring motion in linear motion scenarios or with a low level of nonlinearity (Ferretti et al. 2000; Mora et al. 2003). However, when strong nonlinear components are affecting motion such as a combination of subsidence or heave in the same area, PSI must be combined with classical DInSAR in order to retrieve the occurred motion.

Classical Differential Interferometry SAR (DInSAR) in its initial definition refers to the unwrapped phase of an interferogram pair without compensating any pre-estimated model (Blanco-Sanchez et al. 2008). The limitation of classical DInSAR is that several effects are not possible to be removed only taking in account a single interferometry pair. These include temporal and spatial decorrelation effects, atmosphere disturbances (Hanssen 1998; Zebker & Rosen 1997) and external contributions besides the subsidence, such as the ERH and Thermal compactions and dilations. This sets the precision of the classical DInSAR technique to the order of centimetres.

This paper describes a new approach from the conventional methodology for detecting nonlinear motion and exemplifies it with a tunnelling case study in the City of London. London is affected by complex motion patterns caused by several effects both natural and man-made, making the combination of these advanced methodologies essential for true motion monitoring. This is an effective application for monitoring the impact of the progression of the tunnel boring machine in terms of ground motion, considering a non-linear motion scenario.

2 Methodology approach

In the advanced classical DInSAR technique, once the impact of topography is removed and the flat earth affect compensated, the phase component of these pairs, known as a differential interferogram, shows ground motion that occurred during the period between both acquisitions. The motion signal appears as phase fringes in interferograms, and the number of fringes depends on the magnitude of motion and on the satellite wavelength. In the case study presented, X-band satellites are considered, therefor one fringe corresponds to ground motion of approximately 1.5 cm. Slight motion generates spatially separated fringes, while motion that is occurring at a more accelerated rate, produces closer fringes. Figure 1 shows an example of an interferogram; the colour scale from blue to red represents values between $-\pi$ and $+\pi$ radians. The temporal study of a sequence of interferograms allows the detection of strong nonlinear patterns.

However, despite the potential detection of nonlinear motion with classical DInSAR, the accuracy and precision of the technique is centrimetric and depends on decorrelation phenomena such as geometrical and temporal decorrelation, the spatial baseline of both acquisitions, and the difference of temperature and atmosphere features of both acquisition dates.

In classical DInSAR, the geometrical and temporal decorrelations cannot be corrected as they are fixed and intrinsic both to the acquisition dates and the satellite-pair geometry. Nevertheless, the atmosphere correction and the external contribution effects can be corrected with a larger stack of inteferograms. Advanced classical DInSAR takes advantage of pre-estimated models such as ERH compensation and Thermal compensation, aiming to improve the precision of the classical DInSAR and transforms it to a product between conventional PSI and the raw interferometry.

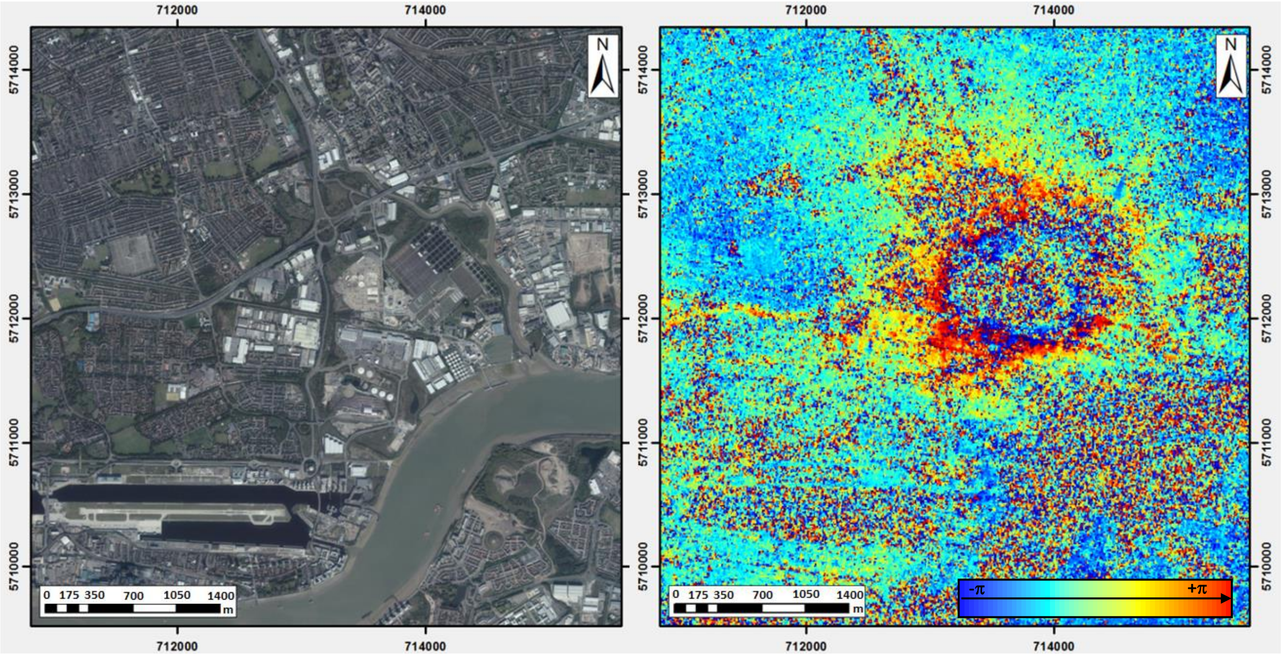


Figure 1 Example of interferogram between 21014 CSK-1 acquisition on 26 April 2011 and 17459 CSK-3 acquisition on 16 January 2012, over a nonlinear ground motion area in London related with a sewage tunnel construction

The radar phase is affected by delays in the signal propagation caused by the atmosphere (troposphere and ionosphere). In regular linear PSI case studies, these perturbations are solved thanks to the fact that the stack of radar images is acquired in different atmospheric conditions (Hanssen 1998; Zebker & Rosen 1997), contrary to the motion which has time dependence. This random statistical feature of the atmospheric behaviour allows for the removal of atmospheric effects in a linear conventional PSI methodology via a regular process, but does not work when the trend of motion is strongly nonlinear. The second step involves the cancellation of the atmosphere component once the lineal deformation component has been removed from each interferogram pair. This is conducted using a low-pass filter in order to estimate the general variations of the atmosphere in the interferogram.

Thus, when the ground motion does not have linear dependence on time, the atmospheric phase screen cannot easily be discriminated from the nonlinear motion. The linear restrictions in finding the parameters of ground deformation models or the inaccuracy of the classical DInSAR is a compromise to be addressed. In order to provide a more accurate measurement in the case of nonlinear motion, the approach must be redefined to achieve more degrees of freedom in the whole system in the estimation of nonlinear ground motion, and its separation from the atmospheric contribution.

