Persistent Scatterer Pair Interferometry: Approach and Application to COSMO-SkyMed SAR Data

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***Abstract*—Persistent scatterer interferometry is a widely used technique to detect and monitor slow terrain movements, with millimetric accuracy, from satellite synthetic aperture radar (SAR) data. We have recently proposed a method, named persistent scatterer pair (PSP), aimed at overcoming some limitations of standard techniques. The PSP method is characterized by the fact of exploiting only the relative properties of neighboring pairs of points for both detection and analysis of persistent scatterers (PSs), intended in the general sense of scatterers that exhibit interferometric coherence for the time period and baseline span of the acquisitions, including both point-like and distributed scatterers. Thanks to the pair-of-point approach, the PSP technique is intrinsically not affected by artifacts slowly variable in space, like those depending on atmosphere or orbits. Moreover, by exploiting a very redundant set of pair-of-point connections, the PSP approach guarantees extremely dense and accurate displacement and elevation measurements, both in correspondence of structures and when the backscattering is weak or distributed as in the case of natural terrains. In all cases, the measurements keep the full resolution of the input SAR images. In this work, the qualifying characteristics of the PSP technique are described, and several application examples and validation tests based on COSMO-SkyMed data are reported, which demonstrate the validity of the proposed approach.**

***Index Terms*—Distributed scatterers, geophysical measurement techniques, ground displacement measurement, persistent scatterers (PSs), synthetic aperture radar (SAR) interferometry.**

I. Introduction

SYNTHETIC aperture radar (SAR) interferometry is a powerful technology for measuring small ground displacements due to subsidence, landslides, earthquakes, and volcanic phenomena from satellite data [1], [2]. The interferometric phase, i.e., the phase difference of SAR images acquired at different times and with slightly different look angles, provides precise information about the elevation of the observed scene and about the possible displacements occurred between the acquisitions. Extracting this information is a complex task. In fact, elevation and displacement contributions to the interferometric phase need to be recognized and separated, whereas the disturbance due to the different atmospheric delays at the various acquisition dates must be eliminated. Moreover, valid interferometric measurements are possible only on radiometrically stable structures that return a coherent backscattering signal at different acquisition times. This set of sparse points, typically corresponding to buildings, structures, rocks, or noncultivated and scarcely vegetated terrain, must be identified as part of the processing. The concept of persistent scatterer (PS), which is characterized by the property of returning a coherent signal over long series of acquisitions, brought important advances in the field, introducing a new way of conceiving SAR interferometry [3], [4]. In the meantime, the more classical approach of working with small baseline interferometric pairs was developed and brought to maturation [5]. In all cases, extracting complete information from interferometric data is made extremely difficult also by the fact that the phase is measured modulo 2π, i.e., with an ambiguity of an integer multiple of phase cycles, and must be unwrapped [6], [7].

We have recently proposed [8] a new approach, named persistent scatterer pair (PSP), to identify PSs (generally intended as scatterers that exhibit interferometric coherence for the time period and baseline span of the acquisitions, including both point-like and distributed scatterers) in series of full-resolution SAR images, and to retrieve the corresponding elevations and displacements. The PSP method differs from standard persistent scatterer interferometry techniques [3], [4] and successive developments [9], principally for the fact that it overcomes the problems due to the presence in the phase of atmospheric and orbital artifacts (and, in general, disturbances slowly varying with the position in the scene) by relying, for both identification and analysis of PSs, only on the relative signal in pairs of points (hence the name PSP) close enough to be affected by the same disturbance. Therefore, the PSP technique is intrinsically robust to spatially correlated disturbances and does not need a preliminary processing aimed at compensating atmosphere and other spatially correlated contributions to the signal. Moreover, deviations from the models of displacement evolution typically used in PS techniques (e.g., due to strong nonlinear evolutions) are mitigated in the PSP approach, because close points likely have similar deviations.

More recently, the availability of COSMO-SkyMed data led to improve the PSP algorithm [10] with the purpose of efficiently identifying and processing the huge number of PSs that can be extracted from high-resolution X-band data. In fact, PSs are typically sparse in the scene, and to identify them, it is necessary to pair points that are relatively close but not only nearest neighbors, which require to test a huge number of arcs connecting potential PSs. To this purpose, a more efficient strategy to pair points was developed to build a highly connected graph whose nodes identify the PSs.

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The higher number of arcs and the higher connectivity of the graph in the enhanced PSP approach (from here on simply PSP) guarantee a more reliable PS identification and more accurate displacement and elevation measurements. Moreover, the PSP technique is capable of fully extracting the coherent information even from low-intensity SAR signals, even when strongly scattering structures are not present and the sensed signal is low and the scattering distributed, as in the case of rather smooth surfaces or natural terrains (provided they do not change with time, due to cultivation works or dense vegetation). To this purpose, the PSP algorithm does not rely on filterings that involve loss of resolution as the recently introduced methods for analyzing distributed scatterers ([11] or analogous approaches), but exploits the redundancy of the pair-of-point connections and keeps the full resolution of the original SAR images.

In this sense, the term PSs can refer to the scatterers whose backscattering properties can range from point-like to fully distributed, as long as they persist unaltered over time (at least for the period of interest), as the name suggests. In fact, thanks to the higher range resolution and/or the stricter orbital control, in the new satellite SAR systems the interferometric baseline is below the critical limit and there are no strong spatial decorrelation phenomena.

The redundant information provided by the highly connected PSP graph is conveniently exploited to guarantee more accurate measurements by a recent method for robust phase unwrapping and finite difference integration [12], [13], which are the key processing steps in the reconstruction of PS elevations and displacements from interferometric SAR data.

The PSP SAR interferometry technique has been successfully validated and extensively used in operational productions based on low- and high-resolution SAR data, in particular ERS, Envisat, and COSMO-SkyMed data, but the method can also be applied to SAR data from other sensors. The results confirm the validity of the PSP approach and demonstrate the important improvement brought in density, accuracy, and frequency of ground displacement measurements by the high-resolution X-band COSMO-SkyMed data with respect to low-resolution C-band SAR data like those from Envisat. Moreover, the capability of the enhanced PSP method to detect also weak backscattering signals results in extremely dense ground displacement measurements on both structures and natural terrains.

In the following sections, after describing the qualifying characteristics of the PSP technique (Section II), several application examples based on COSMO-SkyMed data are shown (Section III). Finally, some validation statistics are reported (Section IV), and conclusions are drawn (Section V).

II. PSP Technique

The fundamental concept at the basis of the PSP SAR interferometry technique [8], [10] is to both identify and analyze PSs by working only with pairs of points ("arcs"). This approach makes the method insensitive to spatially correlated signals such as atmospheric or orbital artifacts and does not require the model-based interpolations of a preliminary set of measurements that standard persistent scatterer interferometry techniques need in order to remove these interfering signals.

