Chapter 1

# Railways' Stability Observation by Satellite Radar Images

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**Abstract**

Remote sensing has many vital civilian applications. Space-borne Interferometric Synthetic Aperture Radar  has been used to measure the Earth's surface deformation widely. In particular, Persistent Scatterer Interferometry (PSI) is designed to estimate the temporal characteristics of the Earth's deformation rates from multiple InSAR images acquired over time. This chapter reviews the space-borne Differential Interferometric Synthetic Aperture Radar techniques that have shown their capabilities in monitoring of railways displacements. After description of the current state of the art and potentials of the available radar remote sensing techniques, one case study is examined, pertaining to a railway bridge in the Campania region, Italy.

**Keywords:** railways deformation, synthetic aperture radar (SAR), interferometry, persistent scatterer interferometry (PSI), Cosmo-SkyMed (CSK)

## 1. Introduction

Radar waves are not influenced significantly by clouds and/or atmosphere, except for very heavy rain and tornados, etc.; therefore, it is a unique engineering tool for monitoring the Earth's surface. One of the brilliant inventions in the field of satellites radar remote sensing is known as persistent scatterer interferometry (PSI), which employs synthetic aperture radar (SAR) image time series. PSI is an advanced, more recent implementation of the differential interferometric synthetic aperture radar (DInSAR) technique. PSI is a powerful approach that has been employed for more than 15 years for studying/monitoring of deformation rates of man-made structures. It uses satellite interferometric synthetic aperture radar (InSAR) imageries as input. The PSI methodology is particularly suitable to urban/man-made regions, rather than to rural areas where the coherency of the radar signals is decreased dramatically. In the traditional DInSAR data analysis methodologies, coherency, geometrical decorrelation, and phase delay due to atmospheric effects on electromagnetic (EM) waves, are three major limitations of the application. However, for some specific conditions like urban areas, highways, or railways, temporal decorrelation decreases dramatically (i.e., coherency is higher), and features remain coherent in the produced interferograms for a long time [1–5]. To overcome the coherency problems of backscatterers (changes of the backscatters during the time) in repeat pass SAR interferometry, PSI was developed.

Historically speaking, different PSI techniques have been proposed in last decades. The first PSI technique was developed by researchers of the Politecnico di Milano (POLIMI) in Italy [1, 2]. Soon after, some other similar methodologies have been rapidly developed. The other similar well-known time series radar interferometric approach is named small baseline subset (SBAS) [6–9]. In PSI analysis, all acquisitions are employed, whereas in SBAS some of them are not, because their spatial baseline is too high. SBAS methodologies are more sensitive to geometric and temporal decorrelation compared to PSI analysis [6, 7].

In SBAS, much more interferograms are created than in a single-master approach (like PSI). The unwrapping procedure for SBAS and PSI is also different. In SBAS, at least in its original implementation, the interferograms are unwrapped first spatially and then temporally, while it is the opposite in the PSI analysis. One of the major disadvantages of SBAS is that in this approach disconnected clusters of interferograms might be obtained in the temporal and perpendicular baseline graphs. However, SBAS allows to measure displacements not only on highly stable point-like scatterers, but also on distributed scatterers (DS), i.e., areas with intermediate coherence. Therefore, several researches have been reported aiming to develop techniques that are able to combine advantages of both PSI and SBAS. For instance, minimization of the baselines and use of all radar images also in SBAS methodology were proposed in the literature, e.g., [10]. Another similar technique for monitoring the Earth's surface change was reported in [11]. A geophysical approach in [12] and a stepwise linear deformation with least square adjustment in [13] has been reported. Interferometric point target analysis (IPTA) and stable point networks are reported in [14, 15], respectively. In [3], multiple image pixels are used within a certain radius to estimate spatially correlated parameters (e.g., deformation rates and atmospheric signal delay). In this methodology, PSI and small baseline analysis have been combined heuristically. The SqueeSAR (Squeeze more information from SAR images) algorithm, capable of simultaneous analysis of PSI (i.e., PS) and DS, was reported in [16]. In SqueeSAR algorithm, combination of PS and DS helps to work in rural areas, where the coherency is lower. In [17], a similar algorithm, with contribution of polarimetric-based radar data, was heuristically proposed.

