TERRESTRIAL SAR INTERFEROMETRY MONITORING OF A CIVIL BUILDING IN THE CITY OF ROME

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ABSTRACT

In the last years the city of Rome is affected by the excavations for the realization of the third Metro line (Line C). In this paper the results of one month continuous TInSAR monitoring of a civil building along the Line C route are presented. More than 7000 Terrestrial SAR images were collected, thus allowing displacement images and time series of Persistent Scatterers to be obtained. Few mm displacement of a portion of the building has been observed by TInSAR data and then confirmed by Total Station monitoring.

1. INTRODUCTION

The increasing need of transportation infrastructures (high-speed railways, highways and urban subways) is leading to the design and construction of long and large-diameter tunnels, also in very complex geological conditions. These conditions usually arise from a combination of adverse ground and groundwater regimes, very high overburden pressures or, in the case of urban tunnels, the existence of sensitive structures within the zone of influence of the excavated tunnel [1]. Hence, the monitoring of effects induced by excavations, especially in terms of ground and structure deformations [2] [3], are becoming a basic requirement and, therefore, new technological solutions are greatly welcome. During the construction of tunnels in mountain areas, the main objective of deformation monitoring is to ensure that ground pressures are in line with expected values (e.g., [4]). Differently, in urban tunnels, the main objective is the monitoring of ground deformation which has to be sufficiently small in order to prevent damages to surface structures and utilities [5]. Hence, the fundamental difference in deformation monitoring stems from the fact that in mountain tunnels the objective is to guard against an ultimate limit state (i.e., collapse) while in urban tunnels the objective is to guard against serviceability limit states (i.e., crack initiation) for structures and utilities at ground surface. Furthermore, in urban areas both geotechnical and structural monitoring is performed during excavation. Focusing on structures both the settlements (and heaves) and tilting must be monitored. Electronic liquid level gauges, electrolytic tilt sensors (electro-levels), surface clinometers/tiltmeters, precise taping, crack-meters as well as geodetic levelling and laser distance measurement (sometimes by automatic total stations) are the most conventional instrumentations [6]. The accuracy of these measurements is typically ±0.2 mm (over about 100 m lengths) for precise levelling and ±5 arcsec (0.025 mm per metre) for angles and 1 mm + 0.2 mm/100 m for distances in the case of monitoring with total stations. However, all these instrumentations are characterized by some limitations especially in the case of critical conditions and for cultural heritages:

- monitoring of a limited number of points;
- installation of instrument or targets directly on the structure.

Above mentioned limitations can be overcome by the Terrestrial SAR Interferometry (TInSAR). TInSAR is an innovative radar remote sensing technique for displacement monitoring [7]. Such a technique has been extensively used in the last years for the monitoring of slopes and scarps [7]. In this paper an experimental application to the monitoring of a building in the city of Rome is presented and achieved results are discussed.

2. TERRESTRIAL SAR INTERFEROMETRY

Synthetic Aperture Radar Interferometry (InSAR) is a powerful technique for displacement monitoring. This technique, which can be applied by satellite, aerial or terrestrial platforms, is based on the SAR principle and the interferometric principles [8].

The SAR principle consists of a combination of several radar images taken while the emitting and receiving antennas move along a predefined trajectory (an orbit for a satellite, a route for an airplane or a rail in the case of ground based instruments). The combination of radar images that are acquired during the movement of the antenna, by the focalization approach [8], allows to obtain 2D images of the sensing scenario with a high range (instrument-scenario joining direction) and cross-range resolution (direction normal to the range direction in the horizontal plane) [8]. Hence, the final SAR image consists of several pixels (matrix of amplitude or phase signal), the size of which strongly depends on the

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instrumentation and the distance between the radar and the investigated scenario. By the phase comparison of SAR images collected at different times, information about the line of sight displacement of each pixel can be obtained. The last development in this field is the Terrestrial SAR Interferometry whose first prototypes date back to the end of '90 and early 2000. First commercial equipment date back to the second half of 2000.