Given a stack of coregistered SAR images, let ϕ_i be the interferometric phase, i.e., the phase difference between the ith acquisition and one acquisition chosen as reference (master), and let B_i and T_i be the associated perpendicular-to-the-line-of-sight baseline and time from the master acquisition, respectively. For a given point, let r be the range between the point and the sensor in correspondence of the master acquisition. The interferometric phase measures the very small range difference between the ith and the master acquisition. Let us assume that the phase ϕ_i is *flattened*, i.e., a phase model obtained from a low-resolution digital elevation model (DEM) (or, if not available, from a geoid) is subtracted to the original interferometric phase. For the given point, let h be the residual between the real height and that of the DEM used to flatten the phase, and d_i be the along-the-line-of-sight displacement occurred at the ith acquisition time with respect to the master observation. In typical conditions, the following inequalities hold $d_i \ll h \ll r$, $d_i \ll B_i \ll r$.

Consider a pair of close (but not necessarily nearest neighboring) points, and let a be the arc connecting them. Let δh_a and $\delta d_{a,i}$ be the differences in the arc end points of the residual heights and along-the-line-of-sight displacements, respectively. Let us model the displacement as a function of the observation time T_i and few parameters $\mathbf{p}_a = (p_{1a}, p_{2a} \ldots, p_{Ka})$, i.e., $\delta d_{a,i} \approx \delta d(\mathbf{p}_a; T_i)$. Note that the components of the interferometric phase that are slowly variable in space, such as those depending on atmosphere propagation delay or inaccurate orbital knowledge, are almost identical in points that are sufficiently close in the scene. Using this property, through a known derivation based on simple trigonometry and approximations, it can be seen that the interferometric phase difference $\delta\phi_{a,i}$ between the two points identified by the arc a can be modeled as a function of δh_a and $\delta d_{a,i}$:

$$\delta\phi_{a,i} = [F(\delta h_a, \delta d(\mathbf{p}_a; T_i)) + \varepsilon_{a,i}]_{2\pi} \tag{1}$$

where $\varepsilon_{a,i}$ is the model error, which, when the length of the arc a is limited, is composed mainly by noise. In the simplest case, the model is a function only of the relative mean velocity δv_a and of the relative height δh_a of the observed targets: $\delta\phi_{a,i} = [4\pi/\lambda(T_i\delta v_a + B_i\delta h_a/(r\sin(\theta)) + \varepsilon_{a,i}]_{2\pi}$, where λ is the wavelength and θ is the incidence angle.

The deviations $\varepsilon_{a,i}$ from the arc phase model (1) are by definition small for a PSP. An important index to measure the statistical similarity of the SAR signals in two points is the temporal or multiacquisition coherence associated with the arc a, defined as:

$$\gamma_a = \max_{\mathbf{p}_a, \delta h_a} \left| \sum_i w_{a,i} e^{j\varepsilon_{a,i}} \right| \tag{2}$$

where $w_{a,i}$ are weights for the terms in the sum. The weights $w_{a,i}$ are all unitary in the simplest case, or they can depend on the amplitude values or other parameters of the acquired SAR images, or can be chosen according to different criteria. More generally, other indices different from (2) could be used to measure the statistical similarity of the SAR signals in two points, but in the following, we will refer to the multiacquisition coherence γ_a defined in (2). This index approaches the value 1 when the deviations $\varepsilon_{a,i}$ from the arc phase model (1) are small. Therefore, γ_a provides a measure of the quality of the corresponding arc as a potential PSP.

It is worth noting that not only atmospheric contributions, but also displacement behaviors not described by the evolution model $\delta d(\mathbf{p}_a; T_i)$, e.g., strongly nonlinear evolution with time, tend to be similar in close points and cancel out in the arc difference. Moreover, the nonlinear global maximization defined in (2) can be performed efficiently and robustly by exploiting the fact that, for relatively short arcs, the differences of the residual height and displacement δh_a and $\delta d_{a,i}$ are typically small.

Whereas it offers the mentioned advantages, working with arcs generally requires many more computations than analyzing single points: in fact, N points can form $(N-1)N/2$ different arcs. Note that considering only the M nearest neighbors of each point of the image is not a viable solution, because the $MN/2$ arcs to analyze are in any case too many, since PSs can be very sparse and therefore M must be large. Hence, an efficient algorithm must be devised.

The goal of the PSP technique is to find a set of valid arcs (in the sense of the coherence γ_a defined in (2) or analogous parameters) to form a graph (or a small number of subgraphs) with given connectivity and cardinality. The PSs are identified as the nodes of this graph.

The strategy to build such a graph is based on the idea of exploring a limited number of arcs: those that are more likely to have high coherence and those that are necessary to achieve the given connectivity of the graph. The main criteria in defining the arc exploration priority are three: 1) arc length, which cannot be too large in order to avoid dependency on atmospheric and other spatially correlated disturbances; 2) arc coherence, which provides an estimate of the reliability of the arc and the probability that its end nodes are good PS candidates and, consequently, that new arcs between these PS candidates have high coherence; and 3) connectivity, which tells which nodes need to be better connected.

The graph is built iteratively. At the beginning, no arc coherence and connectivity are defined and the first graph is built based on the distance between points, i.e., by connecting neighboring points. Then, at each iteration, new arcs are added to the current graph, by testing a limited set of arcs connecting points that are: not too distant, considered good PS candidates based on the coherence of the arcs incident on them, and not yet sufficiently connected. The specific balance between the mentioned criteria depends on the practical implementation and on the specific needs of the analysis to be performed. Typically, longer arcs are considered if the end nodes are good PS candidates and/or if such arcs are necessary to link points or cluster of points not sufficiently connected.

Moreover, the total number of PS candidates and arcs analyzed can be tuned to respond to the specific needs of a given analysis (observed phenomenon, type of terrain, etc.) and, in particular, according to the computational resources and expected/desired density of PSs.

It is important to note that the PSP arc estimates defined by (2) are independent in the sense that, for any cycle of the graph, the parameters $\mathbf{p}_a$, δh_a, and γ_a of a given arc a cannot be determined from the corresponding parameters of the remaining arcs in the cycle. Therefore, by exploiting a highly redundant number of arcs forming a highly connected graph, it is possible to identify more true PSs and less false PSs, and to obtain more reliable and accurate measurements.

When fully exploited, the PSP technique can extract displacement and elevation information corresponding to practically all SAR image pixels where a coherent signal can be expected, even when there are no strongly scattering structures and the sensed signal is low. Therefore, by exploiting the arc redundancy, the PSP method is able to detect and analyze all PSs, intended in the general sense of scatterers that exhibit interferometric coherence for the time period and baseline span of the acquisitions, including both point-like and distributed scatterers. It is worth noting that no spatial averages or filterings are required in the PSP method, and the full resolution of the original SAR images is kept.

It is worth mentioning that, differently from the original formulation of the PSP method [8], where the objective was to identify a minimal graph connecting the PS points with an approach similar to a region growing, the enhanced PSP formulation described here (and first presented in [10]) is based on the different perspective of exploring a larger number of arcs more efficiently, which, as seen, makes for obtaining more PSs and more accurate measurements.