In PSI implementations, a large stack of radar images are considered for the estimation of historical changes of the Earth's surfaces, with proper modeling techniques. The output of PSI algorithms are deformation time series of the scatterers, and the elevation of those scatterers. PSI technique exploits the fact that some radar's pixels remain coherent during the time. With this method and by using a large stack of SAR images (usually more than 20 SAR images), atmospheric errors (i.e., the Atmospheric Phase Screen, APS) can be estimated with sufficient accuracy, and the proper phase correction can be implemented to remove them. In the standard PSI methodologies, a single master image with specific criteria is selected (from $N$ given images), and $(N - 1)$ differential interferograms w.r.t. the master image are generated. Then, with different approaches, permanent scatterers candidates (PSCs) are selected. By refinements of the selected PSCs, and by using permanent scatterers potentials (PSPs) [18], final permanent scatterers (PSs) can be generated. For each radar permanent/persistent Scatterer point, time series of the historical records of the Earth surface's height changes, and the height of each PS with respect to a reference point, are measurable. This methodology shows promising results in urban areas, where it is able to achieve an average of 100 PSs/km$^2$ (points densities) with low resolution sensors like ERS1/2 and ENVISAT-ASAR, and an average of a couple of thousands PSs/km$^2$with high resolution sensors like TerraSAR-X (TSX) and Cosmo-SkyMed. On the contrary, the rural/vegetated areas might not be explored properly with PSI methodology. The main reason is the absence of proper stable scatterers in such areas. Another disadvantage of the PSI is the need for a minimum amount of images for making appropriate phase unwrapping steps, which could severely influence the degree of correctness of the selected PSC. The other limitation of InSAR time series methodologies, is that PSI (and SBAS too) is a relative technique, i.e., all of the calculated time series for PS points are measured w.r.t. a reference point, which is assumed to be without any kind of movements. Nonetheless, many promising methodologies, like continuous GPS or leveling, could resolve this problem properly [18]. Another limitation is mainly due to the observation geometry of the satellite systems. PSI deformation rates are only measured along the satellite line of sight (LOS) direction; therefore, the obtained value of the deformation is actually just the projection of the deformation vector onto the SAR look direction. One example of PSI analysis is given in **Figure 1**. Fifty-two ENVISAT-ASAR imageries in descending mode over the Mexico City region have been analyzed, and the deformation rates over this area have been presented. Nine GPS stations that have been installed in this area to help displacement retrieval, are also depicted in this picture.

## 2. Engineering application review

In this section, we review some of the most important engineering applications of radar monitoring, with main focus on transportation infrastructure control. Several projects dealing with SAR and InSAR applications have been and are currently being carried out by both academic and research groups and by specialized companies: they are described in the scientific literature, as listed below, and on companies' websites (see, e.g., www.altamira-information.com, www.gamma-rs.ch, and www.npagroup.com).

One of the most important and elegant applications of the radar monitoring is about urban areas. With radar images, huge areas can be covered/monitored with high-resolution images,