2.1 The IBIS-L equipment

The herein presented study was performed by the IBIS-L equipment manufactured and commercialized by IDS S.p.A. (www.ids-spa.it). IBIS-L is an active ground-based radar sensor transmitting microwaves with a central frequency of 17.2 GHz (Ku-band), able to collect SAR images by a suitable 2 m long rail. Specifically the sensor moves along a linear rail by discrete step, thus, transmitting a stepped frequency signal and recording the echo at each step [9]. Range resolution is obtained by sampling in the frequency domain using the SF-CW technique [9]. Hence, the maximum range resolution δ_r, which is related to the bandwidth B of the transmitted stepped frequency signal by

$$\delta_r = \frac{c}{2B} \quad (2)$$

(with c being the velocity of light) corresponds to 0.5 m independently to the sensing distance. Differently, the cross-range δ_c (azimuth) resolution is directly related to the synthetic antenna length L and to the sensing distance:

$$\delta_c = \frac{\lambda}{2L} r \quad (1)$$

with λ being the wavelength and r the distance.
The maximum operation distance of the IBIS-L equipment is about 4 kms.

3. MONITORING OF BUILDINGS IN URBAN AREAS BY TINSAR

In recent years, Satellite SAR Interferometry is becoming an emerging technique for the measurement of surface ground displacements. This technique has been extensively used since the beginning of the 1990s to analyze landslides [9] [10] and ground deformations and subsidence in several urban area around the world such as Naples [11], Mexico City [12], Prato [13], Rome [14] and Paris [15]. However, Satellite InSAR it is more hardly applicable to the study of individual phenomena that take place in small areas and during critical phases because of the low temporal frequency of data (about 10-30 days with present satellites) and the predefined geometrical view (given by the satellite orbit). Such a limitation can be overcome by ground-based sensors InSAR technique. As a matter of fact, TInSAR offers a very short measurement time interval (one image every few minutes) in comparison to satellite-based interferometry and high pixel resolution (from few cms to few meters depending on the distance).
However, a terrestrial system (though with an operability range from few meters to some kms) has a very limited observation radius compared to a satellite-based system. These differences suggest that TInSAR is more appropriate for the monitoring of deformation and tilting of individual buildings characterized by small displacements and a rapid fast evolution.
The efficacy of TInSAR has been demonstrated in the last years for the displacement monitoring of volcanoes [16], snow cover [17] landslides [18] [19] and structures [20] [21].

4. TINSAR MONITORING OF A BUILDING IN ROME

In the last years the city of Rome is affected by the excavations for the realization of the third Metro line (Line C). Metro C will have a 25 km long (the main part of each in the underground) route with 30 stations, thus linking neighbourhoods to the city centre. The underground line will run below the urban and historical centre of the city thus encountering civil and historical buildings and monuments like the Colosseum and Palazzo Venezia. In order to ensure the safety of citizens and to protect a unique UNESCO world heritage site a complex monitoring plan has been set up [22]. The most advanced monitoring solutions were tested in the frame of the preparatory phases to the excavation. In this paper the activities, the results and the future developments of the monitoring of a civil building along the Line C route by T-InSAR technique are presented.

4.1 Geological setting

The city of Rome mainly develops in the lower Tiber River valley which is located between the Alban Hills Volcanic District to the south east and the Sabatini Mountains Volcanic District to the north west. The oldest sediments outcropping in the city are represented by the "Monte Vaticano Unit", which is characterised by Middle-Upper Pliocene grey-blue clays [23] with decimetre-scale intercalations of sands that represents the continuous bedrock of the Rome area. Overlying this substratum are the Lower Pleistocene Monte Mario", "Monte Ciocci" and "Monte delle Piche" units. The first and last units are marine sediments, whereas the middle is a 10 to 20 m thick epicontinental deposit of gravels and sands whose stratigraphical unit is still being debated in the literature [24]. The units descript above are overlaid by volcanic deposit of Sabatini Mountains Volcanic District at north west and to the Alban Hills Volcanic District at south east. The huge

volume of pyroclastic flow and fall deposits significantly modified the morphology and confined the paleo-Tiber River to the actual course.
The line of Metro C encounters in its route, starting form south east part, the deposit of Alban Hills Volcanic District, the alluvial deposit of paleo-Tiber River in Historical centre of Rome and the deposit of Sabatini Mountains Volcanic District to the north west.
This study case is located in one of the minor branch of the drainage network of Tiber River. The geological setting of this area is characterised by a complex drainage network, related to the main Tiber river valley and filled with recent alluvial deposits and subsequently hidden by a man-made fill, resulting from many centuries of urban settlements [25]. In what follows the geological stratigraphy of the site starting from the bottom is listed: i) complex of clays, sands and gravels of transitional environment from continental to marine; ii) 30 meters of alluvial material (alternation of silt and sand); iii) 10 meters of anthropic material [26].

