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Does the Geothermal Activity in Southern Paris Induces Detectable Ground Movements? The InSAR Approach.

Catherine Formento[1], Delphine Patriarche1, Frédéric Huguet[1], Patrick Egermann[1], Anne Urdiroz[2], Fifame Koudogbo[2]

[1] Storengy SAS, 12 rue Raoul Nordling, 92274 Bois-Colombes cedex, France

[2] TRE-Altamira SLU, C/ Corsega 381-387, 08037 Barcelona, Spain

catherine.formento@storengy.com

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ABSTRACT

Geothermal activity is particularly developed in the southern suburbs of Paris, with a high density of geothermal doublets. The area is characterized by an extensive human activity, with a limited vegetation cover and numerous anthropic reflectors (buildings, roads, urban materials), which is particularly favorable for the application of the Interferometry Synthetic Aperture Radar (InSAR) technique. Geothermal exploitation in this region involves mainly the deep geological formation of the Dogger, a 1 700-meter-deep limestone aquifer. Due to the thickness and nature of the overlying terrains, the impact of deep pressure variations is expected to be limited at surface. In fact, a simple geomechanical analysis has concluded that the expected effects are millimetric, which is of the same order than the radar interferometry measurement precision.

The present study is based on the large stack of High Resolution TerraSAR-X images acquired over Paris, over a 60-month period, from May 14th, 2011 to October 18th, 2016 (75 measurement dates). The objective is to evaluate the InSAR approach suitability for the assessment of ground surface movements in Paris suburbs. A new methodology for the exploitation of the InSAR measurements has been implemented, based on statistical and geostatistical methods for the characterization of the spatio-temporal distribution of the InSAR displacements and the identification of local extrema. The process is entirely blind and no a priori information on the location and on the exploitation rates of the doublets is integrated in the calculations.

The applied methodology highlighted several important phenomena over the studied area and the different statistical attributes computed over the entire period, such as velocity and acceleration, revealed large regional events, partially correlated with topography.

The temporal analysis of the displacements showed strong seasonal effects, with regional-scale ground elevation in winter and a low subsidence in summer. However, the mechanism causing those periodical variations was not specifically identified: thermal effects, groundwater level variations, or soil properties, or even an association of different factors.

A spatial decomposition of the displacements was carried out, at each measurement date, by successive factorial kriging. This decomposition allowed for the dissociation of ground movements at the regional scale, probably related to topographical, geological or climatic factors, from local movements. The analysis of local displacement maps (mean and standard deviation maps over the period studied), revealed some local anomalies, mainly affecting roads, railways and specific buildings.

In conclusion, the InSAR analysis conducted did not clearly highlight shifts, subsidence or elevation, specifically related to geothermal activity, showing that the Dogger geothermal exploitation has less impact on the surface than regular anthropic activities and natural events. This approach could be very useful in case ground deformation in urbanized environments would need to be further investigated.

1. INTRODUCTION

Interferometric Synthetic Aperture Radar (InSAR) allows, by the acquisition of successive radar data in time, for the monitoring of ground motion with millimeter precision. The measurement quality and spatial coverage is strongly influenced by the presence of permanent reflectors.

The main objective of the study conducted was to evaluate the capability of InSAR measurements for the detection and monitoring of ground deformation related to the exploitation of the Dogger reservoir for geothermal energy, in the southern region of Paris (Grand Paris).

Geothermal activity can cause a modification of the pressure field in the exploited aquifer. If the pressure is sufficiently high or the site sufficiently close to the surface, this variation may induce a mechanical movement of the soil, which can be recorded on the surface. The objective was then to analyse whether it was possible to detect and quantify by InSAR a subsidence or an elevation on the sites the main geothermal drillings are located.

Conventional statistical methods have been implemented, supplemented by the analysis of attributes derived from InSAR processing and by geostatistical methods in order to characterize the different scales and to identify the displacements potentially associated with the geothermal activity.

The overall work was performed blindly, no information on the doublets location or on exploitation (history of production) was integrated in the different computations.

2. LOCATION AND CONTEXT

2.1 Location

The project is located in the southern suburbs of Paris, the area of interest covers approximately 50 km^2. This region is a very urbanized area, with a limited vegetation cover. This is particularly favorable for the acquisition and quality of interferometry data, since there is an abundance of "natural" reflectors (buildings, roads, urban equipment). Furthermore, geothermal activity is particularly developed in Paris region, with a high density of geothermal doublets. Seven doublets (7 injection wells + 7 producing wells) are located in the considered sector for the period of interest.

The region is moreover characterized by strong and diverse human activity: surface and underground works, exploitation of aquifers for drinking water, etc., which represent potential sources of ground movements. Natural phenomena, such as variations in groundwater levels, may complicate the interpretation of the ground movements.

2.2 Topography

The topography over the site of interest is marked by the Bièvre valley, which crosses the map along a south-west/north-east axis and joins the Seine valley at the extreme north-east of the map, at Ivry-sur-Seine (Figure 1). This valley is characterized by the lowest altitudes of the study area, around 90m to 100m, and is 1 km wide in the northern part, 1.5 to 2 km in the southern part. On each side, this valley is bordered by two plateaus: the plateau of Villejuif to the East which culminates between 140 and 170 m of altitude, and the plateau of Velizy to the West reaches 180 m of altitude.

