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Sentinel-1 for monitoring tunnel excavations in Rennes, France

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Abstract

The present study comes in the context of tunnel excavation monitoring. To detect and explain the characteristics of ground displacements due to tunnel excavations, a PsInsar processing chain for Sentinel-1 images using S1TBX and StaMPS tools is set up. Then, it is applied to study surface displacements over the line b of Rennes city metro. This study exploits 20 Sentinel-1 images covering Rennes City, France, over a period of 2.5 years. Mean displacement velocity map and displacement time series show that the detected deformations are correlated in space and in time with the excavation works. Although we did not had the possibility to validate PsInsar results by ground truth data (levelling, GNSS), we demonstrate, through this blind experiment, that we can detect a dense PS cover, the feasibility of small displacement scale and rate monitoring using a small set of Sentinel -1 images. To improve these results, we forecast to use a bigger set of images and to compare the result to ground data.

Keywords: PsInsar; Sentinel-1; SNAP; StaMPS; Excavation; Subsidence

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1. Introduction

The current study exploits Sentinel-1 images and PsInsar technique to monitor ground displacements due to a tunnel excavation in Rennes city, France. Excavation works on this tunnel can give rise to horizontal and vertical movements of a few millimetres. Punctual measurements in time and space were carried out during the works. Because of the low density of these measurements and some access restrictions, INSAR turns out to be another technique to study these displacements that date from 2013. The PsInsar technique gives measurement points with an observation rate of a few days (6 or 12 days for Sentinel-1), a precision order of mm/year and especially a high density of points. Unlike ground-based techniques, PsInsar does not need in-situ instruments though the knowledge of a few ground data may allow improving the precision. It is the only technique that can provide historical measurements and allow historical analysis in the absence of ground data, provided the satellite images are accessible. Sentinel-1 data archives being available since 2014, we test PsInsar technique on these images for this blind experiment on Rennes city. Furthermore, we exploit Sentinel-1 images to demonstrate their ability for such study especially in the case of potential slow and nonlinear displacements on an urban area.

The paper is structured as follow: the part 2 presents the study area and some details on the construction works; the part 3 summarizes the Sentinel-1 dataset and our method using SNAP and StaMPS; the part 4 presents the obtained mean velocity map and time series. Then we propose some concluding remarks.

2. Study area

Rennes is the smallest city in France with a metro line. It is located in Bretagne region in the middle west of France. The city spans over a surface of 50 Km² with 8 Km² of vegetation areas and crossed by two rivers in the North-South and East-West directions. The city lays on a geological basin formed by a rocky substrate. Sediments are composed essentially by Brioverian schist, which is metamorphosed and altered leading to a local heterogeneity and a particular mechanic behaviour. The first metro line: line a, is operational since March 2002. A new line: line b, is under construction since the end of 2013 and will be delivered in 2019. It will serve 15 stations over 14 km, including two transfer stations with line a (Fig. 1.).

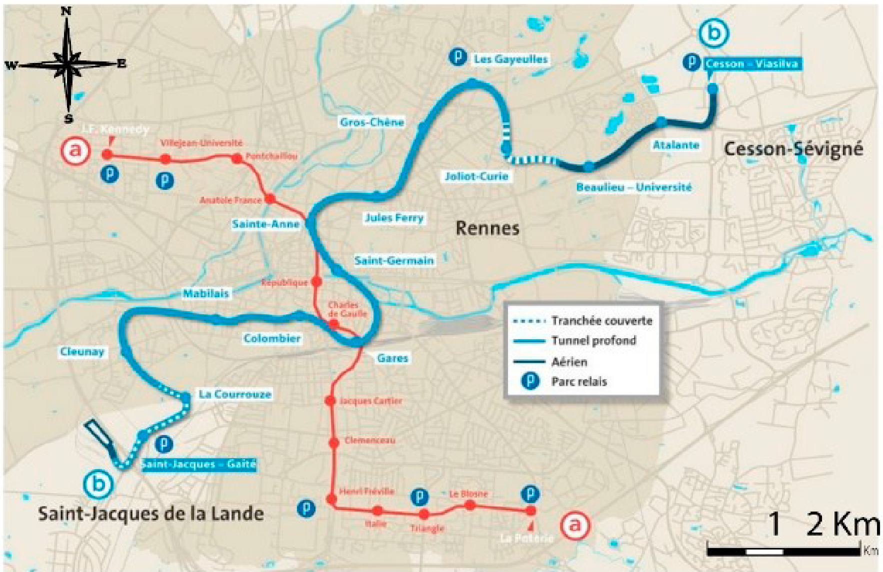

Fig. 1. Map of the new line b of Rennes metro [1]

The line is oriented South-West/North-East and has an 8.6 km-underground layout. The following table (Table 1.) shows the major dates of the excavation works already carried out. Underground excavation can lead to horizontal and vertical displacements of a few millimetres. It could extend along the tunnel and over the geotechnical influence zone of the stations.