After determination of the PSP graph and identification of the related PSs, differential measurements of the residual heights and displacements $\delta h_{a'}$ and $\delta d(\mathbf{p}_{a'}; T_i)$ are determined, according to (2), for each arc a' belonging to the PSP graph. These differential measurements are used to reconstruct, through finite difference integration, the displacement model and the 3-D positions of the PSs. Then, the PS velocity and elevation contributions are removed from the interferometric phase, and the residual phase can be more easily unwrapped, either independently for each 2-D sets of sparse points corresponding to each ith acquisition, or with 3-D approaches that consider all the acquisitions. It is worth noting that the interferometric PSP measurements are relative measurements, referring to the time of the master acquisition and to a reference point. The reference point can be chosen based on prior knowledge or statistical criteria.

The highly redundant but independent arc parameter estimates obtained in the various steps of the PSP technique are optimally exploited to guarantee a reliable and accurate solution by a recently proposed method for 2-D or 3-D robust finite difference integration and phase unwrapping [12], [13]. Moreover, this method enables the weighting of the graph arc estimates, based on their associated parameters (coherence, distance, and so on), and the use of a pyramidal approach, starting from the more reliable points and relative arcs. As a final step, classical spatio–temporal filtering techniques can be applied to the integrated values in order to remove residual artifacts.

III. PSP Applications With COSMO-SkyMed Data

The PSP SAR interferometry method has been validated in different test sites and used in several operational productions, with different types of SAR data, and for several typologies of applications, from studies of large areas affected by subsidence, landslides, earthquakes, and volcanoes phenomena, up to monitoring of single structures, buildings, transport infrastructures, etc. The large number and variety of experiments confirm the validity, and in particular, the sensitivity and the robustness, of the PSP approach. In addition, they show the big improvement brought in ground displacement measurements by the high-resolution X-band COSMO-SkyMed SAR constellation ($3\ \mathrm{m} \times 3\ \mathrm{m}$ resolution for the stripmap acquisition mode considered in this paper) with respect to the old C-band SAR systems like the ERS and Envisat ones ($5\ \mathrm{m}\ \times 25\ \mathrm{m}$ resolution).

The characteristics of the COSMO-SkyMed satellite SAR constellation are very suitable for SAR interferometry and PSP processing. The short wavelength and the low noise level of the COSMO-SkyMed SAR system enable the collection of a significant backscattering signal also from rather smooth surfaces without strong scattering structures, and to appreciate millimetric displacements in interferometric measurements. The baselines between the different acquisitions are kept below the critical limit for interferometry (the critical interferometric baselines are between about 3 and 9 km, depending on the incidence angle, for COSMO-SkyMed stripmap acquisitions, even bigger for spotlight), but sufficiently large (up to 2 km) to guarantee a metric sensitivity to elevation; this, coupled with the fine ground resolution, makes possible a very precise 3-D localization of measurements. The fine ground resolution allows the collection of a coherent backscattering signal even from small spots of bare soil in vegetated terrains. Finally, the COSMO-SkyMed constellation can provide an unprecedented frequency of interferometric observations (up to 8 per month), which enables the monitoring of fast-displacement phenomena.

The sensitivity and robustness of the PSP processing technique make it possible to fully extract the information provided by SAR interferometric data stacks. The tests performed with COSMO-SkyMed data proved that very dense (up to several tens or hundreds of thousands per square km) PSP measurements, characterized by metric localization and millimetric displacement accuracies, are obtained in all type of scenes where a coherent, even if low, backscattering signal is expected (practically excluding only densely vegetated and cultivated terrains, where the signals backscattered at different times are not coherent). The availability of dense and precisely localized measurements is particularly relevant when it is important to distinguish possible different displacements in the different parts of the observed object, as in the cases of monitoring building and infrastructure stability, or in characterizing landslide phenomena.

In the following, a selection of application examples taken from operational projects is presented, in order to show the capabilities of the PSP method and the high quality of the COSMO-SkyMed interferometric data. A first example is taken [14] from an experiment performed in an area of Beijing, China, affected by strong subsidence, probably related to the excessive groundwater exploitation. The project comprised the PSP processing of Envisat and COSMO-SkyMed SAR data and their comparison with optical

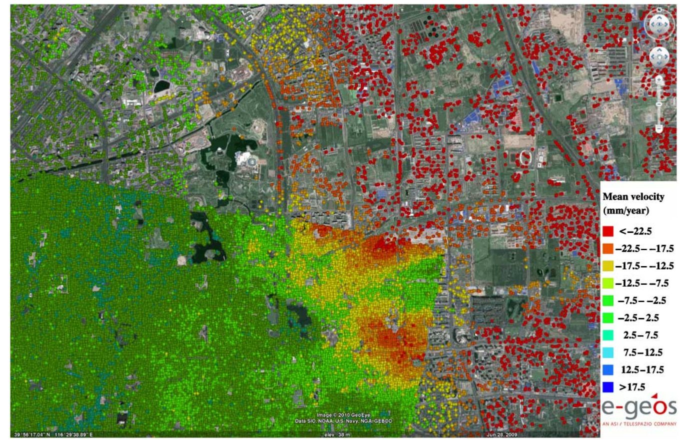

Fig. 1. Beijing, China, subsidence analysis. Comparison between the PSP mean velocity measurements (March 2008–March 2010) obtained from Envisat and COSMO-SkyMed Stripmap SAR images. The image shows the good agreement of the two results, as well as the dramatic increase in PS density allowed by COSMO-SkyMed data. The results were validated through comparison with optical leveling data.

leveling data. The Envisat C-band low-resolution dataset was composed by 49 descending acquisitions taken between June 2003 and May 2010, with interferometric baselines spanning about 1450 m. The COSMO-SkyMed X-band high-resolution dataset consisted of 31 descending Stripmap acquisitions taken between March 2008 and June 2010, with interferometric baselines spanning about 1400 m. The ground displacement measurements obtained from the two datasets showed a good agreement in the overlapping area and period, which confirms the robustness of the PSP method when applied to data with different resolutions and wavelenghts (see Fig. 1). Noticeably, the PS density achieved with COSMO-SkyMed was about two orders of magnitude higher than the one obtained applying the same technique to Envisat data. Such different densities of PSP measurements are due essentially to the higher spatial resolution of COSMO-SkyMed (as previously discussed) and also to the facts that the Envisat acquisitions span a longer period and a baseline range above the critical one for Envisat, which cause temporal and spatial decorrelation (only the point-like scatterers provide a coherent signal). However, long temporal spans or large swaths can be useful to appreciate displacements that are very slow in the time or in the space domain, respectively.