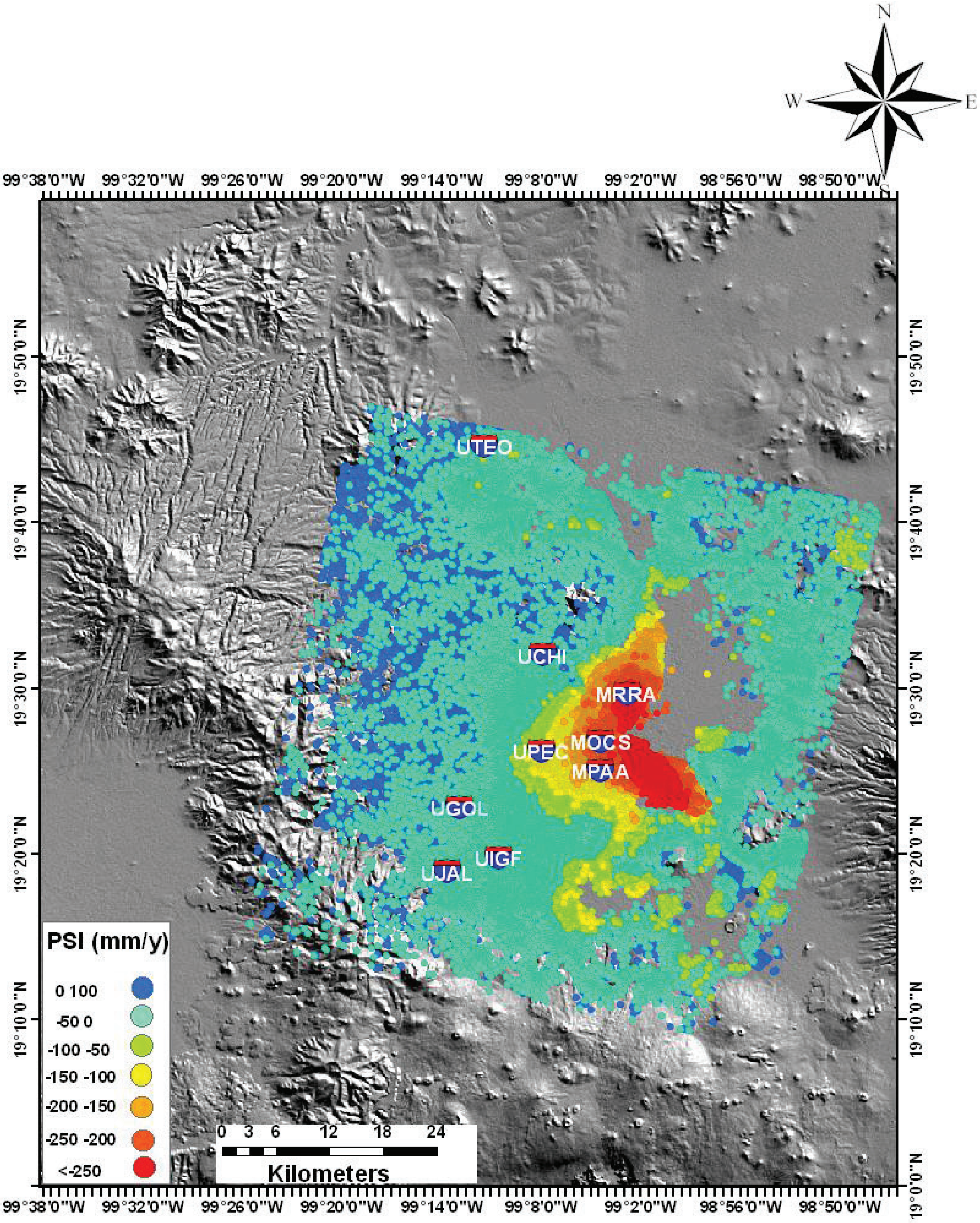

**Figure 1.** Example of PSI deformation velocity map over the Mexico City area. Fifty two ENVSAT-ASAR imageries and nine (permanent) GPS stations that acquired between 2002- June, 2010 and 1998-2012, respectively are analyzed and the results are depicted in this figure. The eastern part of Mexico City metropolitan area, has been subsiding at fast and constant rates for decades. Maximum continued subsidence rate of 352 mm/year in LOS direction is happening in the east and central part of Mexico City metropolitan area (Radar images are from ESA, and background SRTM (Shuttle Radar Topography Mission) images are from NASA).

and with acceptable re-visiting schedules. Historical measurements of the urban area's (at least from 1992) deformations and the cost-effectiveness of the monitoring are two important advantages of satellite radar monitoring in the human-made objects.

Radar remote sensing of the Earth's surface subsidence and uplifting is currently used in several cites all around the world. For instance, in the PanGeo project (http://www.pangeoproject.eu/eng/project_overview), more than 52 cities of the Europe which host around 13% of the entire populations, were under this kind of surveillance continually. This project gives online information to users for possible geo-hazard evaluations in their cities. However, the radar images that this project used are more or less low-resolution imageries, and no detail information could be retrieved. For instance, these results might not be very useful for detailed railways and bridges benefits.

For a detailed study of single target with radar images, one can refer to [19], where subsidence of the New Orleans has been studied. Another brilliant example is given by Zerbini et al. [20], where the Bologna region and Po Plain was the subject of the study. An example of subsidence monitoring due to water extraction is given by Osmanoglu et al. [21] for Mexico City metropolitan area.

Telerilevamento Europa (www.treuropa.com) runs a big project for subsidence monitoring due to oil and gas extractions that might be useful for oil and gas companies.

Faults movements monitoring is also one of the prominent usage of the radar remote sensing techniques. One example is given by Lyons and Sandwell [22]. With satellite radar monitoring of the faults, the rate of the creeping along the fault lines could be measured, and this might be translated to fault's future activities.

Landslide geo-hazard monitoring is also one of the most considered subjects in the radar remote sensing, for instance, see Refs. [23, 24].

In the Netherlands, radar remote sensing of dikes and dams for water defense systems is a common task, for instance, see [25].

Let us now consider the available applications on monitoring of transportation infrastructures (particularly, railways). In [26], a bridge displacement with use of very high (spatial) resolution X-band TerraSAR-X imageries is examined. The performed analysis shows that horizontal movement of the bridge is due to thermal expansion of the bridge and the vertical deformation is due to the settlements (during the time) of the bridge itself. The authors of that study proposed a combined model for thermal and (InSAR) phase residual rates estimations. They claimed that at least 1.5-year-cycle images are needed to reach a reliable estimation of deformations with InSAR techniques.

