Validation of the Submetric Accuracy of Vertical Positioning of PSs in C-Band

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***Abstract*—The permanent scatterers (PSs) technique is an operational tool in the context of spaceborne synthetic aperture radar interferometry for monitoring the displacement of radar targets with millimetric accuracy. Recently, the target localization capability of the PS technique has been subject of study, and the possibility of generating digital elevation models (DEMs) and digital terrain models (DTMs) by means of the height of a sparse set of points has been evaluated. In this letter, for the first time, the PS height estimate has been validated by exploiting about 250 000 spot heights at street level derived from photogrammetric techniques in the urban area around Milan, Italy. The very high correlation between the two independent measurements confirms the theoretical submetric accuracy of vertical positioning. A multitrack PS DTM has then been generated and compared to the spot heights together with the corresponding Shuttle Radar Topography Mission (SRTM) DEM, showing the very high improvement given by the PS technique to the freely available topographic data. The results have been obtained by processing about 300 European Space Agency (ESA) European Remote Sensing (ERS) satellite and Envisat images acquired from two descending tracks and an ascending one over Milan.**

***Index Terms*—Interferometry, remote sensing, synthetic aperture radar (SAR).**

I. Introduction

THE PERMANENT scatterers (PS) technique [1] detects, measures, and monitors ground movements using satellite synthetic aperture radar (SAR) data. Thus, the PS technique takes conventional SAR interferometry (InSAR) [2] a step forward, by identifying single coherent benchmarks (the PSs) and reconstructing their displacement history. PSs are stable "radar targets" that are located across the Earth's surface and that can be monitored by satellites. When targets remain coherent within a multitemporal radar data set, it is possible to detect and measure millimeter variations in the sensor target distance, over time. Indeed, the PSs comprise a sort of "natural geodetic network" for accurately monitoring surface deformation phenomena, as well as the stability of individual structures.

In recent time, the capability of the PS technique to precisely localize targets in the 3-D space has been the subject of study [3]. As a matter of fact, the theoretical precision of target positioning of the PS technique (about 1 m) is much higher than the system resolution of the used sensors (20 m $\times$ 5 m on the ground for the European Space Agency (ESA) European Remote Sensing (ERS) and Envisat satellites). Moreover, ESA SAR data archives guarantee, nowadays, an almost worldwide coverage, and the data are accessible at a very low cost. Therefore, it is really interesting to evaluate the possibility of generating DEMs by means of SAR data that have the following advantages: 1) higher accuracy than freely available height data as SRTM and 2) much less expensive than the ones obtained with optical or LIDAR techniques.

The main problem to be tackled for creating DEMs by means of the PS technique is the spatial density of measure points. As shown in [3], in urban sites, the problem can be solved by combining data acquired from different orbits. In extraurban areas, the task is more difficult because of the lack of coherence, and it is still subject of research. In the second instance, the quality of the elevation estimated by the PS technique has not yet been fully demonstrated. Indeed, in [3], the PS DTMs estimated from different independent orbits have been compared and found in good agreement (dispersion of the estimate on the order of 1 m), but up to now, no cross-validation with external data has been provided. In this letter, for the first time, a multitrack high-accuracy SAR PS DTM is compared to 250 000 spot heights at street level derived with photogrammetric techniques in the urban area of Milan, Italy. The results assess the very high potentiality of the proposed technique.

II. Precision of PS Height Estimate

As derived in [3] and [4], by exploiting the full ESA archive (ERS and Envisat data together) and taking advantage of the variability of all acquisition parameters (normal baseline, Doppler centroid, central frequency, time, and temperature), the interferometric phase can be used to estimate displacement and 3-D coordinates of SAR targets. The theoretical precision of the estimate of the target height h can be expressed as a function of the number N of images of the data set, of the dispersion of their normal baselines σ_{B_n}, and of the phase noise $\sigma_{\Delta\phi}$ [3]

$$\sigma_h^2 = \left(\frac{\lambda R_0 \sin\theta}{4\pi}\right)^2 \frac{\sigma_{\Delta\phi}^2}{N\sigma_{B_n}^2} \tag{2.1}$$

where λ is the wavelength, θ is the incidence angle, and R_0 is the sensor target distance. Using $N = 60$ ERS images (incidence angle $\theta = 23^\circ$, baseline deviation $\sigma_{B_n} = 480$ m), a PS with coherence $\gamma = 0.8$ ($\gamma = e^{-(\sigma_{\Delta\phi}^2)/(2)}$ [5]) can be theoretically positioned with 30 cm of height uncertainty. It is worth noting here that, as analyzed in [3], such precision can be achieved only by avoiding positioning artifacts and correctly managing subpixel quantities. It has also to be pointed out that orbital uncertainties introduce spurious ramps on the estimated DEM [6]. Moreover, the height estimate impacts on the geocoding process [7]. Thus, in order to compare PS data