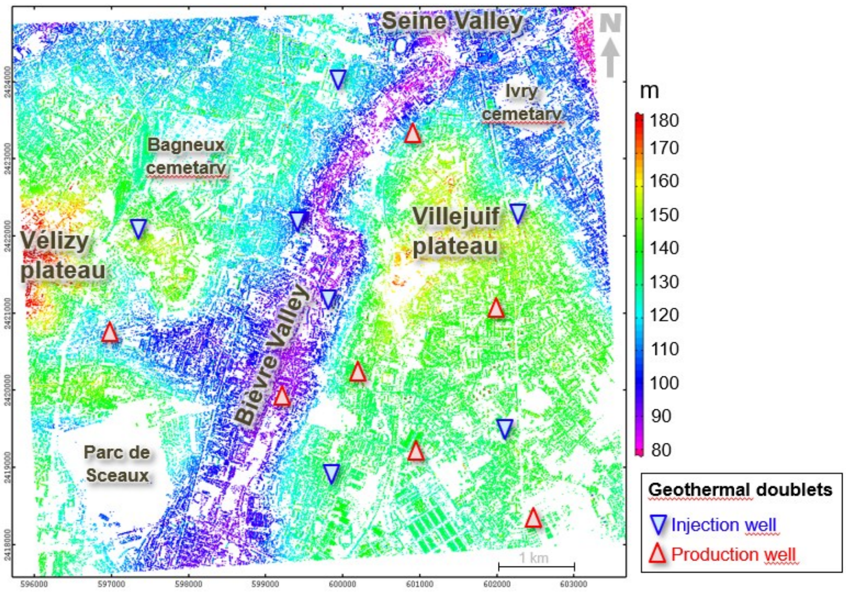

Figure 1 : Height of the measuring point and location of the well (at Dogger depth)

2.3 Geological context

Geothermal exploitation in the Paris region concerns deep geological levels. Thus, in the studied area, the Dogger aquifer is the main geothermal reservoir exploited since late 1970. It is a carbonates reservoir from Middle Jurassic composed of fractured oolithic limestone. It is located between 1400 and 1620 m in the studied area. The geothermal exploitation is performed by doublets, with 1 production well of hot water and 1 reinjection well of cold water distant about 1 km.

Due to the thickness and nature of the overlying terrain, the impact of depth pressure variations may be limited at the surface.

3. DATA DESCRIPTION

3.1 InSAR dataset

The present study benefits of the large stack of High Resolution TerraSAR-X images available over Paris. The image resolution is of 3 m. The period of analysis covers 60 months, 75 images have been acquired from May 14th, 2011 to October 18th, 2016. The interferometric processing was carried out by TRE-Altamira, using the SqueeSAR® algorithm. 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:

- 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.).

- No measurement points are detected in area of vegetation due to the canopy variation over time. The SqueeSAR® processing provides a database containing the time series of the displacement values, for the 75 measurement dates, at each measurement point. The interferometry method measures the movements along the Line of Sight (LOS) of the radar, which is the direction in which the sensor looks at the ground surface. Displacement measurements are relative to a temporal and a spatial references. The time reference corresponds to the first acquisition date (14/05/2011), while the spatial reference is selected during the processing for its excellent electromagnetic characteristics (good and stable reflectivity over time, low phase noise).

3.2 Density, distribution and data quality

About 466,900 measurement points were detected. The points are mainly PS-type points, thanks to the area land cover the average density reaches 10,000 points per km^2. As expected, little or no information on motion is provided in areas of vegetation due to the absence of measurements points.

Figure 2 shows the coherence variation over the site of interest. The coherence is a measure of the quality of the phase adjustment to the linear model, related to the phase noise of the measurement point. This quality index varies between 0 (poor quality) and 1 (good quality). The coherence values vary between 0.67 and 1 representing a good quality index.

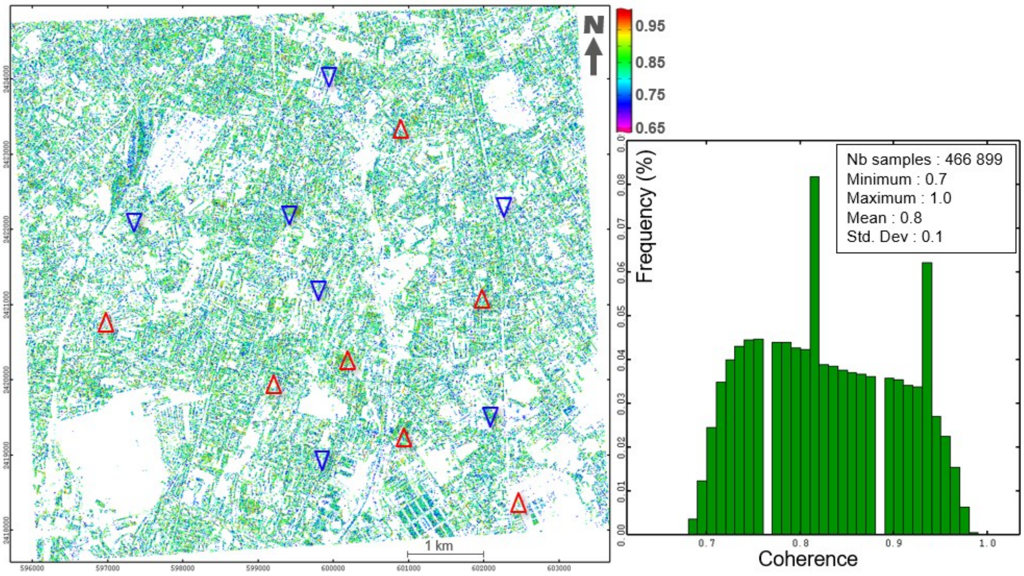

Figure 2 : Data coverage: Coherency map and associated histogram

4. PROPOSED METHODOLOGY

The adopted approach is based on classical statistical and geostatistical methods, in order to characterize the spatial and temporal distribution of displacement data, and to locate extreme displacements.

4.1 Global overview of the displacements over time through InSAR attribute and global statistics

Together with the time-series of displacement, SqueeSAR® database provides a set of attributes, which characterize the evolution of the displacement at each measurement point.

- The average velocity corresponds to the average displacement rate of the measuring point, measured in the direction of the satellite line of sight. A positive velocity corresponds to a global uplift, whereas a negative velocity corresponds to an overall deepening of the soil surface over the entire period studied.
- The acceleration is calculated by approximating the time series with a 2nd degree polynomial. This attribute makes possible to identify zones where an acceleration or a slowdown of the general movement (uplift or deepening) has occurred during the studied period.
- The mean seasonal amplitude calculates the mean difference between the displacements measured in winter and summer, by sinusoidal adjustment of the time series. A temporal series whose seasonal amplitude is zero does not have pseudo-periodicity, so no seasonal variation. In contrast, a strong seasonal amplitude indicates a strong contrast between displacements measured in summer and winter.