Finally, it is worth mentioning that [27] used RADARSAT-2 images for monitoring of the railways instabilities in the entire Netherlands. They use 73 images acquired from 2010 to 2015 to give a clear perspective from deformation scheme of the railways, and with some statistical approaches they evaluate the quality of the PSI analysis.

## 3. A case study of monitoring of railways stability in Italy (Campania region)

In this section, the results of the DInSAR PS technique to the remote monitoring of railways in the Campania region in Italy (**Figure 2**) are reported. In particular, we are interested in monitoring a bridge over the Volturno river, at Triflisco. As widely reported in literature [28–32], Campania region is very unstable in terms of the Earth's surface deformations. Intense urbanization, active volcanoes, complicated fault systems, landslides, subsidence, and hydrological instability (flooding) are the characteristics of this region [28–32]. 246 out of 652 sinkholes (38%) of the entire Italy are located in Campania region itself [31]. Volcanism is very developed in this area and is observed at Roccamonfina, Ischia, Vesuvius, and Phlegraean Fields regions. Historical eruptions happened at Vesuvius (several, the last one in 1944 A.D.), Ischia (1302 A.D.), and Phlegraean Fields (1538 A.D.). Therefore, this area is under geo-based investigation periodically. In addition, in the Campania region, the railways and bridges are pretty old, and are prone to sudden or slow deformation threats. For instance, the bridge over the Volturno river and the railways considered in this study were made in 1953.