The capability to better describe complex phenomena with a higher density of PSs was evident in the analysis of landslide phenomena in the area of the Mormanno junction of the Salerno–Reggio Calabria highway, Italy, performed by PSP processing of Envisat data (42 ascending acquisitions from May 2003 to July 2010, baselines spanning 1898 m) and COSMO-SkyMed data (41 ascending acquisitions from May 2011 to August 2013, baselines spanning 1399 m). For the same reasons explained above in the discussion of Fig. 1, only few PSP measurements could be obtained with the C-band data, allowing the identification of two landslides (on the north-eastern side, affecting the highway, and on the southern side), but providing scarce information on their morphology and none on their mutual influence (see Fig. 2, left image). The characteristics of the X-band data enabled to identify,

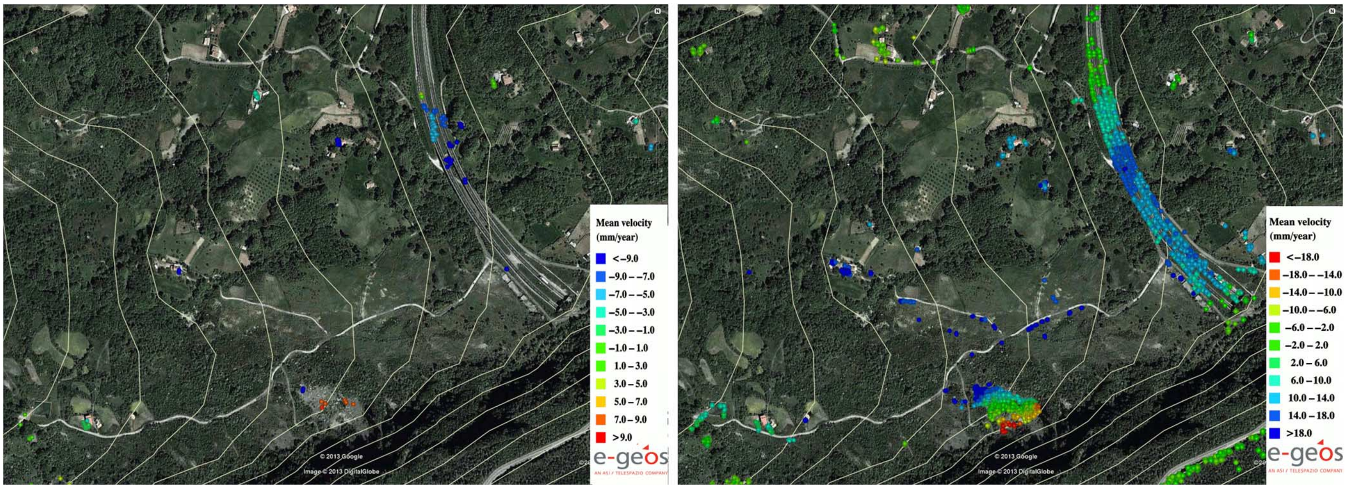

Fig. 2. Mormanno highway junction, Italy, landslide monitoring. Comparison of PSP mean velocity measurements obtained from Envisat (42 ascending acquisitions, May 2003–July 2010, left figure) and from COSMO-SkyMed (41 ascending acquisitions, May 2011–August 2013, right figure) SAR data. The much higher number of measurements obtained with the COSMO-SkyMed data enables the interpretation of complex phenomena, like the two interacting landslides on the south and on the north-eastern side of the shown valley. The reported contour lines (spaced by 20 m and decreasing from east to west) were obtained from a very low resolution DEM.

with the same technique, a higher number of PSs on the same area (see Fig. 2, right image). This made it possible to delineate with more precision the relative movements within each phenomenon (e.g., distinguishing the way the northern landslide affects the highway junction) and to understand their mutual influence. In fact, the southern landslide is characterized by a south-north movement, but in the terminal part it crosses the northeast-southwest movement of the other wider landslide; the final result is a rotational movement of the southern landslide.

SAR interferometry techniques measure the component of the displacement along the line of sight. In several cases, measuring a component of the displacement can be sufficient to describe the phenomenon, in particular, when the direction of the terrain displacement is approximately known, as in the case of simple subsidence or some types of landslides. However, with SAR sensors mounted onboard polar satellites (as COSMO-SkyMed), it is possible to perform measurements along two view directions using the ascending and the descending passes of the satellite. Since the SAR looks in a plane perpendicular to its orbit, these two lines of sight lie approximately in a plane locally perpendicular to the north-south direction. Therefore, SAR interferometry is sensitive only to the vertical and east-west components of a displacement. These two components can be reconstructed separately by combining the results of the ascending and descending pass acquisitions. This combination can be performed only in the areas where PSs are identified in both acquisition geometries, a requisite that the high PS density obtained with PSP processing of high-resolution COSMO-SkyMed SAR data helps to meet. As an example, we report some results relative to the monitoring of displacements in a mining area in Minas Gerais state, Brazil. Two elaborations were performed, with ascending (32 images, May 2012–November 2013, baselines spanning 2127 m) and descending (32 images, March 2012–October 2013, baselines spanning 2050 m) acquisitions. The PSP displacement measurements obtained in the two elaborations (Fig. 3, top images) were combined to extract vertical and east-west displacement components (Fig. 3, bottom images).

It is worth mentioning that in some cases (like those of Fig. 3), the terrain displacements can be significantly large and fast. Since the PSP technique works with differences between close points, it is able to reconstruct large and fast displacements if there are paths in the space domain where the relative displacement of close points between consecutive acquisition times is sufficiently small. If this condition is verified, it is, in principle, possible to reconstruct even very large displacements such, e.g., those due to earthquakes or certain types of landslides. However, in some cases, such paths could not exist either because abrupt displacement phenomena create a fracture (a large relative displacement between two areas) that is too extended, or due to the presence of large strongly vegetated areas without PSs. In such cases, it is possible to process separately either the isolated regions or the acquisitions corresponding to different periods (e.g., before and after an earthquake). These problems are common to all SAR interferometric techniques. However, the capability of the PSP technique to detect many coherent pixels also corresponding to natural terrains, and the fact of working with differences between close pixels, make these problems extremely rare.

It is important to remind that, in addition to the mean velocities, also the displacements d_i occurred at each ith acquisition time are reconstructed by PSP SAR interferometry, as briefly discussed at the end of Section II. In fact, the evolution with time of the displacement is fundamental to understand the nature of the phenomenon and to monitor possible accelerations or decelerations. The above discussed project, relative to the monitoring of displacements in a mining area in Minas Gerais State, Brazil, provides some examples of ground displacements evolving nonlinearly with time (see graphs in Fig. 3).

The availability of high-resolution SAR data opened the way to the possibility of monitoring building and infrastructure