Table 1. Tunnel excavation schedule (Information from press cutting) [2]

Station	Tunnel Boring Machine passage (TBM)
Starting next to La Courrouze	9/1/2015
Cleunay	11/4/2015
Mabilais	5/9/2015
Colombier	12/1/2016
Gares	8/4/2016
Saint-Germain	19/7/2016
Saint-Anne	20/9/2016
Jules-Ferry	16/6/2017

3. Dataset and methods

3.1. Sentinel-1 image for PsInsar

Sentinel-1 constellation is formed by two identical satellites A and B operating in C band (λ = 5.6 cm). They were respectively launched on the 3rd of April 2014 and 25th of April 2016 for an estimated lifetime of 7.25 years. The perpendicular baselines of the Sentinel-1 interferometric pairs are within ± 150 m due to the orbital gap of each satellite which is maintained in a tube of ± 50 m radius from a reference orbit [3]. Having each a 12-day repetitive orbit cycle, this reduces the revisit time to 6 days since the launch of the second satellite in 2016. The system operates in 4 standard acquisition modes, StripMap (SM), Interferometric Wide Swath (IW) (Table 2.) Extra Wide Swath (EW) and Wave Mode (WM). Moreover, it provides data with single and dual polarization (HH, VV, HH + HV and VV + VH).

IW is the main operating mode of this system. The feasibility of interferometry using Sentinel-1 data acquired in IW mode has been demonstrated e.g. by Yagüe-Martínez et al. (2016) [4]. The study of deformations with PsInsar technique using IW Sentinel-1 data was also carried out e.g. by Crosetto et al. (2016) [5] and Fiaschi et al., (2016) [6]. In addition, Parizzi et al. (2016) [7] studied the impact of polarization on the evaluation of deformations and showed that VV and HH give the highest PS density.

Table 2. Sentinel-1 IWA mode properties

IW mode properties	
Resolution	5 x 20 m (Azimuth x Range)
Incidence angle	30°-42°
Swaths Number	3
Extent	250 x 250 km
Cycle	12 / 6 days

3.2. Dataset

Based on the last discussed points, a set of 20 Sentinel-1 SLC images acquired in IW mode on the same relative orbit was used to study the movements (Table 3). Interferometric configuration in term of perpendicular baseline is generally respected for all Sentinel-1 images. The set of selected images cover a period of 2.5 years between 10/23/2014 and 04/10/2017 and an area of 79.2 Km² over Rennes city.

Table 3. Sentinel-1 dataset used for Rennes movements study

Images	10/23/2014	10/30/2015	10/30/2016
	3/28/2015	3/22/2016	3/29/2017
	4/21/2015	4/27/2016	4/4/2017
	5/27/2015	5/21/2016	4/10/2017
	6/20/2015	6/14/2015	
	7/26/2015	7/8/2016	
	8/31/2015	8/25/2016	
	9/24/2015	9/30/2016	
Orbit	Relative number	81	
	Direction	Descending	
	Azimuth	189.7531 °	
	Mean incidence angle	39.88°	
Study area extent	79.2 km²		
Reference zone	-1.6805° E, 48.0831° N, radius 30 m		

3.3. Processing chain for Sentinel-1 images

We exploit the dataset in our processing chain using SNAP v5.0 with Sentinel-1 Toolbox (S1TBX) and Stanford Method for PS (StaMPS) v3.3b1 [8]. The processing chain consists of three steps: interferograms generation using S1TBX, data export for StaMPS format and PsInsar processing on StaMPS.

- Interferograms formation

Elevation Antenna Patterns (EAP) correction is applied for all images acquired before March 2015. This is because of a phase variation in range that appears on interferograms formed between SLC products generated with the Instrument Processing Facility (IPF) V243 and the former version [9]. Sentinel-1 IW products are formed by swaths and bursts. To perform the registration of slave images to the master one, they are splited swath by swath. Then, the bursts, which cover the studied region, are selected. Registration is performed only on overlap bursts of slave and master images with the assistance of precise orbits and the digital elevation model STRM with a resolution of 30 m. Enhanced spectral diversity [10] is performed on bursts overlap to avoid phase ramps across individual bursts and phase discontinuities between bursts [11, 12] which are due to the presence of a linear Doppler frequency variation in azimuth [4, 10]. To achieve this, a registration accuracy of 0.001 pixel is required [11, 12].