The attributes are associated with a precision index: the standard deviation which measures the degree of dispersion of a population of data around a mean value. This measurement thus estimates the degree of precision of this set of data (
Table 1). For SqueeSAR® measurements, the standard deviation refers to the average displacement rate with respect to the reference point (as in traditional geodetic networks, measurement precision decreases as distance from reference point increases).

Table 1: SqueeSAR® measurement precision

Displacement (LOS)	Average displacement rate	Single measurement (time series)
Meas. accuracy	1-2 mm/year	2-3 mm

4.2 Analysis of the temporal statistics

In order to analyze the overall evolution of movements over time, the mean and standard deviation are calculated for each measurement date.

4.3 Spatial assessment and spatial processing using geostatistical tools

The displacements measured during the studied period may be related to several causes (climatic, geological, anthropic origins). Each of these phenomena will have an impact on ground movements at a specific scale. In order to be able to monitor displacements related to geothermal energy, it is important to characterize the ground movements specific to this activity. Geostatistics aims at analyzing and processing any information distributed in space. It provides methods to better understand the spatial variability of regionalized variables.

Variogram

The variogram is the traditional tool to characterize the spatial variability of a given property as a function of the lag distance. The experimental variogram (also called semi-variogram) is computed from the available data as follows:

$$\gamma(h) = \frac{1}{2} Var[Z(x) - Z(x+h)] = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2$$

where Z(x) is the spatial variable at the location x and N(h) is the set of observed pairs separated by a lag vector h.

The experimental variogram is then interpreted in terms of spatial structures. The variogram modeling consists in adjusting a specific covariance model, defined by a mathematical function and associated parameters (range, sill and nugget effect) that best fit to the experimental variogram, according to its spatial interpretation. Nested variograms enable to decompose the semi-variogram into a linear sum of basic functions, each of them related to a spatial scale, as follows:

$$\gamma(h) = \sum_{i=1}^{N} \gamma_i(h)$$

where N is the number of functions and $\gamma_i(h)$ is the basic function representing a given scale.

Factorial kriging

The objective of kriging is originally to estimate a spatially distributed variable, based on some known values, and the description of the spatial variability given by the variogram model (Matheron, 1982). It is a simple linear regression algorithm, that can be expressed as follows:

$$Z^*(x) = \sum_{i=1}^{N} \lambda_i Z_i(x_i)$$

where $Z^*(x)$ is the estimate of the spatial variable at the location x, $Z_i(x_i)$ are the known values of the variable and λ_i are the kriging weights. The interpolation parameters are computed during the kriging process by minimizing the variance of estimation error.

Factorial kriging is a kriging method that decomposes a regionalized variable into a set of independent spatial components, each of which presenting its own variogram model. (Sandjivy, 1987; Abreu, 2009).

Successive factorial kriging procedures are run in order to estimate separately each spatial component of a given variable at each data location.

5. RESULTS AND DISCUSSIONS

5.1 Ground movement are partly related with topography

The average velocity attribute has been studied over the whole area. The average value is 0.2 mm/year with a standard deviation of 0.5 mm/year. The global range of average velocity is +/- 1 mm/year (Figure 3). This value is in the order of the InSAR measurement uncertainty, care should be then taken when interpreting velocity values lower than 1 mm/year. There seems to be some correlation between velocity and topography, since the negative velocities, related to global deepening of the surface, are mainly distributed in the Bièvre valley, and the positive velocities, related to an elevation of the surface, are observed on the plateaus of Villejuif and Vélizy. As the values are lower than the measurement precision, some observed features may also be related to processing residuals.

An area of strong positive acceleration, between 0.4 and 0.7 mm/year^2, is visible in the center of the study area, and extends northwards to Bagneux cemetery. On the opposite, strongly negative acceleration (decelerations) of the order of -0.4 to -0.8 mm/year^2 are visible on the Villejuif plateau east of the map, south of l'Haÿ-les-Roses, and north of the Porte d'Italie.

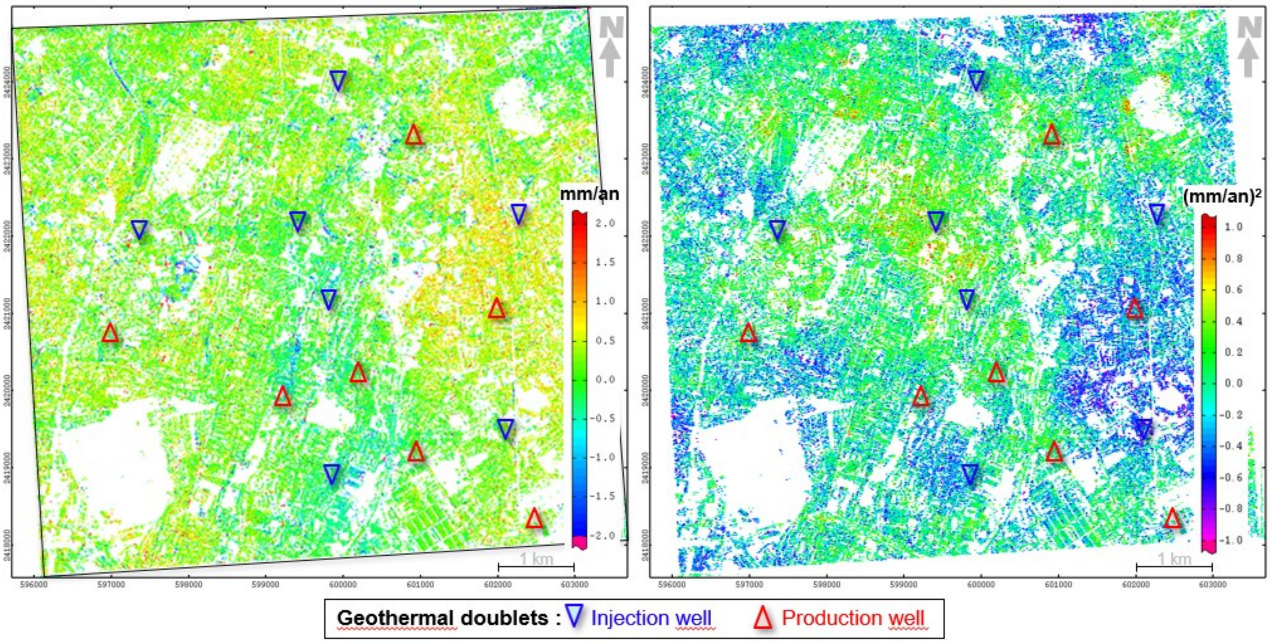

Figure 3 : Average velocity (left) and acceleration over the studied period (right)