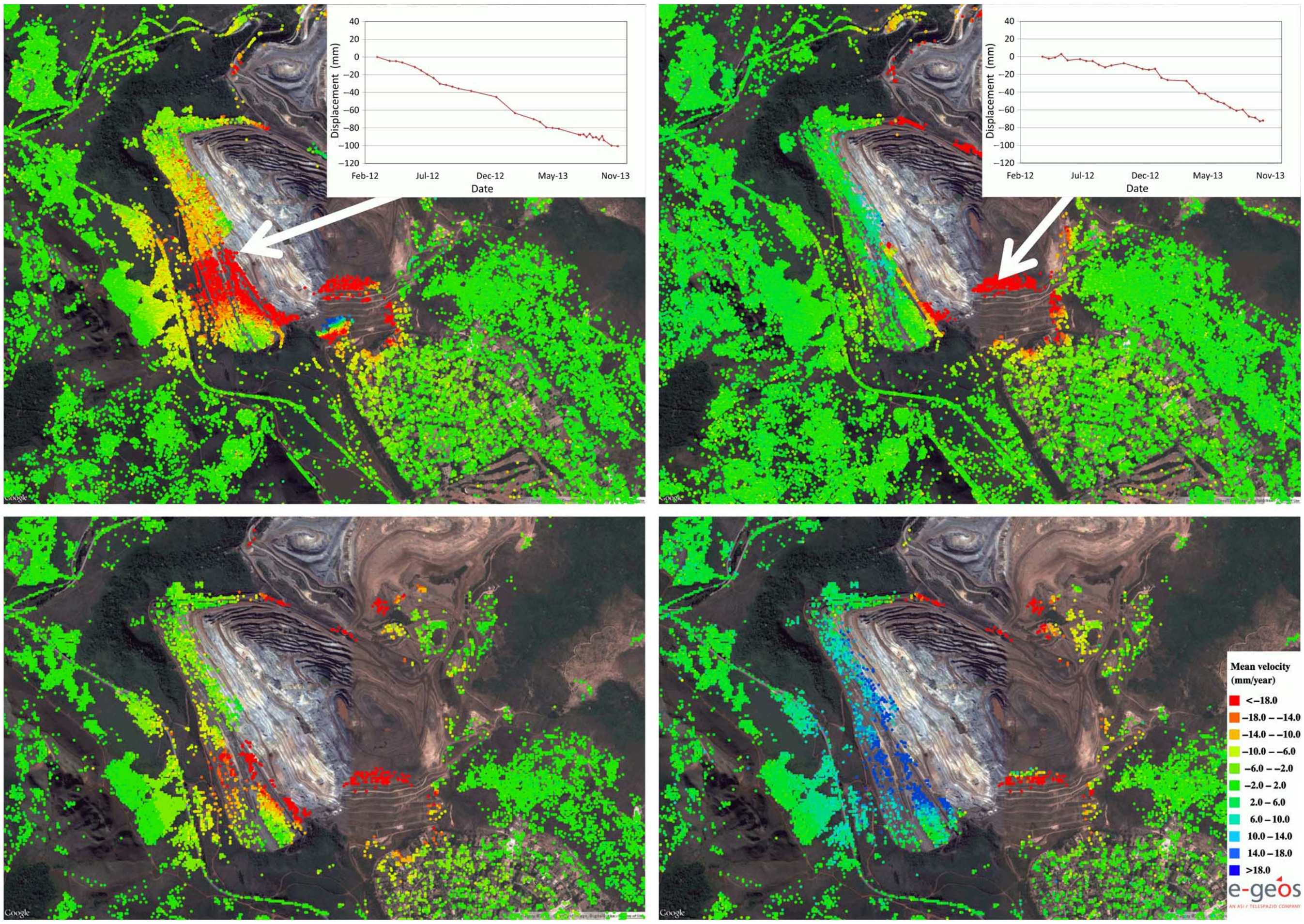

Fig. 3. Terrain displacement monitoring in a mine, Minas Gerais, Brazil. The images on the top show the PSP mean velocity measurements along the line-of-sight of COSMO-SkyMed ascending (32 Stripmap SAR acquisitions, May 2012–November 2013, left figure) and descending (32 Stripmap SAR acquisitions, March 2012–October 2013, right figure) data. In addition to mean velocities, also displacement temporal evolutions are typically measured: as an example, displacement temporal evolutions for the two points indicated by the arrows are shown in the graphs. The bottom images show the vertical (left) and east-west (right) components of the mean velocities reconstructed from the combination of the top image measurements.

stability. In particular, the sufficiently large baselines of COSMO-SkyMed acquisitions provide a very good sensitivity to elevation, and through the PSP technique PSs are localized with metric 3-D precision in correspondence of structures. Examples of this capability can be seen in the PSP analysis of St. Peter's Basilica, Rome, Italy (Fig. 4), obtained from 34 COSMO-SkyMed ascending Stripmap SAR acquisitions (January 2010–May 2012, baselines spanning 1775 m); or in the PSP analysis of an important viaduct (Fig. 5) of the highway that connects Tuapse to Sochi (Russia), performed with 35 descending Stripmap SAR acquisitions (February 2009–December 2010, baselines spanning 1382 m).

The metric localization of the PSP measurements based on COSMO-SkyMed data makes it possible to distinguish different displacements in the different parts of buildings and infrastructures, which is important to monitor their stability. An interesting example comes from the PSP analysis of an area of Shanghai, China (52 COSMO-SkyMed descending Stripmap SAR acquisitions, May 2008–June 2010, baselines spanning about 1800 m). The PSP measurements detected a subsidence pattern that closely follows the track of the subway line 9 (see Fig. 6). The availability of several measurements corresponding to the different parts of each building can help in the evaluation of how much this subsidence endangers each single building.

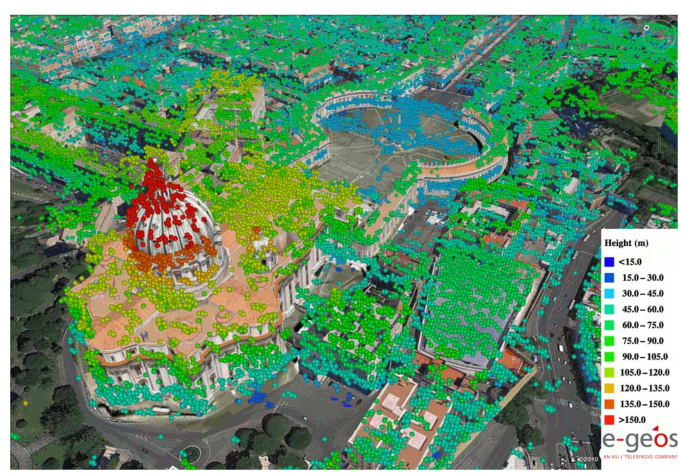

Fig. 4. St. Peter's Basilica, Rome, Italy. PSP height measurements obtained from COSMO-SkyMed Stripmap SAR data (34 ascending acquisitions, January 2010–May 2012). The 3-D view highlights the accurate positioning of the PSP measurements.

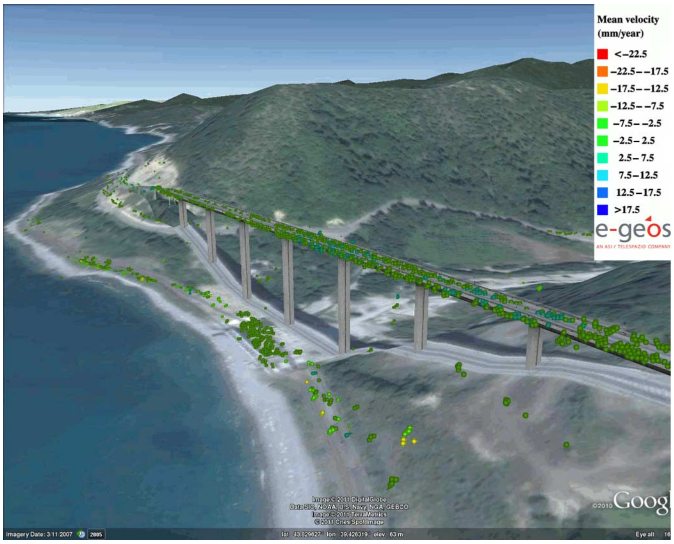

Fig. 5. Viaduct of the Sochi–Tuapse highway, Russia. 3-D view showing accurate positioning of PSP mean velocity measurements obtained from COSMO-SkyMed SAR data (35 descending Stripmap SAR acquisitions, February 2009–December 2010).