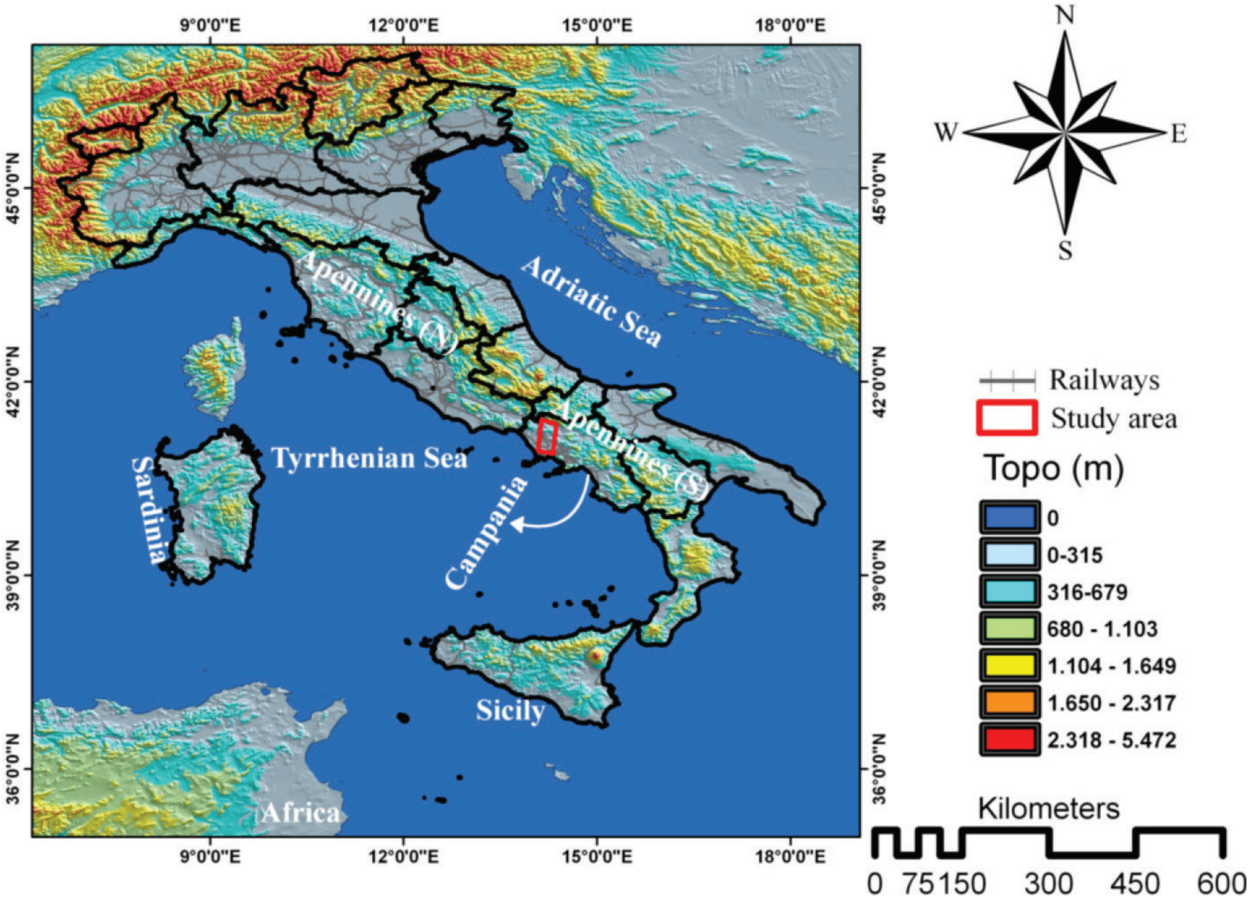

**Figure 2.** Study area and railways networks are depicted in this figure.

We were interested in the area at north of Napoli, including the Volturno river and a local railway, see **Figure 3**, with a bridge at Triflisco on which our interest is mainly focused. This bridge over the Volturno river and the entire railway considered in this study were made in 1953. In order to increase the stability of this bridge, the local railway company (EAV) made some rock bolts installations and cement injections to make the three pillars of the bridge more stable. Despite these efforts, EAV still was interested to evaluate the probable geophysical change of the railways (deformation rates) with other independent methods such as InSAR and PSI.

The study area has already gone under PSI analysis with low-resolution images like ERS, and ENVISAT-ASAR from PlaneTek Company before [33]. However, with these sensors, the number of PSs in the study area is too small. For instance, on the bridge over the Volturno river considered in this study, with ERS data sets from 1992 to 2000, in the ascending mode, only two, and, with the descending mode, only one PS have been selected. With ENVISAT-ASAR sensor in temporal baseline of 2003–2010, in the ascending mode six, and in the descending mode only one PS have been selected. Therefore, the need for using high-resolution imageries for a better understanding of the deformation phenomena on the bridge is obvious. In [33], first results on Cosmo-SkyMed data are reported, obtained by using the SPINUA (Stable Point Interferometry over Un-urbanised Areas) algorithm. We more recently performed a new analysis [34] by using a different algorithm [18]. Results of this analysis are recalled in the following.

Twenty-five InSAR images of Cosmo-SkyMed sensors at descending mode of HIMAGE/Stripmap were used for the considered study area, (it is depicted in **Figure 2** as a red rectangle). Images are acquired in HH polarization, right looking, X-band (EM wavelength: 3.1228 cm), with mean incident angle of 26.60° (incidence angle at the center of the transmitted beam).

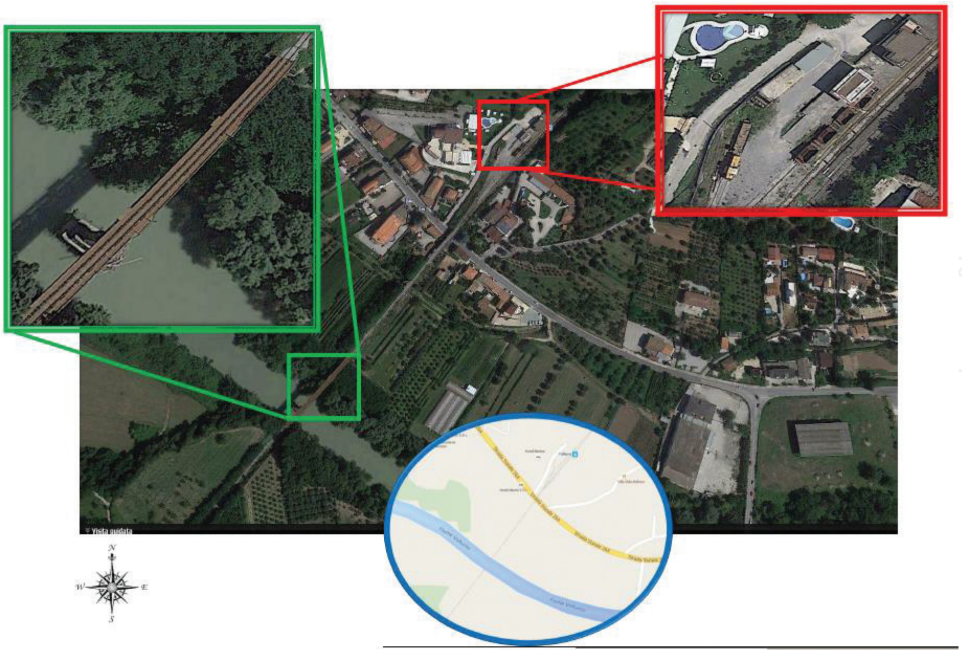

**Figure 3.** Study area, railways, targeted bridge, and the Volturno river are depicted in this figure. Down in the middle a global view of the study area is depicted (from Google Maps). On top left, the targeted bridge of the Volturno river, and on the top right, the train station are enlarged.