4.2 Monitoring setting

The topographic and geotechnical monitoring of the ground surface and buildings is characterized by different sensors such as inclinometers, piezometers, strain gauges, and automatic total stations. During the preliminary underground activities specific attention has been devoted to buildings characterized by pre-existing structural problem, thus providing to compensation and stabilisation works before the excavation. Among them the Carducci School, located at the intersection between La Spezia and Altamura streets, has been selected as the ideal test site for the application of the Terrestrial SAR Interferometry monitoring (Fig. 1).
One month continuous monitoring (from March 6th to April 4th, 2009) has been performed by using the IBIS-L instrument, thus collecting a total amount of 7229 SAR image.
The monitoring platform, made of a concrete basement of sizes 2,10x0,6x0,9 m and covered by a wood roof, was located inside the Metro C yard at a distance of 40m from the building's corner facing the intersection from the La Spezia and Altamura streets (Fig. 2). A power connection was realised in order to guarantee a 24/7 power supply, thus allowing the continuous operability of the equipment. The equipment was installed, calibrated and set up for an automatic continuous with a 5 minutes sampling rate (Tab. 1).

Figure 1. Location of the Carducci School

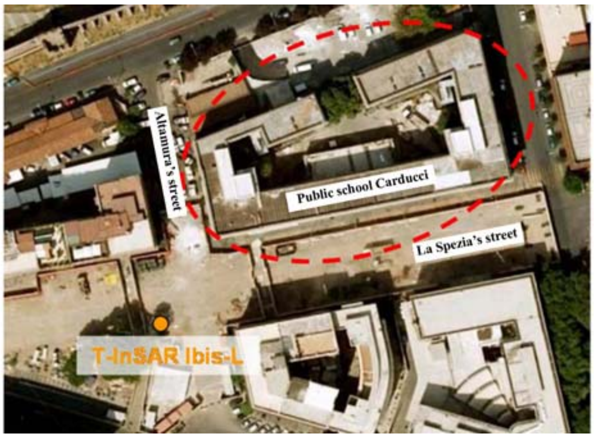

Figure 2. Aerial view of the monitoring area: the red dashed ellipse identifies the public school Carducci; the full orange circle identifies the IBIS-L installation site

IBIS-L configuration

Central frequency	17.2 GHz
Polarization	VV
Bandwidth	200 MHz
Length of the track	2 m
Max number of single image for SAR focusing	401
Inter-scan delay	6 s
Range resolution	0.5 m
Cross-range (azimuth) resolution	4.5 mrad (0.5 m at 110 m)
Accuracy	0.1 to 1 mm
Maximum distance	130 m
Vertical beamwidth	17° a -3 dB and 34° a -10 dB
Cross-range beamwidth	17° a -3 dB and 34° a -10 dB (200 m at 130 m in range)
Sampling rate	≈ 5 min

Table 1. Specifications of IBIS-L

4.3 Monitoring geometry

The scenario monitored by the interferometer IBIS-L was on the order of 130x200 m (i.e. 0-130 m in range direction and ±100 m in cross-range direction) (Figure 3). As one can see in the SNR (Signal to Noise Ratio) image (Figure 3) both the building faces in front of the equipment are clearly visible. The shortest face is along the Altamura street, instead the other one is along the La Spezia street. As one can see the closer part of the building (about 35 m), corresponding to the angle between the Altamura and La Spezia street, shows the maximum SRN values. Then they suddenly decrease along the La Spezia face of the building up to 90 m far from the monitoring site (mainly due to geometrical reasons).

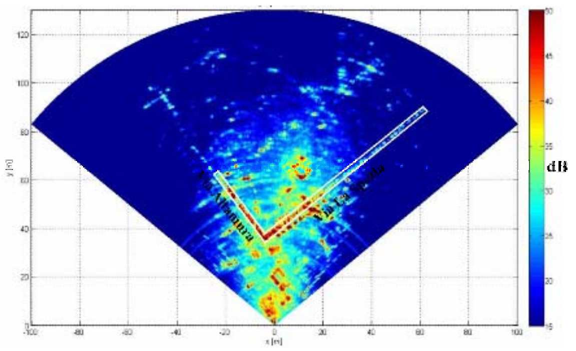

Figure 3. SNR radar map of the; the white line encloses the Carducci building. In the scalebar from blue to red highest values of SNR values

Fig. 4 shows the comparison between the SAR image and the optical image from the monitoring site.