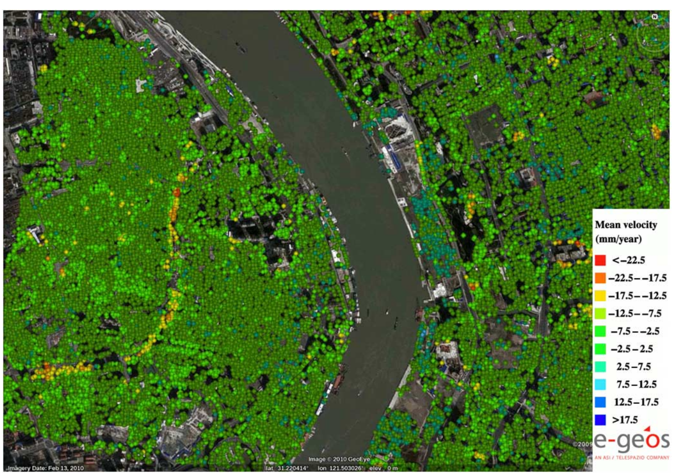

Fig. 6. Shanghai, China. Subsidence along the track of the subway line 9 detected by PSP mean velocity measurements from COSMO-SkyMed Stripmap SAR data (52 descending acquisitions, May 2008–June 2010).

As mentioned in the discussion of the PSP technique in Section II, the processing parameters and, in particular, the total number of analyzed arcs can be tuned to reduce or increase the number of identified PSs and, correspondingly, the computational cost. In the examples discussed till now, the PSP processing was performed with tradeoff parameters typically used for wide areas. In the following, we present some examples showing the capacity to achieve extremely dense PSP measurements and also to cover areas not characterized by strong scatterers, when the PSP capabilities are intensively exploited.

A first demonstration is taken from the PSP analysis of a tract of the railway Padua–Venice, Italy, using a stack of 50 ascending COSMO-SkyMed Stripmap SAR images acquired from May 2009 to September 2011 with baselines spanning 1574 m. By selectively increasing the number of arcs analyzed, the PSP techniques were able to obtain displacement measurements for almost all SAR image pixels corresponding

Fig. 7. High speed railway Padua–Venice, Italy. Very high density PSP analysis of COSMO-SkyMed Stripmap SAR data (50 ascending acquisitions, May 2009–September 2011). Many additional PSs (in red, or dark gray for black and white version of the paper) with respect to those found with standard processing (yellow points, or light gray) can be identified by intensive PSP processing. The measurement points are projected on a regular grid corresponding to the COSMO-SkyMed image posting, to highlight that they correspond to almost all the pixels of the SAR image in the areas where a coherent signal is expected.

Fig. 8. Piazza Plebiscito, Naples, Italy. PSP mean velocity measurements obtained from COSMO-SkyMed Stripmap SAR data (30 descending acquisitions, February 2010–February 2011). Very dense and precisely localized deformation measurements are present not only in correspondence of strongly scattering structures, but also over the pavement of the square.

to the railway, thus characterizing with continuity the 3-D displacements of the structure (see Fig. 7).

A second example is taken from the PSP processing of a stack of 30 COSMO-SkyMed descending Stripmap SAR images acquired from February 2010 to February 2011 over Naples, Italy, with baselines spanning 1294 m. Very dense and precisely localized displacement measurements were found not only in correspondence of structures, but also in areas characterized by a weak backscattering, such as the pavement of the city square (see Fig. 8).

A further example of the extreme high PS density reachable with PSP technique is relative to the analysis of 30 COSMO-SkyMed ascending Stripmap SAR images acquired

Fig. 9. Very high density PSP height measurements precisely reconstructing structures such as link roads, highway, railway, warehouses, etc., near Novara, Italy, obtained from COSMO-SkyMed Stripmap SAR data (30 ascending acquisitions, February 2011–June 2013).

from February 2011 to June 2013 in an area near Novara, Italy, with baselines spanning 1590 m. The PSP measurements were able to reconstruct in detail structures such as link roads, highway, railway, warehouses, etc. (see Fig. 9).

When intensively exploited, the PSP technique is able to identify a very high number of PSs also in rural or mountainous areas characterized by the absence of strong scatterers. To demonstrate this capability, we report two examples of PSP analysis on two different types of natural terrains. The first natural scenario is a mountain area near L'Aquila, Italy (see Fig. 10, left image), analyzed by PSP processing of 35 COSMO-SkyMed ascending Stripmap SAR acquisitions taken in the period April 2009–August 2010 with baselines spanning 1489 m. The second example, where 30 COSMO-SkyMed ascending Stripmap SAR images acquired from April 2012 to October 2012 with baselines spanning 1382 m were used, is relative to a rural area in Russia (Fig. 10, right image). In both cases, dense sets of PSP measurements were obtained in correspondence of bare soil or grassland, despite the absence of strong scatterers, whereas no PSs were found, as expected, in areas characterized by scattering properties changing with time, as forests or cultivated fields. Note, in the rural area example, that PSs are found even on part of the fields where probably no cultivation work was performed in the short acquisition period from April 2012 to October 2012.

It is finally important to remark that the PSP analysis did not require spatial averages to obtain such measurements, even over natural terrains and weakly scattering surfaces, thus avoiding loss of resolution.

IV. Validation Tests

The examples of applications reported in Section III show that the PSP SAR interferometry approach is effective in the study of deformations affecting man-made structures or natural terrains. In order to perform a quantitative assessment of the PSP measurements obtained from COSMO-SkyMed data, three types of tests were performed on the datasets described in Section III, in order to evaluate: 1) the deformation measurement accuracy by comparison with corresponding measurements obtained by optical leveling; 2) the height precision of the measurement points on a flat known surface; and 3) the noise of the displacement measurements on different types of ground surfaces.

An absolute validation of the PSP measurements from COSMO-SkyMed data was performed by comparison with optical leveling measurements [14] on the dataset of Beijing (Fig. 1). The standard deviation of the difference between the two set of measurements in corresponding points was smaller than 2 mm, whereas the mean value was 1.2 mm (see Table I).

In order to assess the precision of the PSP measurements from COSMO-SkyMed data, we evaluated the statistics of the height measurements on the flat roofs of two industrial buildings on the dataset of Novara (see Figs. 9 and 11). The standard deviation was about 0.7 m (see Table II), which is consistent with the about 2 mm standard deviation of the deformation measurements.