Afterward, Interferograms are generated between one master and different slave images. Orbital and topographic phases are removed with the assistance of the STRM DEM and precise orbits. Then, the phase offsets are estimated on overlay regions between bursts to merge burst interferograms. Amplitude images are also generated from registrated images then debursted.

- Data export to StaMPS

PS processing on StaMPS needs a set of data entries: DEM, longitude and latitude bands, amplitude images and corresponding interferograms. These data layers are clipped, using the study area geographic limits to optimize processing time in next steps, and exported in gamma format with S1TBX. Amplitude images will be used in PSs candidate identification; interferograms contain phase data for PS selection; DEM allows calculating DEM errors and longitude/latitude bands are used to geocode PSs.

- PsInsar processing

PsInsar processing consists generally of the identification and selection of permanent scatterers using amplitude thresholding and phase stability estimation. Then the phase of selected PS is corrected from incidence angle errors and unwrapped using a 3D spatiotemporal algorithm [8]. A reference point or area is selected in this step. Line Of Sight (LOS) displacements relative to this point or area can be estimated after the correction of spatially correlated look angle errors (SCLA), master atmosphere and orbit error (AOE) and slave images atmospheric errors (SCN).

4. Results

4.1. PS distribution

The method allowed us to detect 137390 PS spreaded out on an area of 79.2 km², which represents a density of 1734 PS / km². PSs are located especially on built surface and bare ground (Fig. 2. (a)). Vegetated regions and water areas are not covered.

4.2. LOS displacements

Cumulated LOS displacements maps do not make it possible to clearly follow the displacements caused by Tunnel Boring Machine (TBM) progress during excavation works (Fig. 2. (b)). On the other hand, displacements are weak enough to confuse them with phase and processing noise. They have a magnitude, which varies between 15.21 and -18 mm in LOS direction.

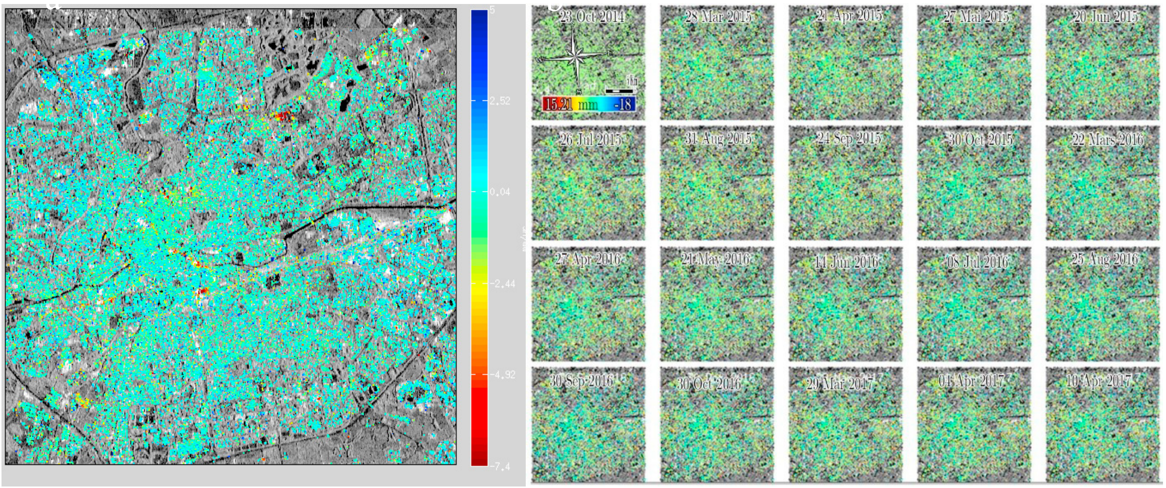

Fig. 2. (a) Mean deformations velocity on Rennes city for the period of 10/23/2014-04/10/2017. (b) Cumulated LOS deformation maps relative to 10/23/2014. Images are in radar geometry and values are expressed in mm.