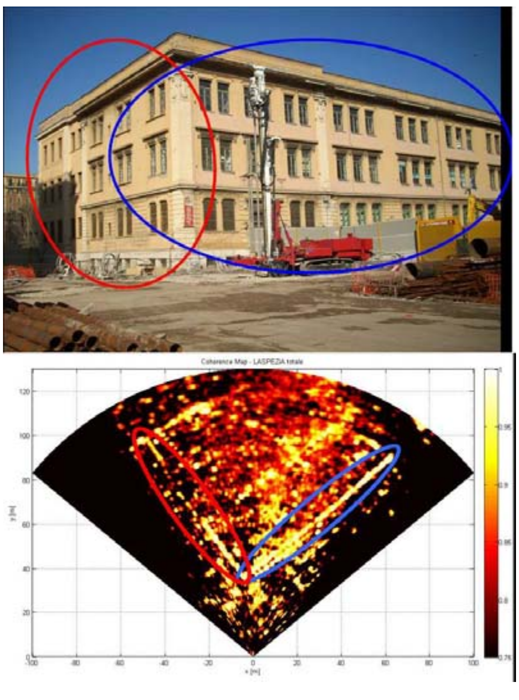

Figure 4. Comparison between the optical image (view, from installation site) and the coherence radar image of the building: the red and blue ellipses identify the Altamura street and the La Spezia street, respectively

It is worth to note that TInSAR monitoring is able only to collect the displacement along the instrument LOS (Line Of Sight), hence the measured displacement is always a component of the total displacement along a predefined direction (that correspond to the total displacement only in the case of a displacement direction parallel to the LOS). In the present case study the components of the total displacement ranges from 10% to 90 % of the real displacement for the vertical and horizontal displacement, respectively (Fig. 5).

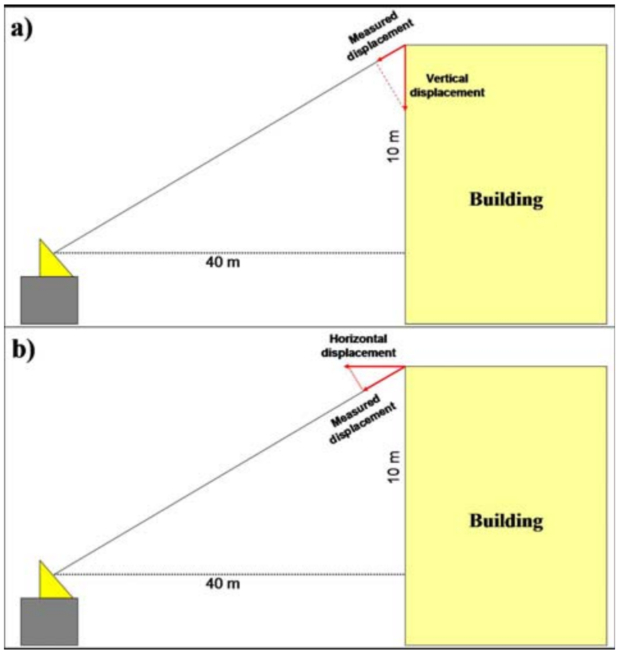

Figure 5. a) scheme of acquisition of the vertical component of displacement; b) scheme of acquisition of the horizontal component of displacement

5. RESULTS

Collected data were processed in order to obtain displacement images and time series of displacement of single pixels. Both conventional D-InSAR (Differential-Interferometric Synthetic Aperture Radar) analysis, by couples of images collected at different times, and multi-stack analysis were performed by using the large dataset available (more than 7000 SAR images). The main aspects contributing to the displacement accuracy were the following: i) variation of atmospheric conditions; ii) transit and parking of the working vehicles especially during the day.

Atmospheric error on the data were on the order of some mms during the overall period (i.e. significantly higher that expected displacement).

Differently, the presence of working vehicles mainly lead to a reduction of continuity in the data collecting which strongly affects the multi-stack analysis. Fig. 6 and Fig. 7 clearly show that the accuracy of the data during the day is significantly lower than during the night of at least one order of magnitude.