Data cover a temporal baseline between February 24, 2011 and March 23, 2015. We examine this stack of images to identify the number of scatterers on the ground that consistently/permanently show stable reflections back to the satellite on all images in the temporal baseline. With PSI analysis, historical motion of the permanent scatterers on the ground was determined. Image of June 5, 2013 has been selected as master image, and radar images were cropped in an area as big as 7.5 × 7.5 $km^2$, centered at the bridge on the Volturno river (**Figure 3**). Then, 24 differential interferograms have been generated w.r.t. the master image. With Cosmo-SkyMed data sets and for the selected study area of 7.5 × 7.5 $km^2$, more than 190,000 PSs including some on the railways, and some on the bridge of the Volturno river have been selected. The average velocity and ensemble coherence are as big as −1.8 mm/year (for whole area) and 73%, respectively, and the density of selected PSs is equal to 3378 PSs/$km^2$ for the entire area.

The majority of the PSs are from man-made structures such as houses, highways, railways, etc. **Figure 4** shows the mean velocity (deformation rate) of the Earth's surface in the study area. As it is clear from this figure, man-made structures such as highways, railways, and cities are designated as potential permanent radar wave reflectors (i.e., PSs).

**Figure 5** shows the selected scatterers (PSs) on the railways and the bridge itself. It turns out that they are 1385 and, as it is obvious from this figure, most of them are stable. Minimum and maximum displacement rates are −9.58 and 9.97 mm/year, respectively, but these high values are only obtained in some isolated points (dots in **Figure 5**), surrounded by points for which the displacement rates are much lower, so that they are probably due to phase noise.