5.2 Ground movements are seasonal

The average displacement was computed for each date considering all the data points in the area (Figure 4). This average displacement is characterized by a pseudo-periodicity, with a maximum displacement during the first months of the year (January - March) and a minimum displacement in the middle of the year (July - September). There is therefore a seasonal effect, whose origin is still unexplained. It may be related to actual ground movements, possibly associated with climatic conditions such as pluviometry or groundwater level variations. It may also be related to processing residuals, as the range of values is quite low, below the measurement resolution.

Over the entire period studied, a general positive displacement is observed, which reflects a slight global uplift. The amplitude of this phenomenon remains very limited, of the order of 1 mm over 5 years.

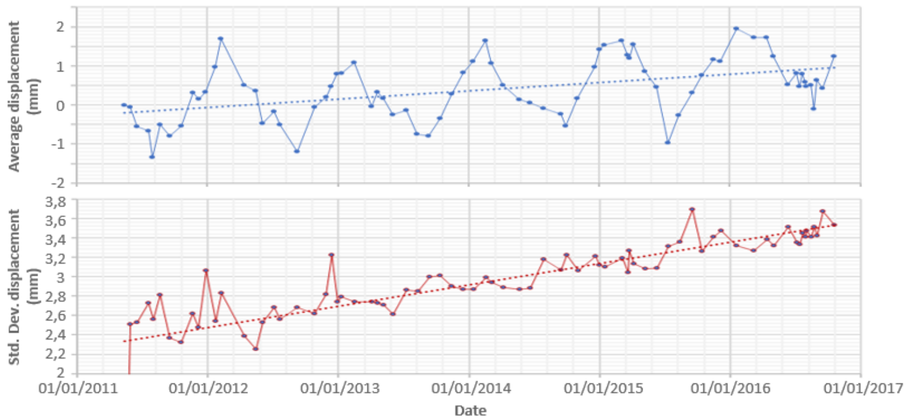

Figure 4 : Average displacement (top) and standard deviation (bottom) by date

The standard deviation of the displacements reflects the variability (dispersion) of the displacement values for each measurement date. The increase of variability is very clear, of the order of 1mm over 5 years. This increase in the standard deviation corresponds to an increase of the differences between the low values (minimum) and the high values (maximum) of displacement. Figure 5 shows the displacement maps at different dates in 2015. The spatial evolution during the 1-year period is clearly visible (Figure 5), with an increase of displacement (dilation) in winter and a decrease of displacement (subsidence) in summer, and contrasts that tend to be accentuated from year to year.

InSAR seasonal amplitude attribute highlights the areas with highest seasonal variations (Figure 6). In the study area, the seasonal amplitudes vary between 0 and 3 mm (maximum 5.13 mm), which means that differences in the order of 3 mm can be observed between summer and winter (Figure 5). Seasonal variations are locally visible in the south-western part of the study area, and along the Bievre valley.

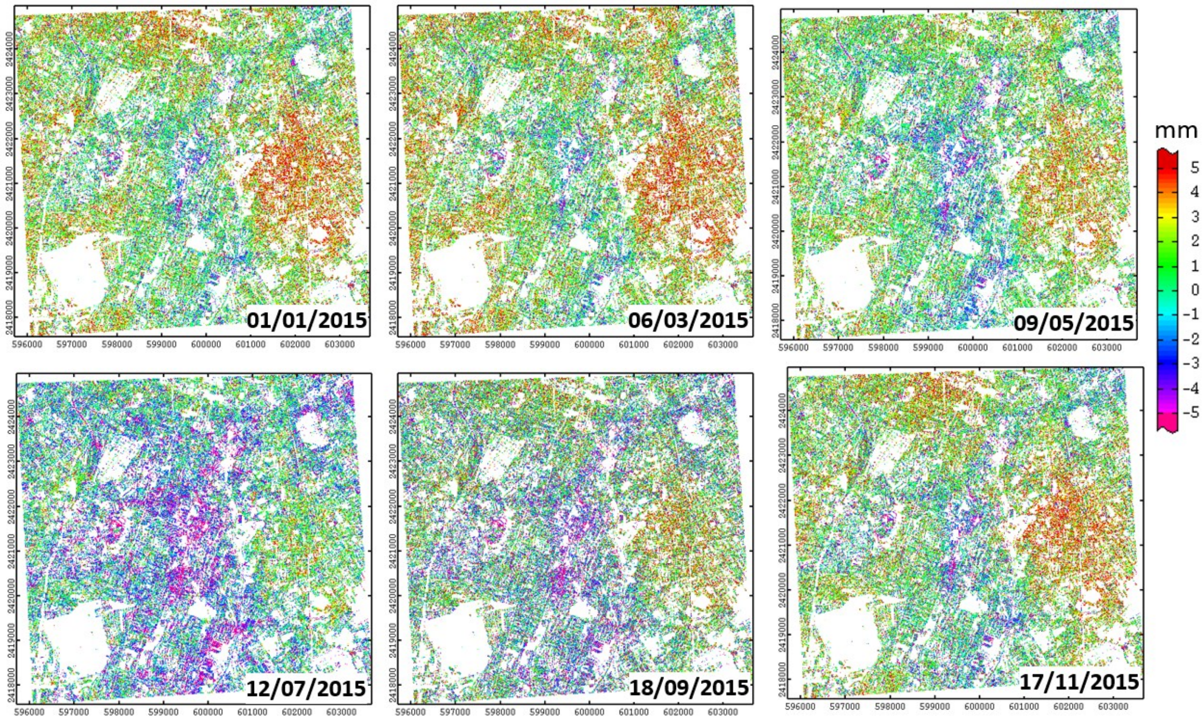

Figure 5 : Cumulated displacements over a 1 year-period (2015)