The noise of the COSMO-SkyMed PSP displacement measurements was estimated in five datasets corresponding to areas characterized by different land cover types: urban area (cities of Rome and Naples, Italy, Figs. 4 and 8); railway (Padua-Venice railway, Italy, Fig. 7); grassland (L'Aquila, Italy, Fig. 10 left); and rural uncultivated bare soil (Gay, Russia, Fig. 10 right). For obtaining a significant statistics, we considered larger areas (between 0.5 and 2 km^2) than those shown in the mentioned figures, however, selecting only the parts with the type of land cover of interest. Since noise is characterized by being uncorrelated both in space and time, we applied a high-pass filter both in space and in time to estimate the noise associated with the displacement measurements. In particular, we used a Gaussian kernel with sigma values equal to 100 m and 50 days in space and time, respectively, which guarantee not to underestimate the noise. Of course, this filter would tend to hide possibly temporally or spatially correlated errors, such as, in some cases, phase unwrapping errors. But this subject is beyond the scope of this paper (see, [12], [13]), and does not affect the presented analysis.

For each PS, the standard deviation of the estimated noise was evaluated on the samples corresponding to the several acquisition times. The histogram of the obtained values (see Fig. 12) shows that for practically all points, the standard deviation of the deformation measurement error ranged between 1 and 3 mm, with small variations depending on the type of ground cover. In particular, we found that the average standard deviation of the PSP displacement measurement noise ranged between 1.7 and 1.8 mm for the urban areas of Rome and Naples, and for the Padua–Venice railway, with measurement densities around or even over $100\,000\ \mathrm{PS/km^2}$ in the most urbanized areas and along the railway. In the rural/bare terrains near Gay, Russia and in the grassland areas near L'Aquila, Italy, the average standard deviations of the PSP displacement measurement noise were 2.1 and 2.3 mm, with corresponding measurement densities around $100\,000$ and $30\,000\ \mathrm{PS/km^2}$, respectively. These results are coherent with those obtained in the comparison with optical leveling and in the roof height measurements.

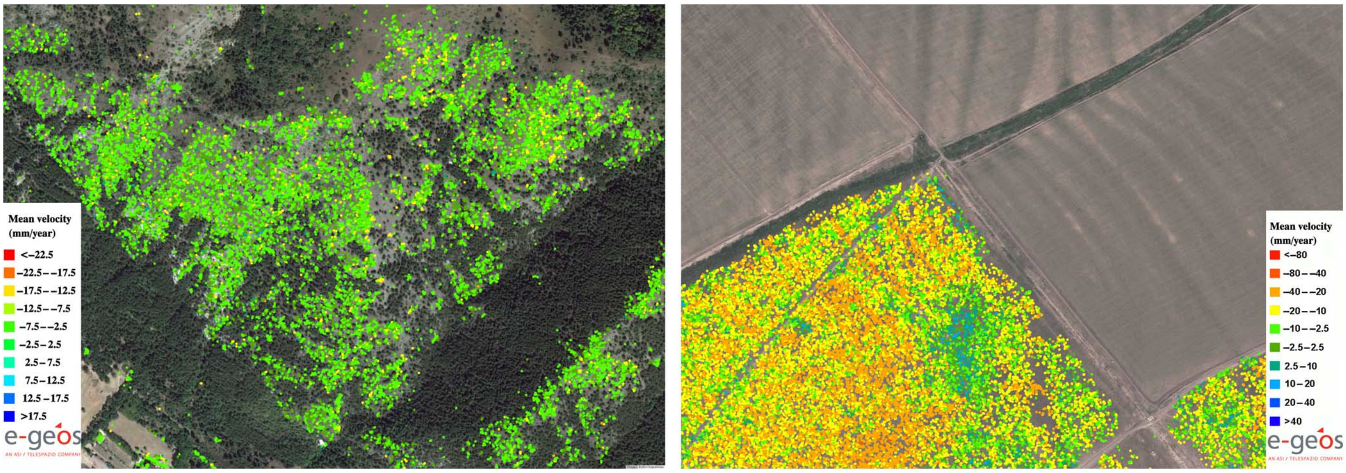

Fig. 10. PSP analysis on natural terrains. The images show the PSP mean velocity measurements obtained from COSMO-SkyMed Stripmap SAR data on a mountainous area near L'Aquila, Italy (left figure, 35 ascending acquisitions, April 2009–August 2010) and on a rural area in Russia (right figure, 30 ascending acquisitions, April 2012–October 2012). The images highlight that very dense PSP measurements can be obtained over grassland and bare soil, despite the absence of strong scatterers, whereas, as expected, PSP measurements are not found in cultivated fields or forests, whose backscattering properties change with time. Note in the right image that PSP measurements are present on the part of the fields where no cultivation works were likely performed in the short acquisition period from April 2012 to October 2012.

TABLE I
DIFFERENCE BETWEEN OPTICAL LEVELING AND PSP MEASUREMENTS OVER BEIJING, CHINA (SEE FIG. 1)

Mean (mm)	Standard deviation (mm)
1.2	1.9

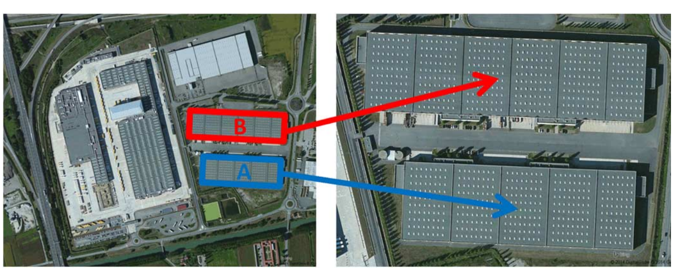

Fig. 11. Flat-roofed buildings in an industrial area near the city of Novara, Italy (same as Fig. 9). The precision of PSP height measurements was evaluated (Table II) over the flat roofs delimited by the rectangles A and B.

TABLE II
HEIGHT MEASUREMENT ERROR STATISTICS OVER FLAT ROOFS

Test area (see Fig.11)	Standard deviation (m)
A	0.67
B	0.71

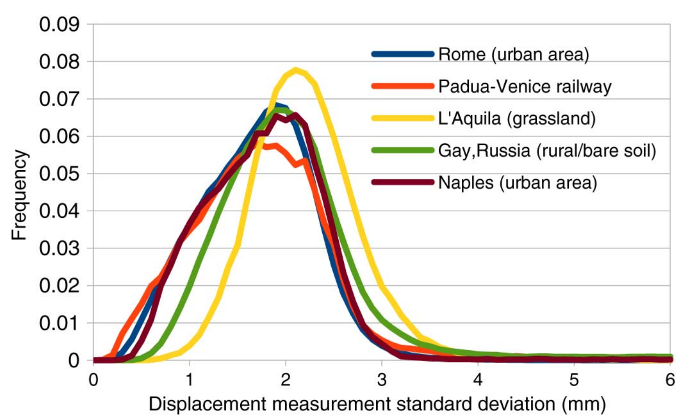

Fig. 12. Distribution densities (normalized histograms) of COSMO-SkyMed PSP displacement measurement noise in different datasets corresponding to different types of ground cover (see Figs. 4, 7, 8, 10).