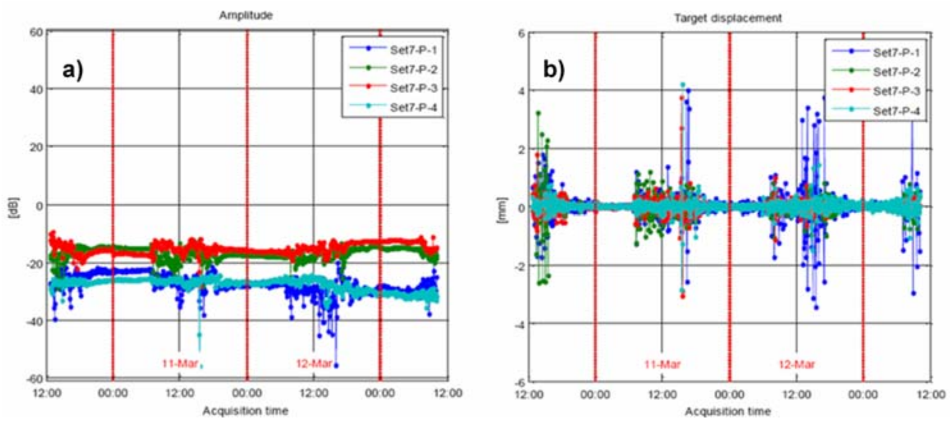

Figure 6. a) back-scattering signal and b) displacement, over the same time period.

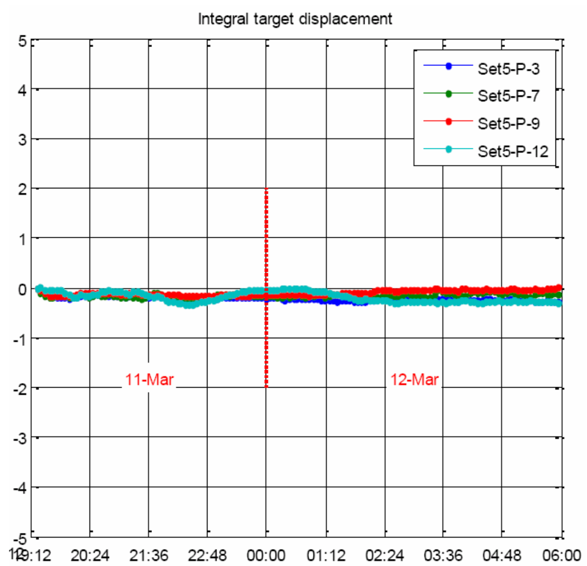

Figure 7. Temporal series of displacement of some pixels located near the corner of the building, for the weekend of March 11th-12th, 2010

Therefore, based on these achievements, images affected by the transit of vehicles were identified and removed from the stack by a specific algorithm based on the identification of anomalous back-scattering values.

Then, the displacement was computed by applying suitable phase screen procedures, thus achieving results showed in Fig. 8 and Fig. 9.

Specifically, a total amount of displacement toward the instrument ranging from 1 to 2 mm was observed in the portion of the slope facing the Altamura Street and the intersection between Altamura and La Spezia streets. Differently, no displacement was observed in the other portion of the building. The sharp boundary between the stable and the unstable portion of the building is clearly visible by the red full line of Fig. 8. Fig. 9 shows the displacement evolution at different cumulative time steps from the beginning of the monitoring activities.

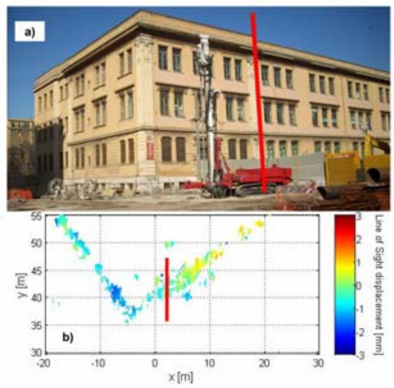

Figure 8. b) map of displacement of the period March 7th-28th, 2010: the blue colour identifies displacement toward the instrument. The red line, as for a), identifies the two portions of building at different behaviour

5.1 Comparison of TInSAR results with data collected by conventional monitoring

Besides the TInSAR monitoring the building was continuously monitored by conventional techniques like tiltmeters and two robotic total stations. 20 mini-prisms were installed at two different heights onto the faced of the school along the Almaura's and La Spezia streets. By the total station monitoring the real displacement of each mini-prisms along three main directions (Nord-Sud, Est-Ovest, Quota) were collected with a sample frequency of about 1 hour.