The new methodology used in this study, summarised in Figure 2, involves the use of conventional PSI algorithm techniques, combined with a nonlinear module which is based on the advanced Differential InSAR technique with the aid of lineal-dependent models, such as ERH, which is dependent on the spatial baseline of the satellite orbits, and thermal compensation which is dependent on an empiric model of temperatures in each acquisition. The aim of using these lineal-dependent models is to easily tackle the atmosphere phase screen (APS) estimation and improve the accuracy of the classical DInSAR technique and consequently measuring nonlinear motion with the same precision and accuracy as conventional PSI.

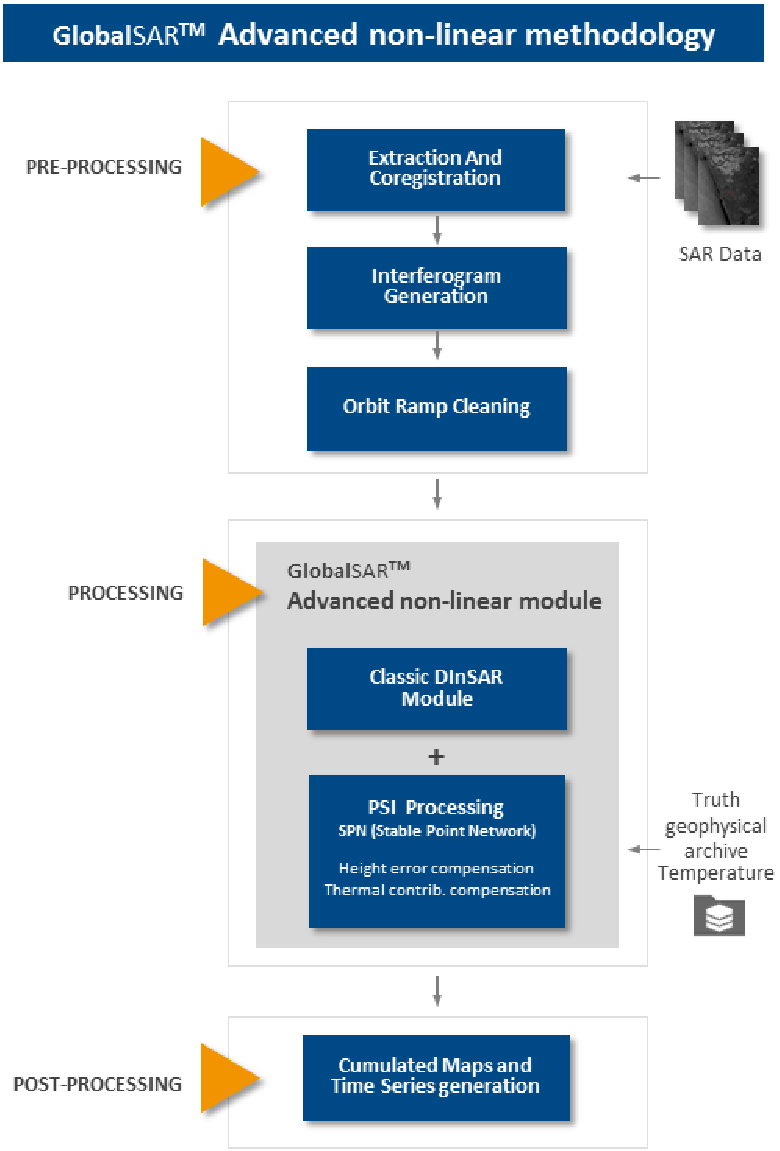
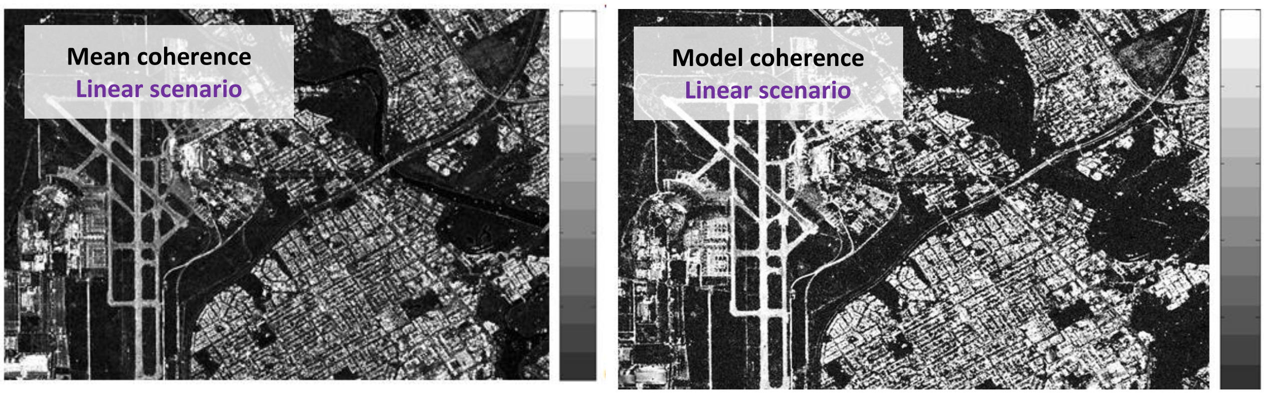


Figure 2 GlobalSAR^{TM} processing chain adapted to the new advanced nonlinear methodology designed by Altamira Information

Coherence is the most appropriate statistical indicator to check whether the studied area has nonlinear behaviour or not. There are two types of coherence indicators: the mean interferometric coherence, which is dependent on the spatial and temporal decorrelations but not in the nonlinearity of the motion; and the lineal deformation model coherence, which is dependent on how the evolution of the measurement phase is adapted to a particular deformation rate trend.

- Mean interferometric coherence — the coherence is a measure of the correlation of the phase information of two corresponding signals and varies in the range of 0 to 1. The degree of coherence can be used as a quality measure: coherence near 1 means the phase information is reliable (and the images have a high degree of correlation), whereas coherence < ~ 0.3 means the images have low correlation (noisy). In this case, the phase information is probably not useful.
- Lineal model deformation coherence — quality measure which relates to the millimetric measurement model (average annual displacement rate) fit. Values between 0 and 1, where 1 indicates best fit. The fitting quality depends on the characteristics of each processing, like the number of images used, the noise level of the measurement point and the reliability of the model fitting.

In Figure 3, a comparison between mean interferometric coherence and linear deformation model coherence is shown, whereas in Figure 4, it is obvious the diminution of the coherence value in the nonlinear case of a sewerage facility, which presented motion in Figure 1.