4.3. Deformation mean velocity

Unlike LOS displacements, the mean deformation velocity map (Fig. 2. (a) and Fig. 3.) for the period of 10/23/2014-04/10/2017 shows that the ground subsidence is spatially correlated with tunnel line, even if similar order of magnitude of displacements are also identified far away from the excavation. Ground subsidence extends over about 200 m around tunnel and stations. The mean LOS deformation velocity values vary between +5 and -7.4 mm/year with a maximum subsidence values observed around stations and some parts of the tunnel. Which means that detected displacements are small in terms of rate and extent.

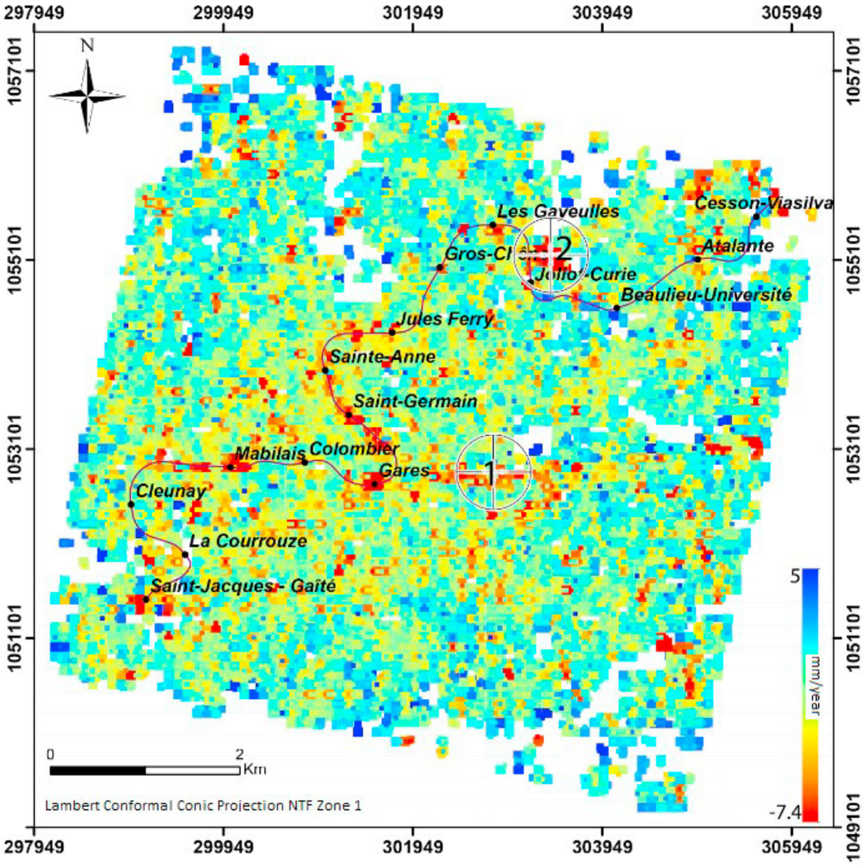

Fig. 3. Georeferenced map of mean LOS deformation velocity (expressed in mm/year) around Rennes metro line b for the period of 10/23/2014-04/10/2017. The line b layout is drawn in black and the station names are indicated along it.

4.4. Displacement time series

Displacements time series are calculated by averaging PSs measurements within a radius of 200m around the stations by inverse distance weighting method. They show that the movements have usually a non-linear subsidence trend, which is on most of stations consists in a succession of movement and stability periods. We used polynomial fitting curves with varied degrees (from 1 to 3) to show this trend. The time series show also that the movement can take place just after the TBM passage (La Courrouze and Cleunay stations) or before and after TBM passage (Other stations). Indeed, the cumulated displacements around the metro stations, where excavations were performed, can reach more than 5 mm in subsidence. The subsidence cannot be linked with evidence to the tunnel passage but should be correlated with the excavation workings. More information on the work calendar is needed to conclude on these matters.

All time series also exhibit some sudden phase variations at certain dates (31 August 2015 and 21 May 2016), which are independent of the location of the measurement. They generally correspond to 0.5 mm and this could be due to a phase noise caused by image registration errors on these dates or a persistent noise after processing with StaMPS, such as atmospheric residuals. The temporal resolution on these series is more than a month so the exploitation of more images could reduce this effect and allows more choices to eliminate some images that are exhibiting this effect.