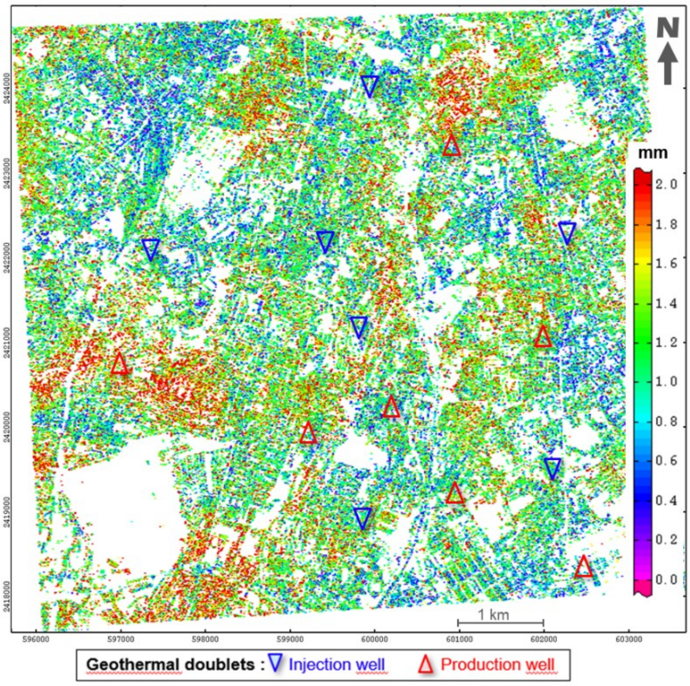

Figure 6 : Seasonal amplitude map

5.3 Displacement variogram at the final date

The displacement measured at the final date (18/10/2016) is equivalent to a cumulative displacement over the 60-month period (Figure 7).

Final displacements vary between -10 and +10 mm. Its statistical distribution is unimodal, close to a Gaussian, with an average of about 1 mm, which is about the noise level of the InSAR measurement.