(a) (b)

Figure 3 Mean coherence (a) and lineal-model coherence (b) in a lineal scenario of an urban area close to an airport

In Figure 4, it is evident that the mean interferometric coherence shows high coherence level in an area where the model coherence shows lower values. This behaviour of the model coherence is typical in nonlinear ground motion areas.

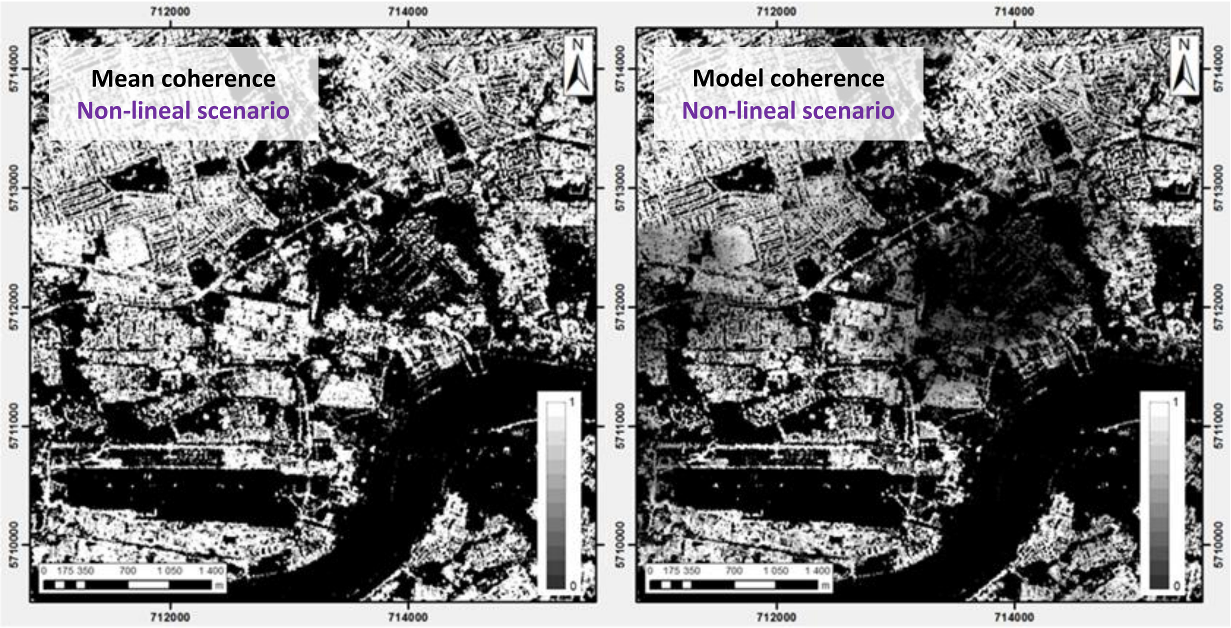


Figure 4 Mean interferometric coherence and lineal-model coherence on a sewerage tunnelling, reflecting nonlinear motion

Some general conclusions can be extracted analysing the comparison between both coherences in the lineal and nonlinear deformation cases:

- Either linear or nonlinear motion areas present high interferometric mean coherence for the full interferometric stack (see left plots on Figures 3 and 4).
- Nonlinear motion areas present low-model coherence in regular lineal velocity estimation (see right plot on Figure 4).

In order to retrieve the motion and discard other contributions in the phase such as the atmosphere phase screen, the latter has to be removed leaving only the contribution of the ground motion in the interferograms. Both coherences (model and mean interferometric coherence) can be compared to delimitate the nonlinear areas. These nonlinear ground motion areas must be isolated from the atmosphere estimation in order to avoid its contribution to the spatial atmosphere computation. After this step, the atmosphere is deducted using a set of reliable coherent points from the lineal ground motion areas. These points should be well spatial distributed in order to both estimate and interpolate accurately the atmosphere with temporal and spatial filters based on stochastic processes methods and image processing theory.

Figure 5 shows a stack of inteferograms of the study, but with the atmosphere disturbances removed. The green bar above the timeline refers to the time period of each interferogram. It is visible that the tunnelling started in the north part of the image sometime between August and the beginning of September 2012 and continued until the mid-2013, as it is obvious the path of the tunnel in the raw interferogram highlighted with the blue cyan colour. The colour scale from blue to red represents values between $-\pi$ and $+\pi$ radians. One complete phase fringe corresponds to displacement of 15 mm. Comparing the plots, the extension of the tunnelling path over time is becomes clear, thus it is clear the nonlinearity behaviour of the case study exposed in this paper.