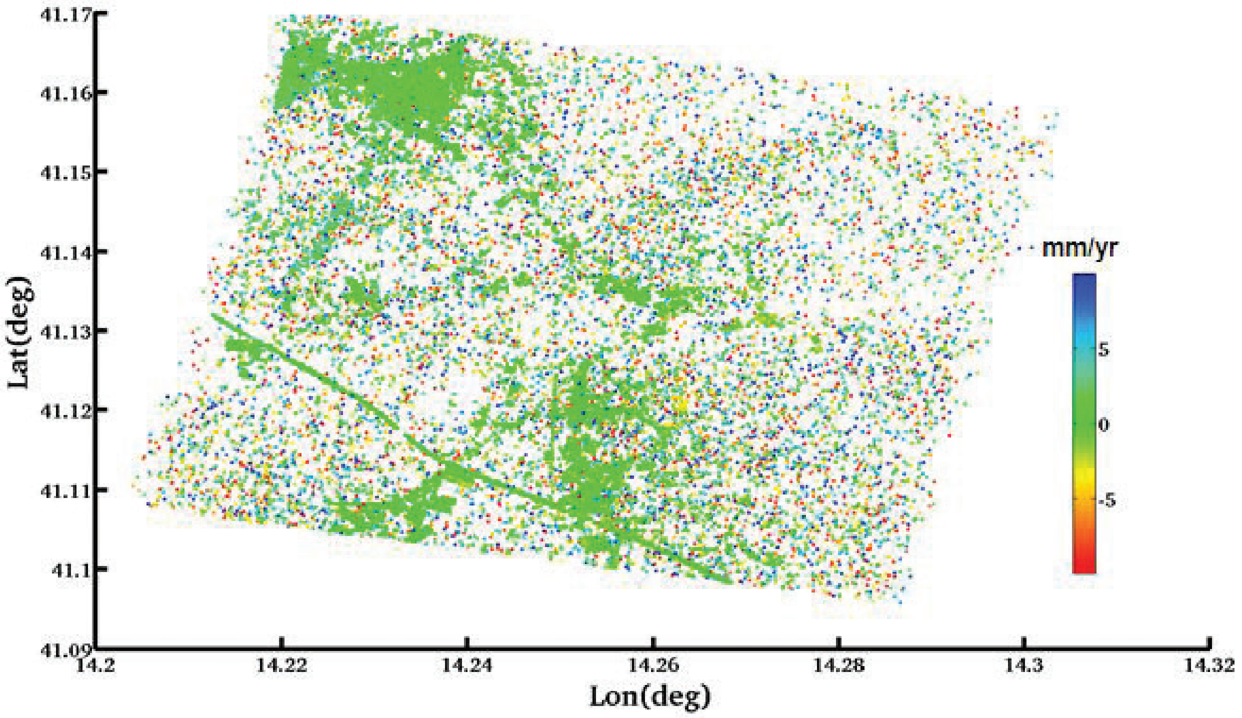

**Figure 4.** Mean surface displacement velocity of the study area based on 25 InSAR images from 2011 02 24 until 2015 03 23, estimated with PSI methodology. Gray pixels are PSs, white pixels are not PSs and no velocity estimation is obtained for them (for more details see [34]).

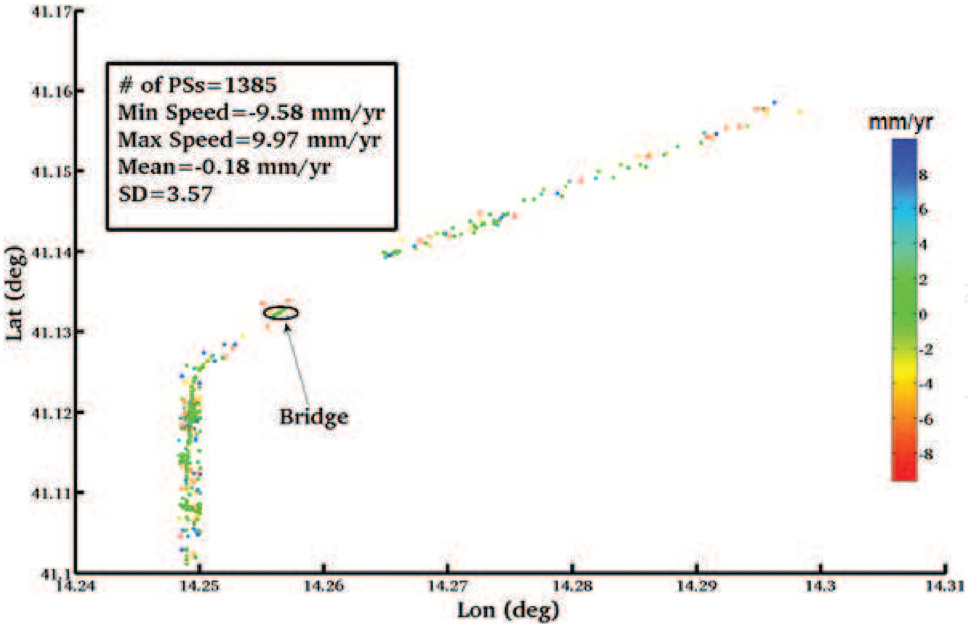

**Figure 5.** Mean displacement rates of PSs on the railways and statistics of these PSs (for more details see [34]).

The velocity averaged over all the 1385 PSs is 1.8 mm/year, and standard deviation (SD) is 3.57 mm/year. The PSs on the railways and nearby structures are selected in the GIS environment manually. Thirty of these PSs are located on the bridge, and they are highlighted by an ellipse in **Figure 5**. For these 30 PSs, minimum and maximum velocities of −0.9 and 0.05 mm/year have been observed, respectively, with an average of −0.3 mm/year and SD = 0.3 mm/year.

For each PS, not only the displacement rate, but also the entire time series of displacements is obtained. This allows for a deeper analysis of the bridge displacements' behavior and identifying probable acceleration along the temporal baselines. In particular, we have compared the time variations of the bridge displacement (or deformation) with the time variations of temperature in the same considered area and in the same time interval. In **Figure 6**, the points connected by lines show the deformation time series averaged over the 30 PSs' on the bridge, and the dots points represent the temperature in the Neapolitan metropolitan area [35]. As it is obvious from this figure, the deformation and temperature time series are very similar, demonstrating that most of the deformation is cyclical and it is related to the temperature seasonal changes in winter and summer time. Decreasing of the detected amplitude of deformation yearly cycle in 2013 and 2014 (**Figure 6**) is actually probably due to undersampling: in fact, it is related to the smaller number of images in that period, with no image acquired in summer 2013 and only one (at the end of August) in summer 2014.

In conclusion, comparison of average PSs time series on the bridge with thermal data shows that most of the line of sight (LOS) changes are due to the periodical variations of the temperature (i.e., winter and summer), with cyclical, seasonal deformations superimposed to a small rate of deformation of −0.30 mm/year.