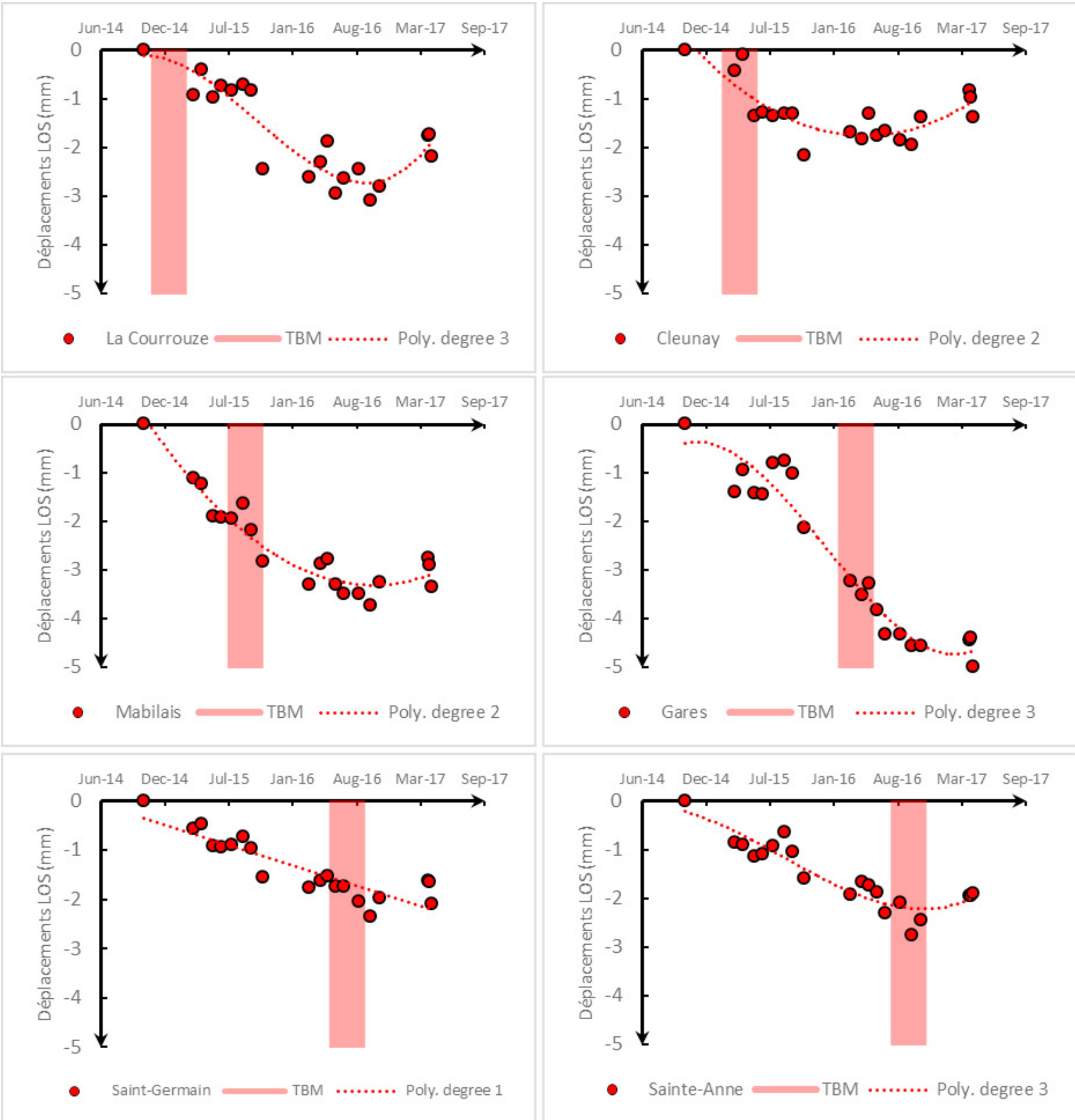

Fig. 4. LOS displacements time series for some stations on line b of Rennes metro. TBM passage is indicated with a red interval.

5. Conclusions

We had shown trough this study the feasibility of nonlinear and small displacements detection using Sentinel-1 images and PsInsar technique. Displacement rate varies around +5 and -7.4 mm/year over Rennes city with a maximum subsidence rate observed over about 200 m around tunnel and stations of the new line b of Rennes metro. Time series show a nonlinear trend of the displacement, which consists of a consecutive subsidence and steady periods. This show the ability of the method to detect ground displacement and control works even without ground measurements. Yet, time series used were not dense enough to clearly monitor ground displacements in relation with construction works but, a bigger set of images on ascending and descending orbits will serve to have more observations in time and allows to progress results analysis, especially to detect and analyse eventual dissymmetrical displacements over tunnel sides in relationship with Brioverian schists structural orientations.

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