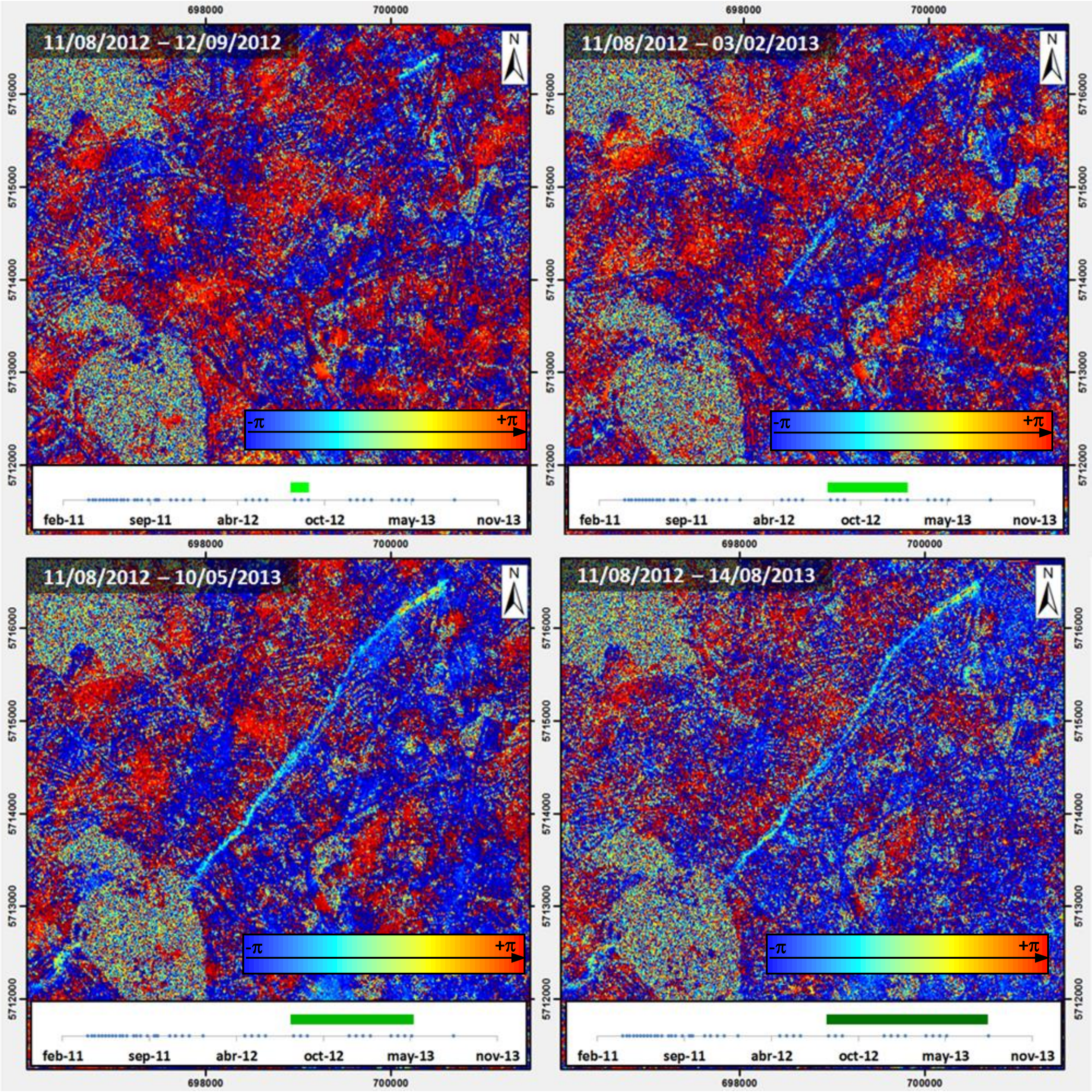


Figure 5 Evolution in time of four inteferograms with the same image in the beginning. The green bar above the timescale shows the timespan. Comparing the plots, the extension of the tunnelling path becomes clear

Constant modification of the ground surface because of activities such as construction work or position change of targets decreases the number of measurement points obtained. This decrease is directly related to the variation produced in the returned radar signal to the satellite in repeat passes. Such variation, known as temporal decorrelation, creates additional fluctuations of noise levels in the measurements and makes it difficult to produce consistent ground motion maps over these areas.

3 Data

The case study, shown in Figure 6, corresponds to the City of London, where a global study has been conducted. Subsidence was detected in the proximity of the underground track of London Power Tunnels (National Grid). In February 2011, the UK National Grid embarked upon a seven-year project to rewire the capital via deep underground tunnels, in order to meet increasing electricity demand and help London access the renewable energy of the future.

An historical motion study, which could assess the possible impact of the underground urban tunnelling on the city buildings and other infrastructures located on the surface above the track, was carried out. The selected area of interest corresponds to the St John's Wood and Hackney tunnelling and is marked with an orange square in Figure 6.

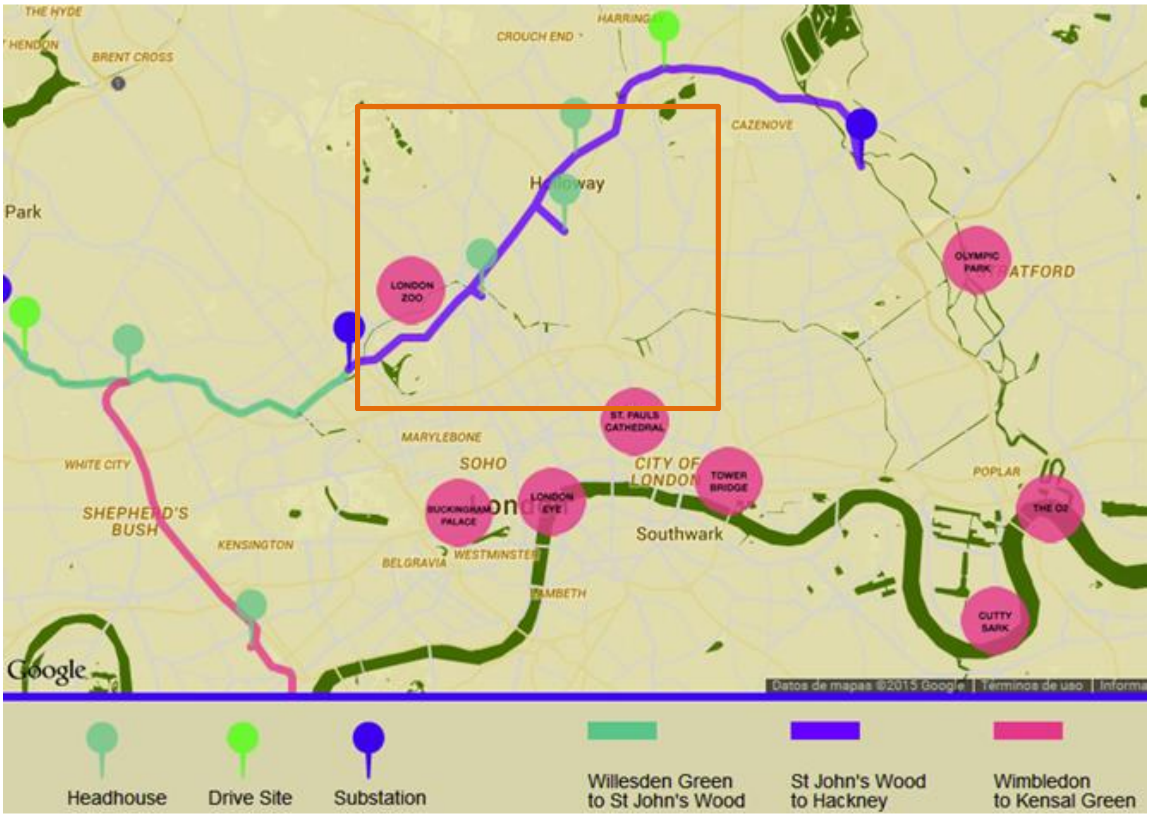


Figure 6 Schema map of the area of Interest in orange in North London

A final number of 40 Cosmo-SkyMed acquisitions (descending mode) were selected from the historical available dataset for this project, but only 38 were used, as two of them had very rapid atmosphere artefacts likely caused by local storms. Dates for these images range from April 2011 to August 2013. The number of acquisitions was sufficient in order to carry out advanced DInSAR processing using GlobalSAR^{TM} chain in order to detect any nonlinear motion over time.

Figure 7 shows the temporal distribution of these acquisitions. It is noticeable that the sampling is not constant and thus there is more accumulation of acquisitions at the beginning of the period. It is important to note that each acquisition represents a measurement in time.