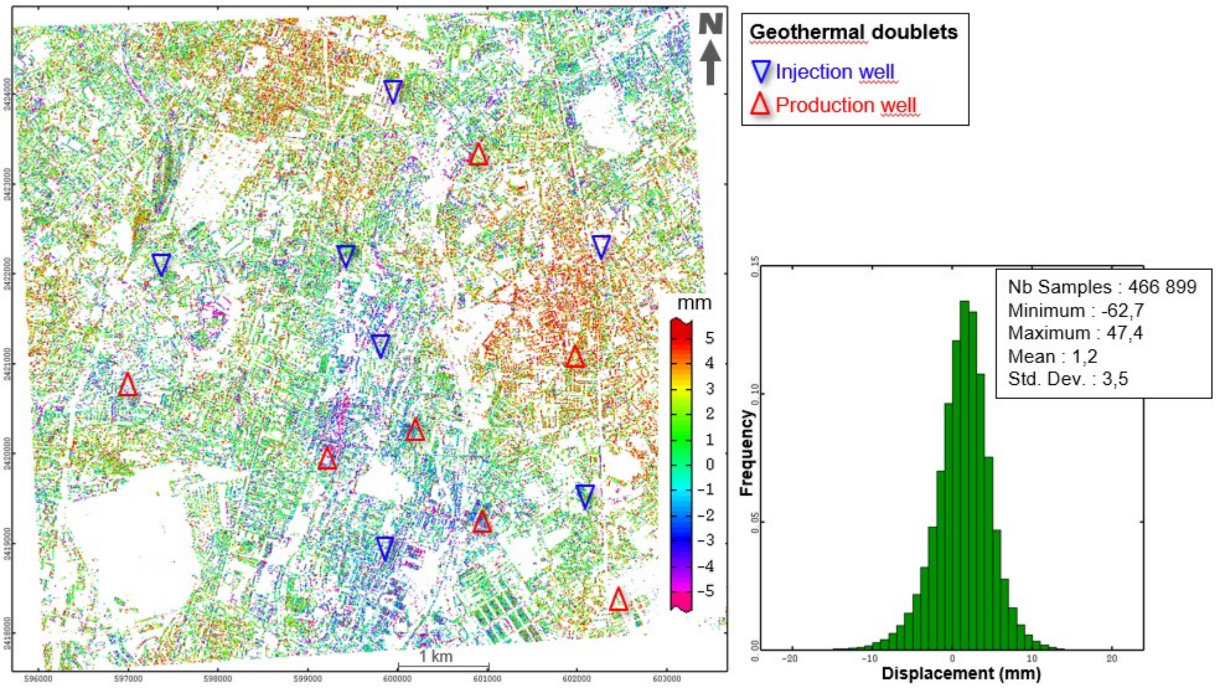

Figure 7 : Final displacement (18/10/2016) map and histogram

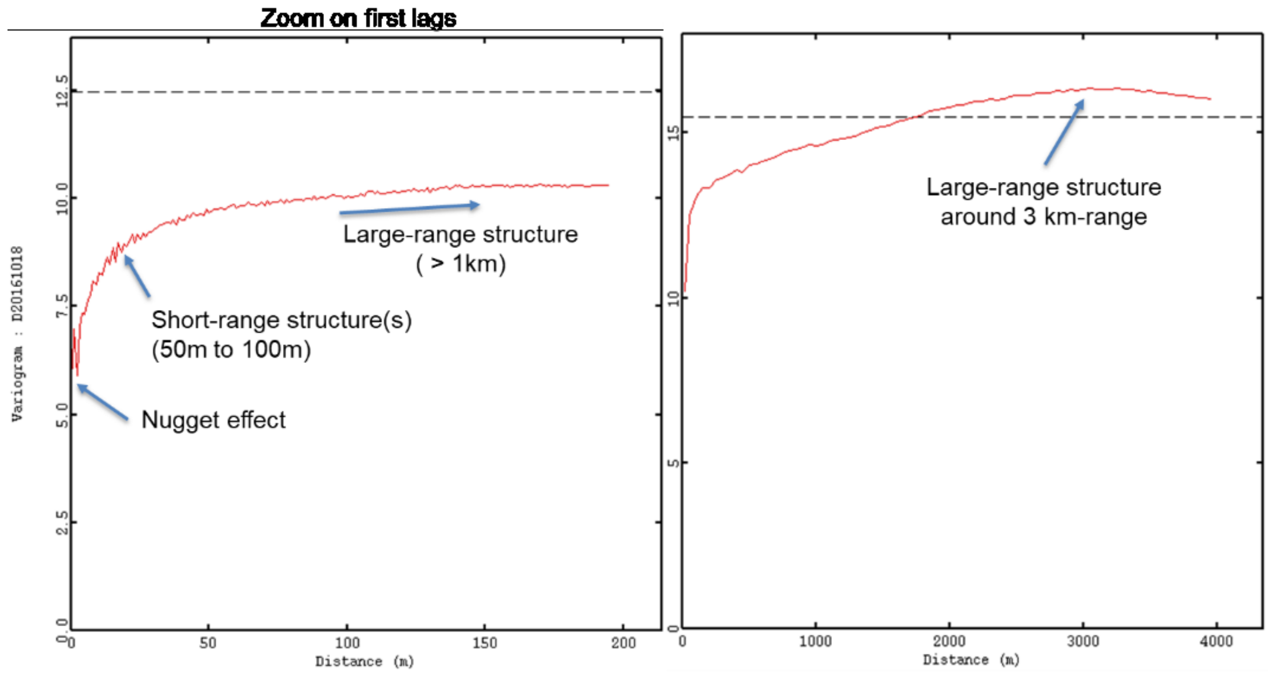

Figure 8 : Experimental variogram of the final displacement (the image on the left is a zoom on the first 200m lags)

The analysis of the experimental variogram (Figure 8) reveals several nested spatial structures, which can be interpreted as follows:

- A nugget effect, representing approximately 50% of the total variability, corresponds to a strongly marked white noise,
- One or more short-range structures, of the order of 50 to 100m-range, correspond to local variations. This is the order of magnitude of a building or block of houses,
- A large-range structure, of the order of 3km-range, may correspond to more regional variations, possibly related to topography, geology, hydrology ...

In order to monitor motions linked to geothermal exploitation, it is important to characterize the possible range of the ground movements specific to this activity. Thus, the statistical analysis revealed seasonal variations independent of the geothermal activity. What are the spatial structures associated with the observed phenomena, and how do they vary with time?

5.4 Temporal evolution of the variogram

The similarity between the different experimental variograms at each measurement date is remarkable. They can be decomposed using the same spatial structures as previously identified on the final displacement map (Figure 9). Only the sill, corresponding to the variability of each structure, varies time. The total variability increases continuously over the entire studied period, from 6.3 to 12.3 mm^2, which is consistent with the temporal evolution of the standard deviation by measurement date presented previously (Figure 4). Peaks of variability are observed during periods of stronger contrasts in late summer or winter.

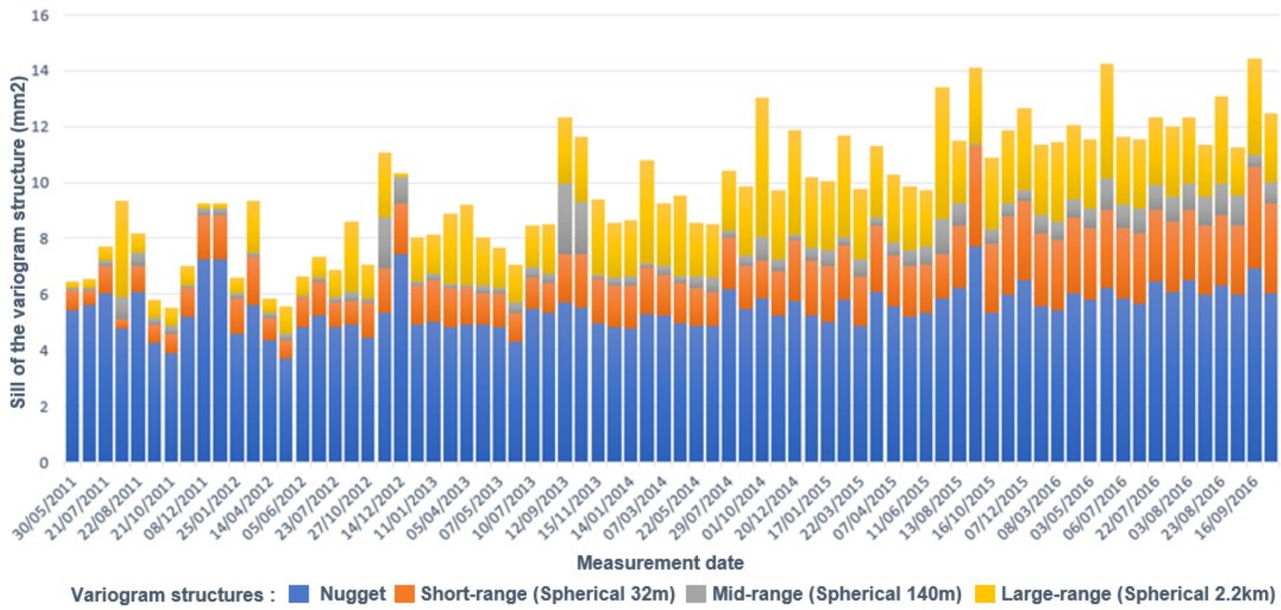

Figure 9 : Temporal evolution of the variogram model

The nugget effect is relatively constant, of the order of 6 mm^2. On the other hand, the variability of the 3 other spatial structures increases with time, from 1 mm^2 in May 2011 to almost 6 mm^2 at the end of 2016. The proportion of the nugget effect decreases, and conversely the proportion of the 3 spatial structures increases, from less from 20 % in 2011 to about 50 % of spatial variability in 2016. Pseudo-periodic variability peaks in summer appear to be mainly associated with a particularly sharp increase in the proportion of large-range structure.