Accordingly, the use of higher resolution imageries like Cosmo-SkyMed (CSK) and TSX to have better and smooth time series has been demonstrated by using CSK data. However,

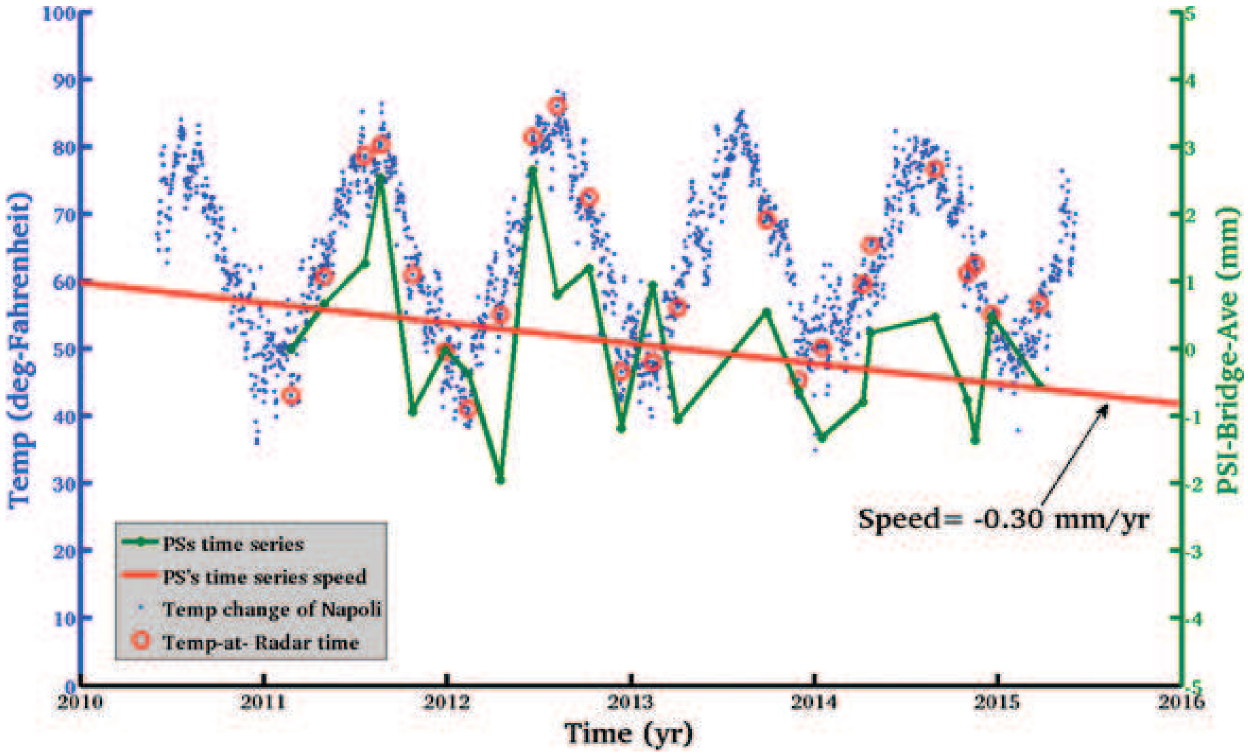

**Figure 6.** Bridge deformation as a function of time (points connected by lines) compared with temperature of the Neapolitan metropolitan area as a function of time (dots). Bridge deformation is obtained by averaging the values of all the 30 PSs on the bridge, and temperature data are taken from NOAA (for more details see [34]).

the combination of descending mode with ascending mode imageries to achieve the deformation rates in both vertical and horizontal directions (i.e., not only along the line of sight), continuous GPS deformation monitoring, corner reflector establishment, and leveling data might improve understanding of this study area. Comparison of SBAS methodology with the employed PSI technique also would be helpful and is the subject of our group's assignment.

## 4. Conclusion

In this chapter, the monitoring of railways based on the radar remote sensing and mainly PSI technique has been discussed. The key characteristics of InSAR-based technique have been described and benefits/disadvantages of the techniques have been highlighted. The main products of radar remote sensing surveillance have been briefly described and some of the most important projects have been concisely reviewed, providing a comprehensive list of references.

An important point that we stress here is that the availability of high-resolution SAR data is a key need for interferometric approaches if we want to monitor deformation rates of infrastructures like railways. In addition, it should be pointed out that, due to limited (re)visiting and SAR viewing geometries, PSI is not always capable of providing a real-time warning of possible critical deformations that might be occurred on railways, so that for this latter aim PSI should be employed in conjunction with other monitoring methods.

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