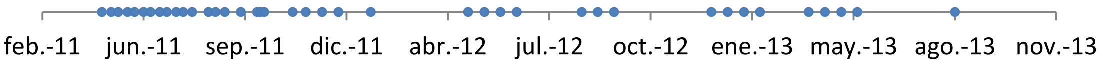


Figure 7 Temporal distribution of acquisitions between 2011 and 2013

4 Results

The period of the study spanned two years and four months, from April 2011 to August 2013. Results are presented as accumulated deformation maps as well as TS and several cross-sections (CS) across the tunnel track. These maps have been created using shapefiles in WGS-84 UTM 30N projection system. The background is an orthophoto based on imagery basemap. Over this orthophoto, coloured points are presented corresponding to measurements that reflect a good quality signal to the satellite throughout the period of study. The colour scaling relates to the value of the accumulated motion where green represents stability over the period of study, blue represents heave and red indicates subsidence.

Figure 8 shows the colour scale used in the images presented in this document. The quantification levels are set according to the amount of displacements detected, in order to show their evolution in time. Taking into account the dynamics of the site and the intensity of the motion patterns observed, the colour scale includes values of up to 15 mm of accumulated ground motion between April 2011 and August 2013. The stability is set at 5 mm which is the precision achieved by this new approach of the technique throughout the two years.

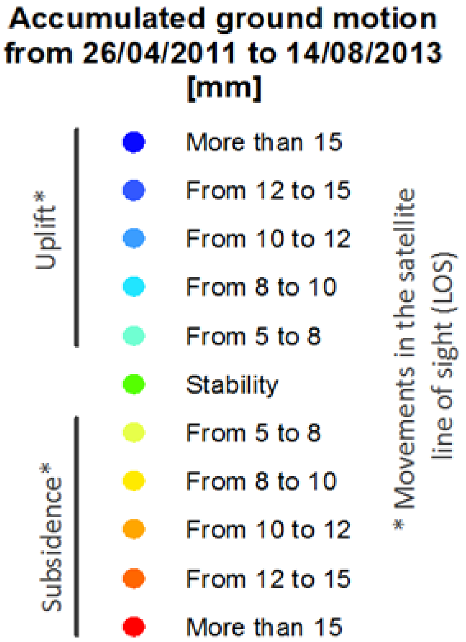
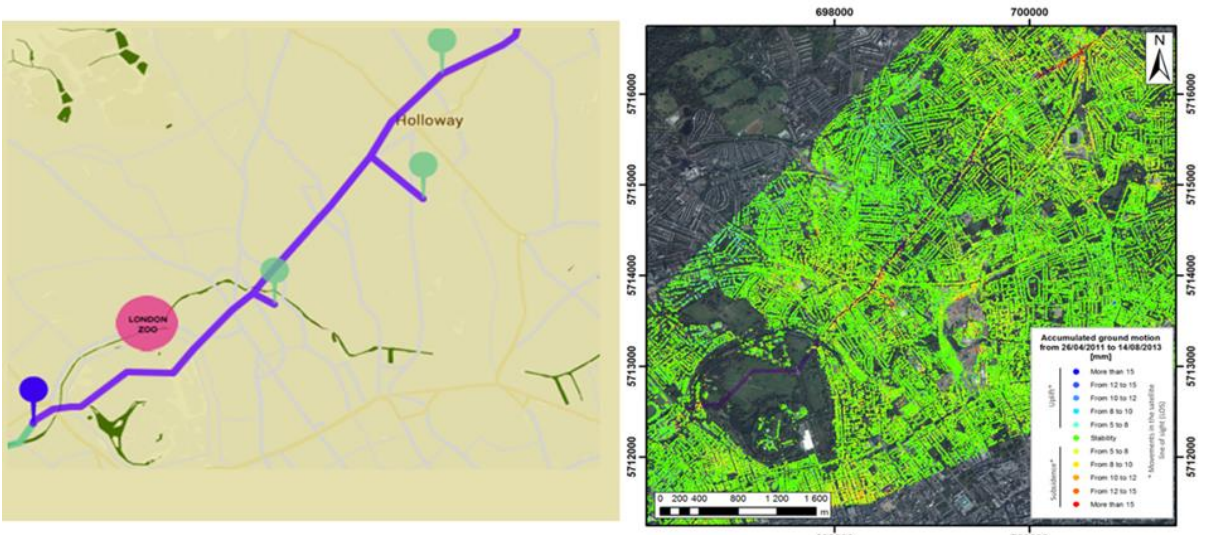


Figure 8 Level colours used to display motion

Figure 9 shows the schematic map of the line (a) with the accumulated ground motion displacement map (b). Regarding the evolution of motion, in the last accumulated map the linear path of subsidence above the track is clearly visible. Other areas may be affected by construction work and would show different patterns of motion depending on the work carried out on the surface.

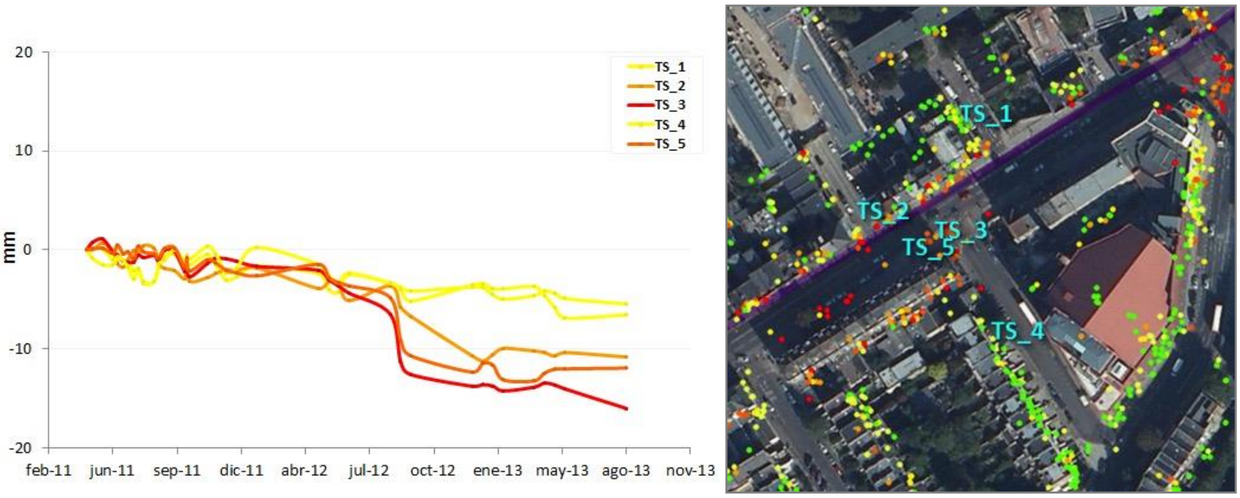
Nonlinear ground motion has been detected over the tunnel track on later dates of the study, moving throughout the line from north to south. The evolution of accumulated motion shows that the motion started after April 2012 and had higher rates during August 2012. After this date, lower subsidence intensity is detected. The impact on the ground motion seems to be higher and constant in the areas where a shaft is constructed, being easily detected with a linear processing.