5.5 Spatial decomposition of the displacement maps

The variogram analysis carried out on the map of the final displacements revealed several nested spatial structures. The factorial kriging method is used to decompose the displacement map according to the different structures modeled in the variogram (Figure 10). This approach makes it possible to answer several problems:

- Filter the nugget effect, to get rid of the noise that hides the coherent structures
- Interpolate data in less densely informed areas to facilitate regional and local interpretation
- Decompose the displacement maps according to the different ranges of structures identified on the variogram, in order to interpret, if possible, the origin of the different components of the displacement.

Factorial kriging was used to interpolate displacement values in zones with few measurement points, thus improving the readability of the displacement map. Unlike a classical smoothing, factorial kriging performs noise filtering without "spreading": the fine resolution of the initial map is preserved, despite the overall decrease in variability, related to the elimination of the nugget effect. This is particularly visible in the north-west corner of the map, where the railway is marked by a very localized deepening, preserved by filtering.

On the "low frequency" regional component (large-range structure in Figure 10), mainly the large elements previously identified remain: the elevations at Villejuif plateau, and the marked subsidence along the Bièvre and in the southern part of the area. This map represents large-scale displacements related to kilometer-scale phenomena.

At the studied scale, the short-range component (short-range structure in Figure 10) provides little useful information. On the other hand, the medium-range component (mid-range structure in Figure 10) emphasizes variations at the local scale and makes it possible to identify elements (blocks of buildings, sections of roads or tracks) subject to local displacements.

The same spatial decomposition was carried out at each measurement date, by successive factorial kriging. This decomposition dissociates ground movements at the regional scale, probably related to topographic, geological or climatic factors, from local movements.

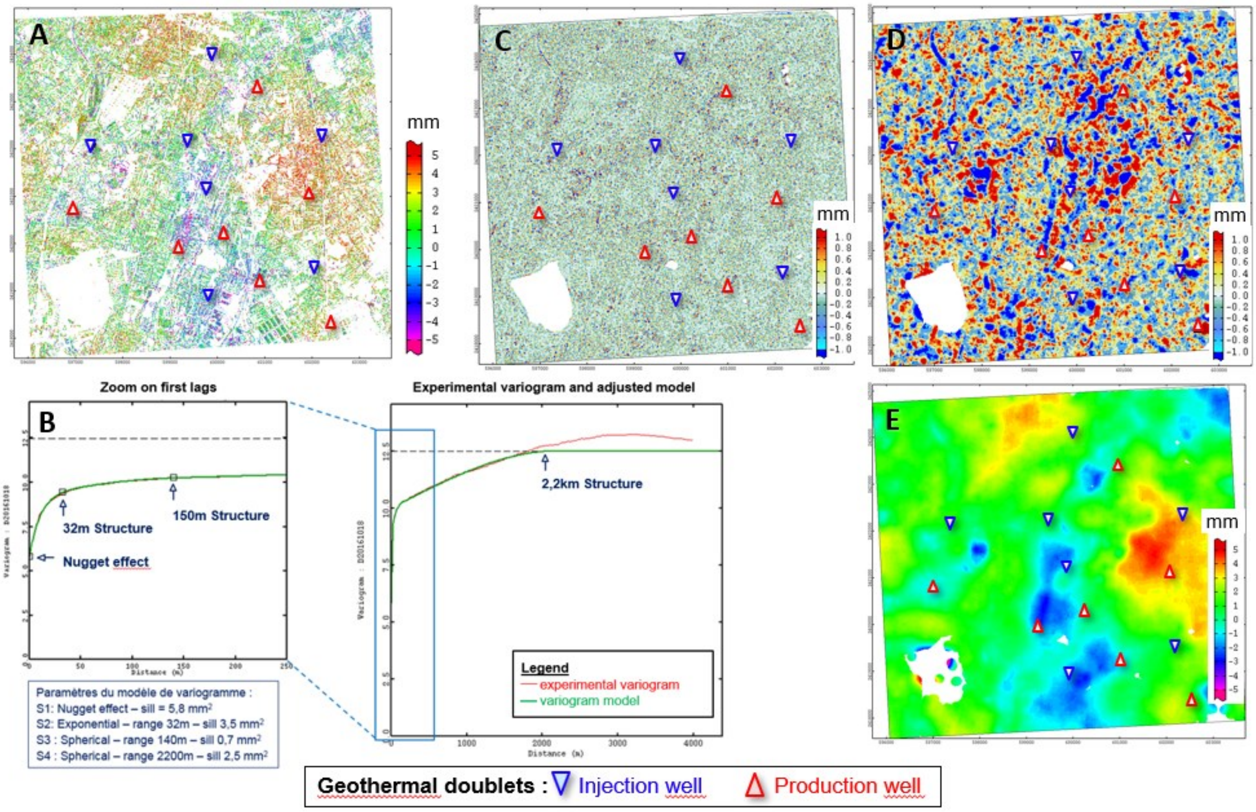

Figure 10 : Spatial decomposition of the final displacement map (18/10/2016) A: raw displacement / B: experimental variogram and model of displacement / CDE : results of the decomposition of the raw displacement by factorial kriging (C : small-range structure / D : mid-range structure / E : large-range structure)

5.6 Outliers identification

In order to complete the analysis of the filtering results over the entire study period, the directional statistics were calculated, considering only the local displacements (short-range components). Once again, it is important to remember that the displacements observed are very small, of the order of a millimeter, which is close to the noise level of the InSAR measurement. However, a certain number of local anomalies can be identified, corresponding to local displacements greater than 1 mm in absolute value (subsidence or uplift) (Figure 11).