Therefore, must be considered that the comparison of results achieved by Total Station and TInSAR must take into account for the different monitoring geometry.

During the same monitoring period the mini-prisms at the corner of the building showed a displacement of 3,5 mm and 1,5 in the a vertical and in the North-South direction, respectively. Differently, mini-prisms located on the La Spezia face of the building did not show relevant displacements.

In order to rightly compare Total Station and TInSAR data the TS displacement along the LOS of TInSAR have been derived. Results of the comparison are showed in Fig. 10b.

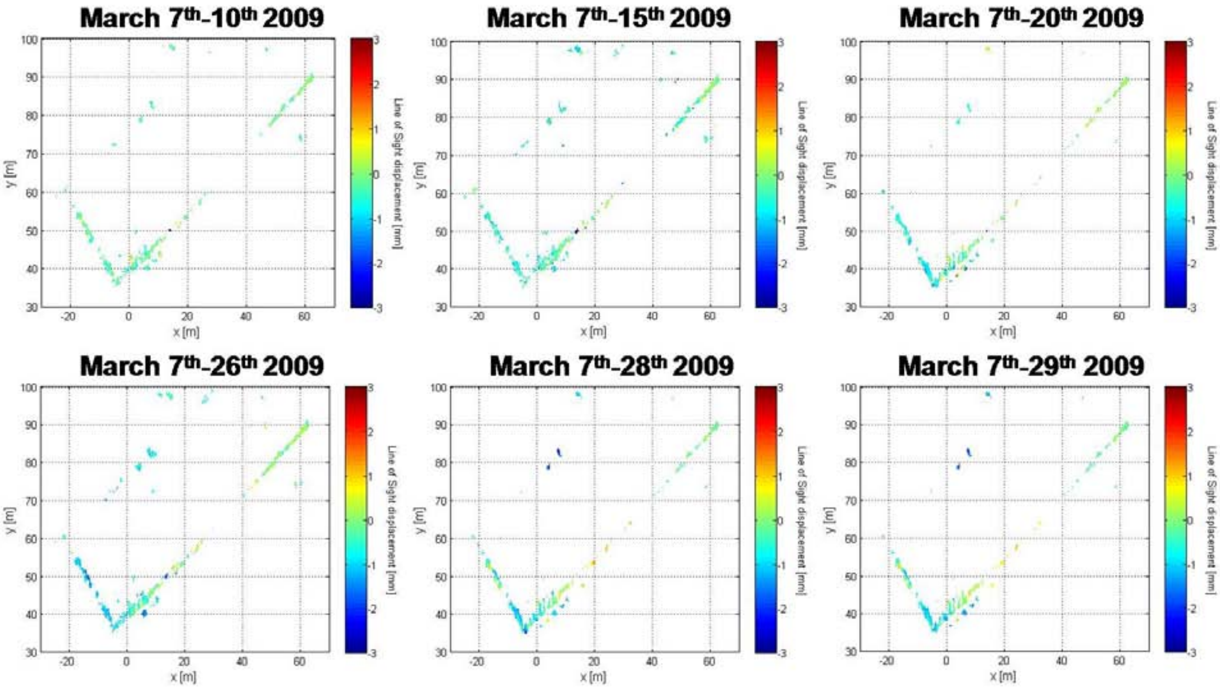

Figure 9. Series of cumulative displacement map

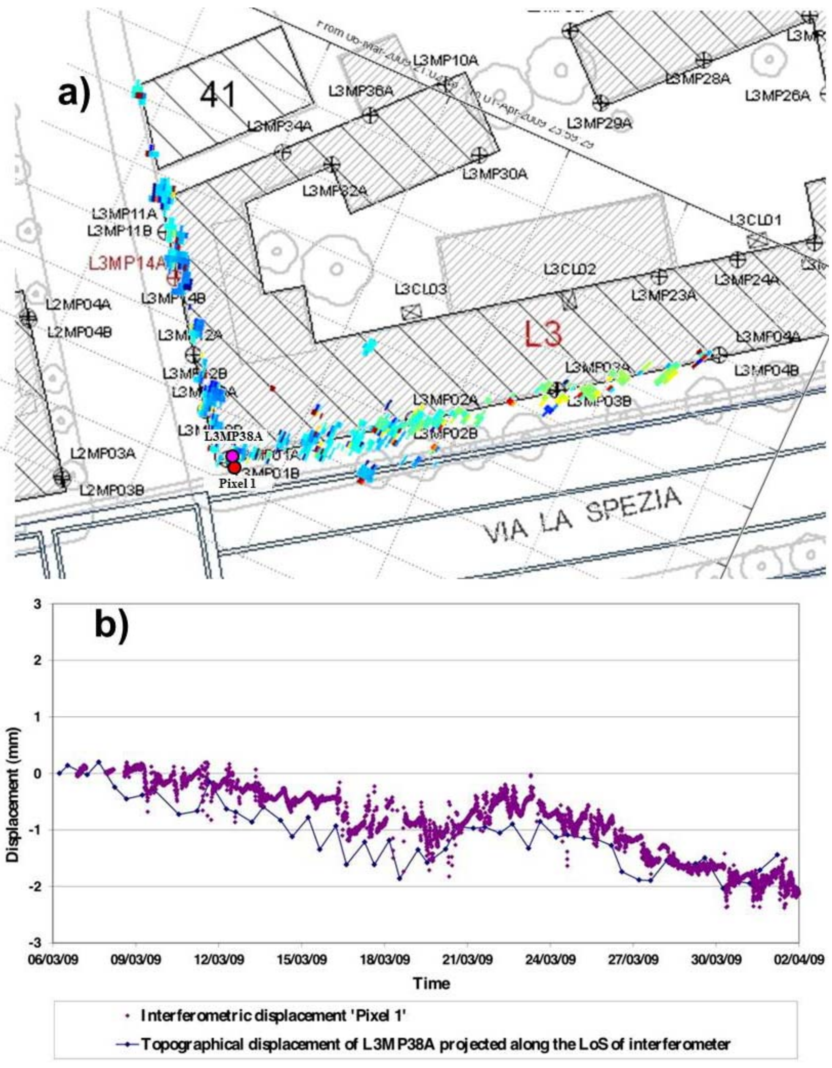

Figure 10. a) identification in plan of the two targets (red and pink circles) showing in figure b). b) time series of displacement derived from TS and TInSAR monitoring on the same area.

6. DISCUSSION AND CONCLUSIONS

One month continuous monitoring by TInSAR of a building affected by underground activities for a subway project has been performed in 2009. More than 7000 SAR images have been collected, thus allowing multi-stack advanced analysis of displacements to be performed. Few mm displacement of a portion of the building has been observed in spite of the complex acquisition geometry. As a matter of fact, monitoring of low-rise buildings in urban areas by TInSAR is very complex due to the following reasons: i) monitoring geometry often unfavourable for vertical displacement; ii) intense human activities; iii) small displacements. For example, in the herein presented study a limited percentage of vertical displacement could be detected due to the unfavourable monitoring geometry. This features, combined with the small displacement and the noise related to the working activities (which affect the long term