(a) (b)

Figure 9 Approximate alignment of the power tunnel related with the detected motion

Time series over the north area suggest that the tunnelling would have occurred during August 2012, as shown in TS 5 and TS 3 in Figure 10. The plot also shows that TS 2 has a delay in its deformation pattern which sharply occurs between September 2012 and December 2012. That may be due to the distance between the point and the real tunnel path as opposed to the drawn one, whose information was extracted from the website and might not be completely accurate.



(a) (b)

Figure 10 TS 1 and TS 4 show the slight affectation of the motion in a certain distance of the tunnel. TS 3 and TS 5 show the sudden increase of the motion in August 2012

In order to assess the impact and risk for the buildings under the tunnel alignment, CS can be analysed as a powerful and useful tool to check the behaviour of the TS. CS show the evolution of the ground deformation in a drawn section.

In each point of the section-line, which is linked to the X axis, the measurement points contained within a 30 m radius are averaged to reduce the noise fluctuation inherent of the technique accuracy and also to have measurements in each distance of the X CS-axis. In order to reduce the amount of data shown on the plots, quarterly TS have been selected to reflect the trend and its evolution during the whole period, and not only in the timespan when motion occurs.

An example of CS is shown on Figure 11. Not all the infrastructure underneath tunnelled areas have a continued trend over the period of study, as the CS 3 example demonstrates. It shows that the involved area has no apparent motion between April 2011 and January 2013, showing later an increase of the motion around the street under which the tunnelling may have occurred.

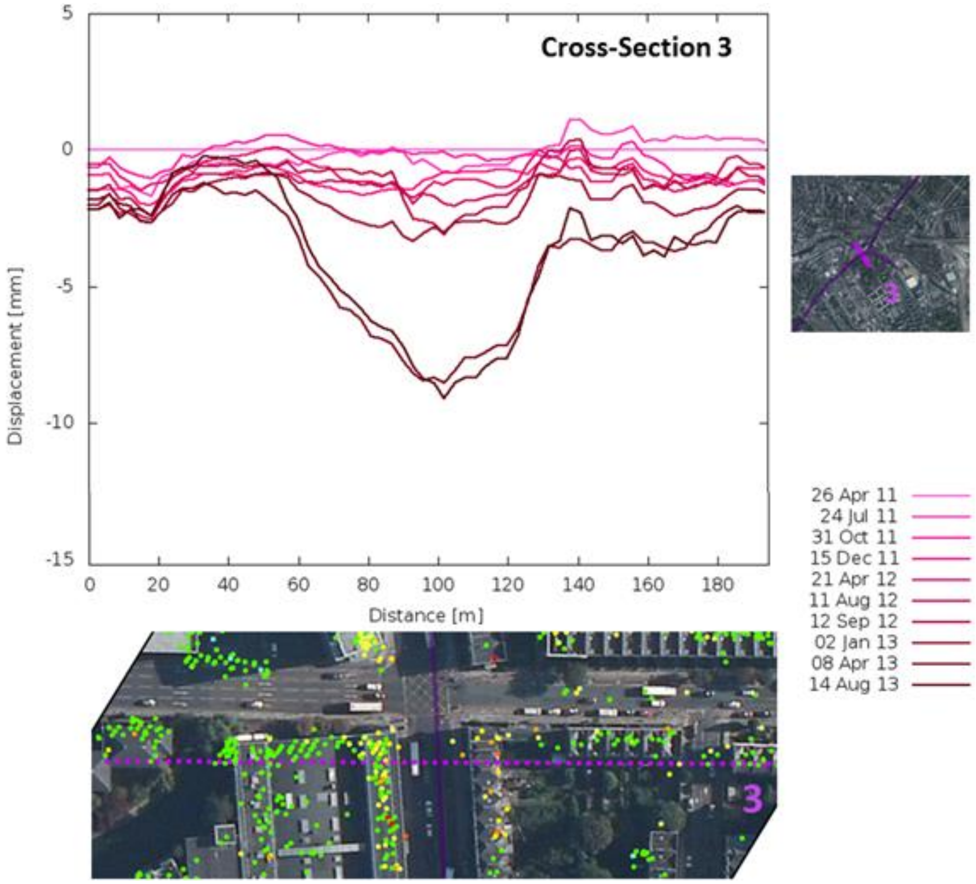


Figure 11 CS 3 shows the sudden increase of motion between January and April 2013 and its subsequent stabilisation after that period

Adopting only cumulative ground motion, it is complicated to extract and evaluate the whole information process of these features can offer. It is absolutely necessary, especially in cases where nonlinear motion is expected, to analyse these maps to generate ancillary data like CS and TS in order to develop conclusions.

In the borough of St John's Wood, near London Zoo in North West London, subsidence near some buildings has been detected in the last quarter of the study. The subsidence strongly coincides with the alignment of the tunnel; this could therefore illustrate a relationship between the motion and the tunnelling work. Cumulative ground motion maps illustrating this fact are shown on Figure 12.