It is worth noting that the less noisy PSs (basically corresponding to the left parts in the histograms of Fig. 12) could be selected by choosing more conservative parameters in the PSP processing, of course accepting to obtain a smaller number of PSs. Normally, we choose the processing parameters that guarantee the maximum number of PSs without evident false PSs (i.e., points identified as PSs where they should not be, like, e.g., in vegetated areas).

In all the examples discussed in this paper, practically no false PSs are visible. In fact, the PSP technique is able to very well discriminate and detect even weak signals without introducing false detections. However, the discriminating capacity depends on the number of images in the stack and on the distribution of temporal and spatial baselines. Therefore, the processing must adjust to these parameters in order to avoid false detections, which is a mandatory requirement to allow automatic processing. In particular, a stack with a reduced number of images must be processed with more conservative thresholds for selection of PSs, as obvious from the fact that one of the main selecting criteria for the PSPs, the multiacquisition coherence γ_a defined in (2), is less discriminating with fewer images. In this case, a smaller number of PSs can be identified.

Therefore, to further characterize the PSP SAR interferometry technique, we studied the variation of performance with the number of SAR images in the stack to be analyzed. For this test, we considered the datasets of Rome urban area (Fig. 4) and L'Aquila grassland (Fig. 10, left). The complete stacks consisted in 34 and 35 acquisitions, respectively. Without changing the total time span, i.e., keeping the first and the last acquisition, we eliminated some of the intermediate images to form smaller stacks with fewer acquisitions (approximately equidistant), and then we processed these smaller stacks by the PSP technique.

We found that, with 25 and 15 images, approximately two-third and one-third of the total number of PSs selected with the full stack were identified, respectively, which still correspond to very good densities. However, it remains advisable to use more images if possible (a need common to many stack interferometry techniques), because a reduced PS density, together with longer times between the acquisitions, could cause missed detections and wrong results in case of strong or fast displacements, or in areas with vegetation, as already discussed in the comments to Fig. 3.

V. Conclusion

In this work, a new approach for identification and analysis of PSs in time series of full resolution SAR images has been described. In this context, PSs are generally intended as scatterers that exhibit interferometric coherence for the time period and baseline span of the acquisitions, including both point-like and distributed scatterers. The method, named persistent scatterer pair (PSP), is characterized by the fact that it exploits only the relative properties of neighboring pairs of points for both selection and analysis of PSs. Therefore, it is intrinsically not affected by artifacts slowly variable in space, like those depending on atmosphere or orbits.

Working with pairs-of-points, or arcs, instead of single points, is in principle much more complex from the computational point of view. A strategy to make the problem affordable has been presented. It is based on the possibility of exploring a limited number of arcs, by iteratively building a graph, and deriving, based on its structure, the most convenient arcs to explore at the successive iteration. The obtained graph is characterized by a high connectivity, which makes for obtaining more PSs and more accurate measurements.

Several examples of applications taken from operational projects based on COSMO-SkyMed data have been reported and discussed, showing that extremely dense displacement and elevation measurements are obtained on most types of land cover, not only in correspondence of structures, but also when the backscattering is weak or distributed as, e.g., in the case of natural terrains. To this purpose, differently from distributed scatterer techniques, the PSP algorithm does not rely on filterings that imply reduction of resolution. The high dense PSP measurements are useful to better characterize the displacement phenomena and the stability of structures.

Finally, we have reported the result of some validation tests showing the robustness of the method, and demonstrating that the PSP measurements obtained from COSMO-SkyMed data have millimetric and metric precisions for displacement and 3-D localization, respectively.

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References

[1] P. A. Rosen *et al.*, "Synthetic aperture radar interferometry," *Proc. IEEE*, vol. 88, no. 3, pp. 333–382, Mar. 2000.

[2] R. Bamler and P. Hartl, "Topical review: Synthetic aperture radar interferometry," *Inverse Prob.*, vol. 14, pp. Rl–R54, 1998.

[3] A. Ferretti, C. Prati, and F. Rocca, "Permanent scatterers in SAR interferometry," *IEEE Trans. Geosci. Remote Sens.*, vol. 39, no. 1, pp. 8–20, Jan. 2001.

[4] A. Ferretti, C. Prati, and F. Rocca, "Non-linear subsidence rate estimation using permanent scatterers in differential SAR interferometry," *IEEE Trans. Geosci. Remote Sens.*, vol. 38, no. 5, pp. 2202–2212, Sep. 2000.

[5] P. Berardino, G. Fornaro, R. Lanari, and E. Sansosti, "A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms," *IEEE Trans. Geosci. Remote Sens.*, vol. 40, no. 11, pp. 2375–2383, Nov. 2002.

[6] M. Costantini, "A novel phase unwrapping method based on network programming," *IEEE Trans. Geosci. Remote Sens.*, vol. 36, no. 3, pp. 813–821, May 1998.

[7] M. Costantini and P. A. Rosen, "A generalized phase unwrapping approach for sparse data," in *Proc. Int. Geosci. Remote Sens. Symp. (IGARSS)*, Hamburg, Germany, Jun./Jul. 1999, vol. 1, pp. 267–269.

[8] M. Costantini, S. Falco, F. Malvarosa, and F. Minati, "A new method for identification and analysis of persistent scatterers in series of SAR images," in *Proc. Int. Geosci. Remote Sens. Symp. (IGARSS)*, Boston, MA, USA, Jul. 2008, vol. 2, pp. 449–452.

[9] A. Hooper, H. Zebker, P. Segall, and B. Kampes, "A new method for measuring deformation on volcanoes and other natural terrains using InSAR persistent scatterers." *Geophys. Res. Lett.*, vol. 31, no. 23, L23611, Dec. 2004.

[10] M. Costantini, F. Minati, F. Trillo, and F. Vecchioli, "Enhanced PSP SAR interferometry for analysis of weak scatterers and high definition monitoring of deformations over structures and natural terrains," in *Proc. Int. Geosci. Remote Sens. Symp. (IGARSS)*, Melbourne, Australia, Jul. 2013, pp. 876–879.

[11] A. Ferretti *et al.*, "A new algorithm for processing interferometric datastacks: SqueeSAR," *IEEE Trans. Geosci. Remote Sens.*, vol. 49, no. 9, pp. 3460–3470, Sep. 2011.

[12] M. Costantini, F. Malvarosa, and F. Minati, "A general formulation for redundant integration of finite differences and phase unwrapping on a sparse multidimensional domain," *IEEE Trans. Geosci. Remote Sens.*, vol. 50, no. 3, pp. 758–768, Mar. 2012.

[13] M. Costantini, F. Malvarosa, F. Minati, and F. Vecchioli, "Multiscale and block decomposition methods for finite difference integration and phase unwrapping of very large datasets in high resolution SAR interferometry," in *Proc. Int. Geosci. Remote Sens. Symp. (IGARSS)*, Munich, Germany, Jul. 2012, pp. 5574–5577.

[14] M. Costantini *et al.*, "High resolution ground deformations monitoring by COSMO-SkyMed PSP SAR interferometry: Accuracy analysis and validation," in *Proc. ESA FRINGE*, Frascati, Italy, Sep. 2011.

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