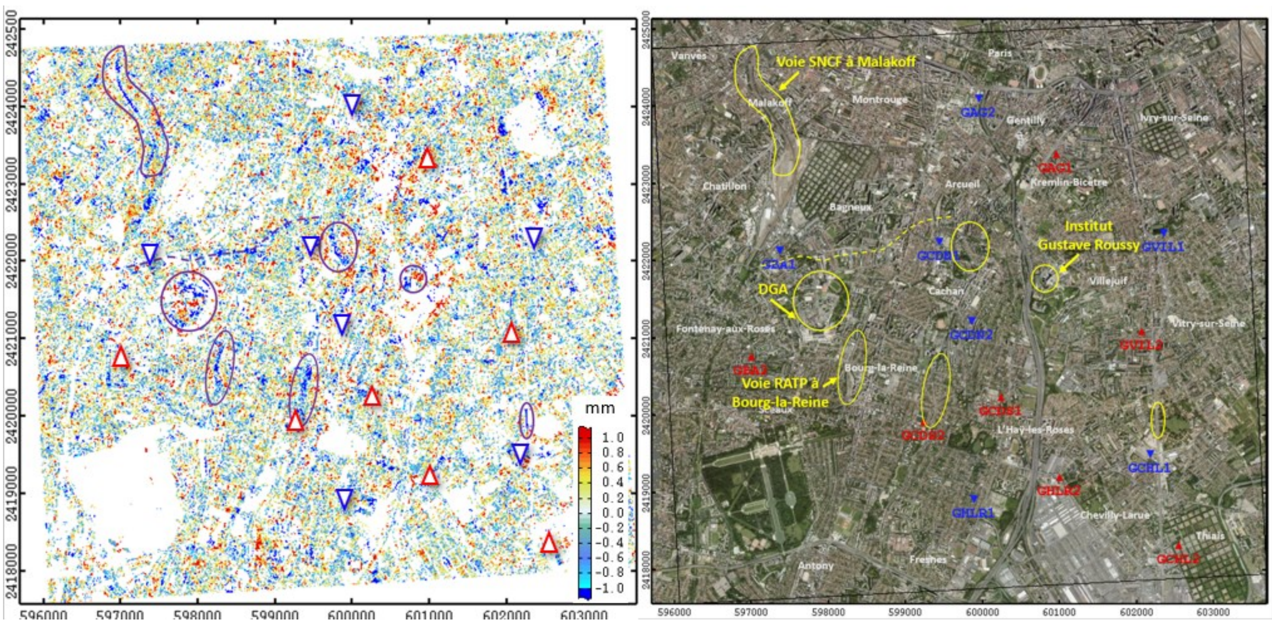

Figure 11 : Location of main outliers on the average local displacement map (left) and satellite view of the area (right)

The main movements highlighted are mainly located close to railways, sections of road, and some specific buildings. It would be interesting to relate these outliers with the anthropic surface activities. These outliers may be related to on-going construction activities. Local subsidence movements also manifest themselves in certain neighborhoods, as is the case between Arcueil and Cachan. However, no specific displacement could be systematically identified around the geothermal doublets (subsidence movements above or around the exploitation wells / uplift at the injection wells).

5.7 Ground displacements at the geothermal doublets location

To refine the analysis, a control of the evolution of the displacements was realized at each geothermal well. The global displacements, as well as the two spatial components resulting from the factorial kriging (local component and regional component) were extracted for each well.

It is not possible to identify a clear relationship between the type of well and the evolution of the ground movements in its close neighborhood. Figure 12 shows the temporal evolution of the median of the displacements according to the nature of the well (injection or withdrawal). Both types of wells behave similarly. The difference between the displacements of the two types of wells is systematically less than 1 mm, for both the local component and the regional component of displacements, which is lower than the measurement resolution.

Figure 12 : Temporal evolution of the median of total displacements (top), regional scale displacements related to large-range structures (middle) and local scale displacements related to small and mid-range structures (bottom) according to the nature of the well: injection or production

As previously observed in the statistical analysis, a seasonality is observed for the total displacements, with general uplifts in winter and subsidence in summer, for both producing and injection wells. This seasonality is found in the regional-scale displacements, but it totally disappears in the local-scale displacements. It confirms that this seasonality is associated with large-scale ground movements, maybe related with climatic variations.

At the first measurement dates, a shift between the median displacement of producing wells and the median of the injection wells appears. It accountis for less than 2 mm in the total displacements, and less than 1 mm in both regional-scale and local-scale displacements. This means that a relative displacement occurred, with an overall deepening of the producing wells compared to their initial position at the first measurement date. This shift remains constant over the entire studied period. If this shift was related to geothermal exploitation, it should increase or evolve over time, as geothermal activity was continuous over the studied period. Therefore, the hypothesis that this shift is associated with geothermal activity has been ruled out, and its origin remains to be investigated.

Consequently, the analysis of the InSAR measurements over the studied period does not make it possible to clearly identify movements, subsidence or elevation, specifically related to geothermal activity in the southern area of Paris.

6. CONCLUSIONS

InSAR attributes make it possible to understand global behaviors over the entire period studied. In the study area, the displacement values are at the resolution limit of the method, with displacements of the order of +/- 1mm / year, close to the noise level of the InSAR measurement. Attribute maps are mainly marked by major regional events, partly correlated with topography. Very marked local anomalies have also been identified on the attribute maps. The temporal statistical analysis of the displacements revealed strong seasonal effects, with a tendency to a regional elevation in winter and a relative deepening in summer. However, it is difficult to determine which phenomena are at the origin of this trend: it may be related to thermal effects, to the level of groundwater, or to the nature of the soil, or even more certainly to an association of different factors.

The variographic analysis of the displacements by date of measurement highlight different ranges of spatial structures. The same structures were identified at all measurement dates, with different proportions. A simple "multi-2D" approach was adopted, consisting in performing independent filtering at each measurement date. A spatial decomposition of the displacements was carried out, at each date of measurement, by successive filtering of the various structures identified on the variogram. This decomposition dissociated the ground movements at the regional scale, probably related to topographical, geological or climatic factors, from local movements. The analysis of local displacement maps, supplemented by mean and standard deviation maps over the entire period studied, revealed local anomalies, mainly affecting roads, roadways of iron and specific buildings.

The adopted approach proposed a way for analyzing ground movement in urban areas with numerous reflectors. It confirms that surface impacts of the Dogger's exploitation by geothermal wells are not significant as a geomechanical calculation considering the sedimentary structure of the geological pile, and the pressures induced at depth (at the injection and producer wells). This is consistent with the forecasts of a simple 1D-geomechanical analysis, which estimated a subsidence at the wells of millimeter, at the limit of the resolution of the interferometry method.

The whole process was done blindly, with no a priori information on the location nor and on the exploitation rates of the doublets integrated in the calculations. In a next step, the observation done will be correlated with exploitation data.

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