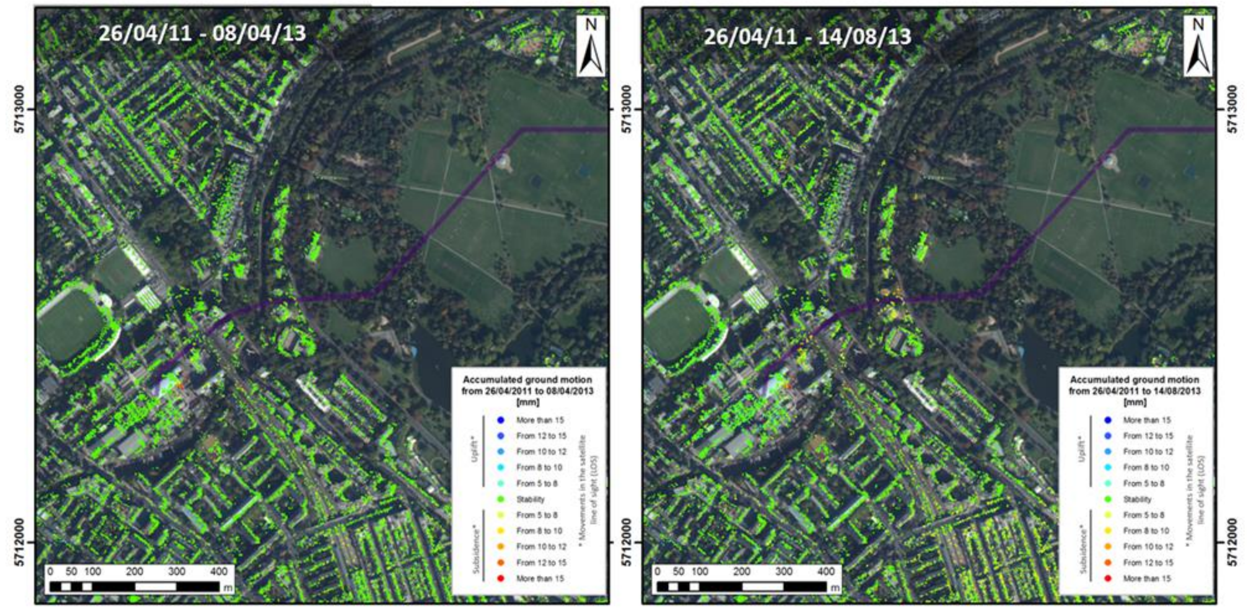


Figure 12 Evolution of the cumulated motion between two different periods. The last date reflects the increase of the motion in the track of the tunnel

Studying this area with the classical linear PSI methodology, it would imply an inaccurate or a mistaken result. According to the interferometric stack the ground motion occurs at the very end of the study, thus having an inappreciable impact on the global trend of the TS.

In Figure 13, a comparison between the conventional linear technique and the new nonlinear technique is shown. In the orange square, buildings are highlighted whose measurements strongly differ between both methodologies. Consequently, it is clear that the new indicated approach achieves more exactitude, rigor and certitude. When strong nonlinear motion occurs, varying from subsidence to uplift in the same study, like the extraction and recharge of aquifers, no points will be obtained if a linear process is carried out. Nevertheless, this is not the case of the subsidence caused by the advance of a tunnel boring machine, and this implies not only a lack of measurement points with the regular methodology but also a biased result. Figure 13 shows procurement of measurement points in both of the methodologies; however, only the nonlinear methodology is capable of reproducing the correct trend.

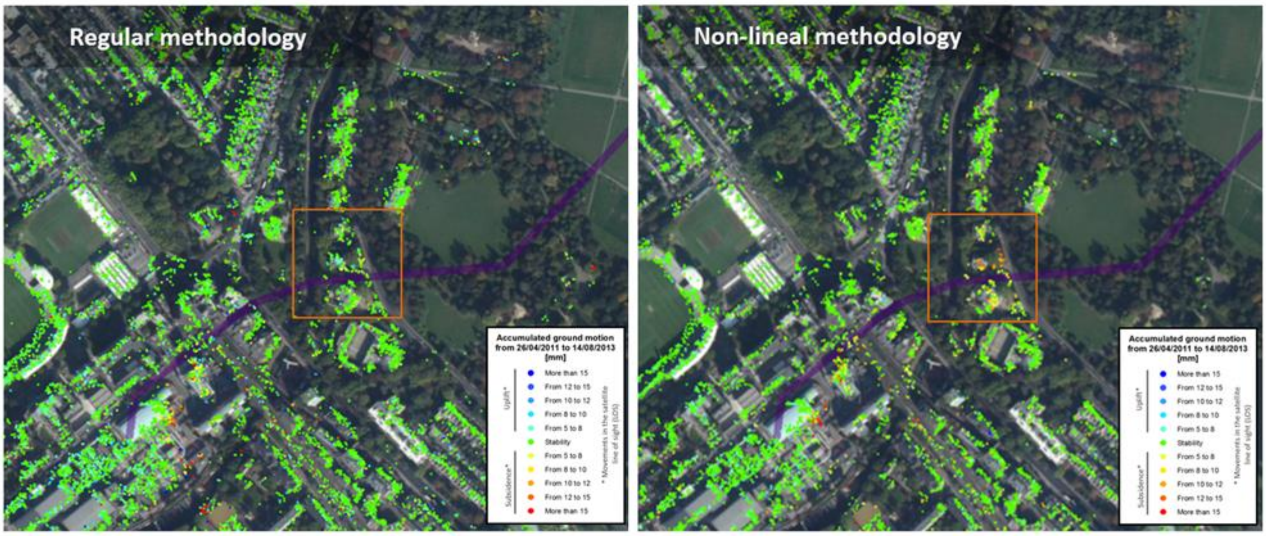


Figure 13 Comparison between the regular/conventional methodology and the new approach, nonlinear methodology, oriented to detect temporal variation in motion

In line with what was previously discussed, TS over the area of St John's Wood show an increase of subsidence between the two last acquisitions of the processing. That may reflect that the eventual tunnelling in this area would have occurred in the timespan of May-August 2013. As shown in the TS of Figure 14, major subsidence is detected 20-30 mm from the drawn location of the tunnel. TS 7 shows the strongest increase of motion between the last two images, and thus would mean a bias in the approximate polygon location, done freehand with website information.

Deriving TS from the nonlinear processing results in more noise and accumulated error compared to the values obtained when the TS are derived from the linear processing. This is due to the combination of DInSAR and PSI techniques implemented in the nonlinear processing results. The DInSAR methodology adds a small noise component (approximately +/-3 mm) to each measurement of the TS. However, the correct trend of motion achieved by using DInSAR compensates this minor constraint.