displacement accuracy), do not allow to identify the vertical displacement. Differently, horizontal displacements have been easily detected with a sub-mm accuracy. A specific procedure for filtering SAR images affected by the transit of working vehicles during working hours has been also developed by using the backscatter values (that suddenly change with respect to their standard values during the transit). Such a processing tool has been demonstrated to be very effective in performing multi-stack analyses.

Projection of TS displacement collected during the same period along the TInSAR LOS direction allowed to validate measurements obtained by Terrestrial SAR monitoring. However, must be pointed out that TInSAR has several advantages with respect to TS monitoring. First of all, continuous displacement images of the building were achieved thus allowing to precisely identify the portion of the building affected by displacement with respect to the stable one. Furthermore, the data sampling rate is higher than those achieved by TS and no targets must be installed on the edifice.

These features suggest that TInSAR can be a very useful technique for the monitoring of buildings in urban areas especially in the following cases: 1) emergency conditions that require high sample rate and do not allow a suitable planning and installation of targets; 2) investigation monitoring in order to map in detail the area affected by displacement with respect to stable ones.

Furthermore, future developments will allow to improve the efficacy of TInSAR monitoring both in terms of displacement accuracy, data handling and interpretation. At this regard, correction of atmospheric noise by using weather data and the rigorous projection of TInSAR data on Terrestrial Laser Scanner derived point clouds seems to be very promising.

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