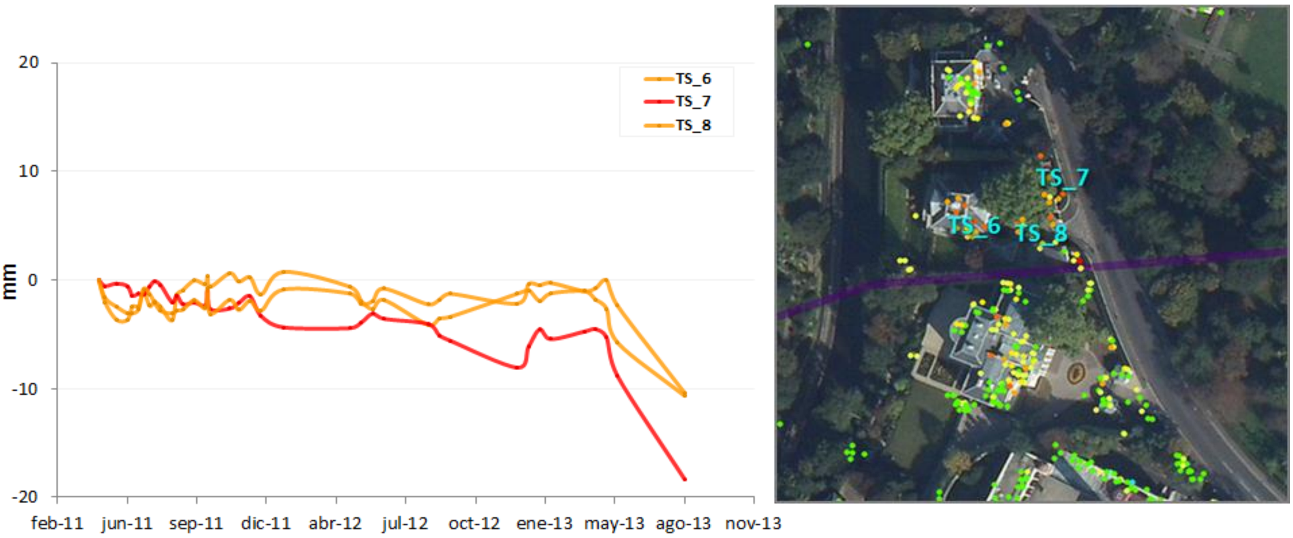


Figure 14 TS showing a strong increase of the cumulative ground motion between the last two acquisitions in St John's Wood area

For this reason, the cumulated fluctuations below 5 mm are considered as noise inherent in the system. Several spatially averaging methods can be carried out to reduce this noise and extract more accurate and clear information. Working on this field would improve the precision to assure the same one as regular PSI.

Results over the following CS of St John's Wood are notable in the base of using nonlinear estimation technique. As shown on both CS shown on Figure 15, the ground motion appears suddenly between April 2013 and August 2013. This fact seems to be crucial for understanding the usefulness of this new approach with almost the same PSI precision. Regarding this example, it becomes clear that the tunnelling would have started in the northern areas and then continued through this area at the end of the period analysed.

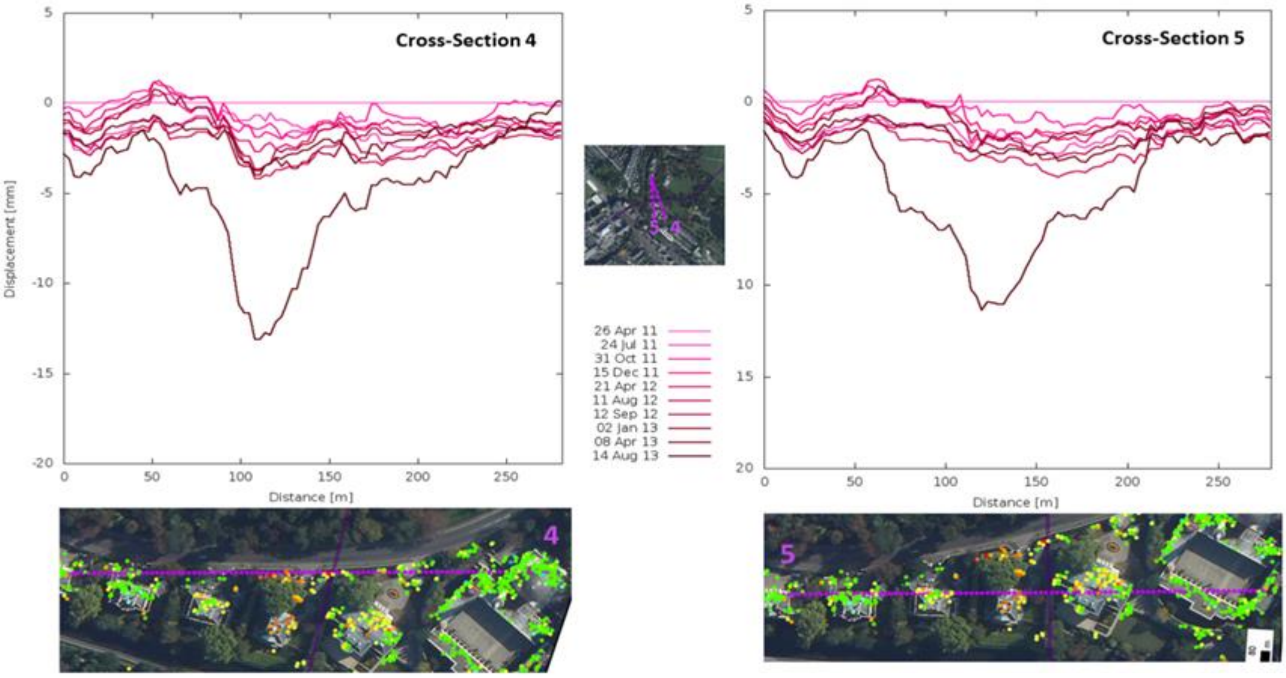


Figure 15 Both CS corroborate the former information of a strong increase of the cumulated motion between the last two acquisitions in St John's Wood area

5 Conclusion

The new approach discussed in the paper is a valuable technique for the future surveying of construction work scenarios. It can follow up the risk on buildings and any impact of civil engineering works in terms of ground motion. With this new PSI nonlinear specific approach, the evolution of nonlinear motion can be perfectly monitored in space and time in urban areas.

The examples shown are crucial for understanding the usefulness of this new methodology with almost the same PSI for linear motion precision and accuracy. It is absolutely essential to consider this kind of methodology, especially in cases where nonlinear motion is expected. Once the results have been obtained, it is worth painstakingly analysing them to generate ancillary data like CS, accumulated maps between two dates and TS in order to extract further conclusions. When strong and rapid motion is expected, it is essential to follow a sufficient acquisition rate sampling in order to retrieve all the possible events.

The approximate alignment of the tunnel obtained from project website noticeably coincides with the detected motion (http://www.londonpowertunnels.co.uk/). Results over Holloway determine that major motion occurred in August 2012 and show the higher rates of motion of the case study. This could be caused because of the sufficient sampling after and prior to the tunnelling event unlike the example of St John's Wood area, whose motion is located between the two last images. The impact on the level of ground motion seems to be higher and constant in the areas where a shaft is constructed. These areas are the only ones to be retrieved either with linear or nonlinear processing. In order to retrieve the subsidence caused by the pass of a boring machine nonlinear processing must be conducted. Strong settlement occurs in the days following boring and after that, residual settlement can remain in the following months.

Results over the CS of St John's Wood are noticeable and prove the importance of using the nonlinear estimation technique. CS allow ease of determining the date when the main subsidence occurred and the range of its effect. CS over infrastructures affected by nonlinear motion are able to combine spatial and temporal dimensions all together to enhance the understanding of the behaviour of the motion and its evolution in critical areas.

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