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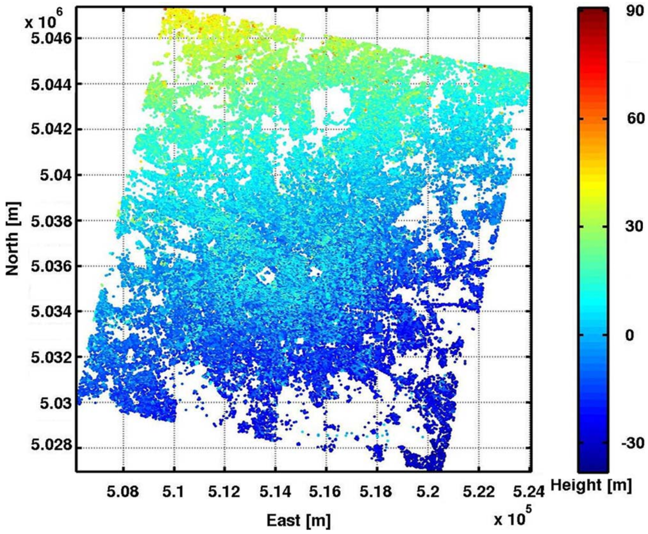

Fig. 1. PSs detected in Milan from Track 208 (about 100 000 targets) in Gauss–Boaga coordinates. (Color) PS ellipsoidal height with respect to a reference point.

with independent measurements on a common geographical layer for validating the theoretical accuracy, orbital data must be precisely corrected.

Fig. 1 shows more than 100 000 PSs detected in Milan in 350 km^2. The data used in the analysis (about 100 images) have been acquired by the ESA satellites ERS-1, ERS-2, and Envisat (Track 208). The coordinate system is the Italian Gauss–Boaga. The color scale in Fig. 1 shows the height of the targets with respect to a reference point, highlighting the slope of the plane on which Milan lies but also many details of the city surface.

III. Multitrack Combination and Urban DTM Retrieval

As already mentioned, the main defect that stands out from Fig. 1 is the relative low spatial density of the targets. The study on the physical nature of PS in urban sites, carried out in the last years [10], has allowed the recognition of multitrack targets as dihedrals and poles, which are very useful to connect data acquired by different orbits with submetric precision, thus increasing significantly the number of measurement points. As an example, Fig. 2 shows more than 300 000 PSs in about 400 km^2 estimated in two descending and one ascending tracks over Milan (about 300 images acquired by ERS-1/2 and Envisat, Tracks 208, 480, and 487). The reached density is such as to appreciate details on the single building, as shown in Fig. 3, where the PSs detected in the three tracks are plotted in 3-D coordinates around the Meazza soccer stadium, San Siro, Milan.

By analyzing the local distribution of the PS height in urban sites (without *a priori* information on the topography), it was discovered that most targets lie on the ground [3], [10]. Discarding elevated points, as done in [3], it then becomes possible to apply a spatial filtering and resample the height data on a regular grid to retrieve a digital terrain map. Fig. 4 shows the DTM estimated in Milan from the detected PSs using a kriging process (300 m of decorrelation distance), as described in [3]. A second-order surface has been removed from the DTM for better appreciating the high-quality details. The color-scale range of Fig. 4 is -3 to 3 m. The red lines in the image are the main watercourses in Milan, and they are in correspondence of the blue depressions. The red prominence in the middle is the historical center of Milan.

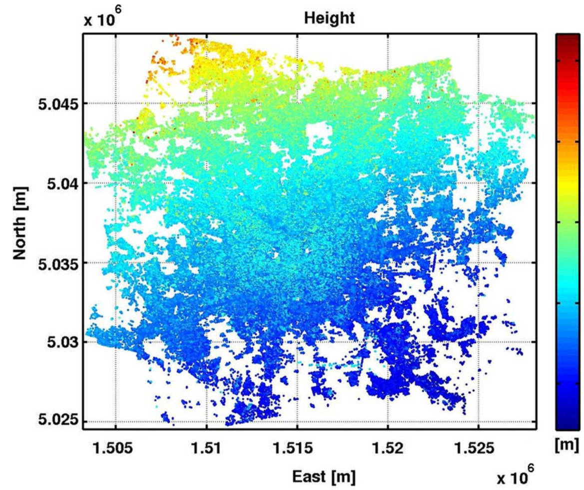

Fig. 2. PSs detected in Milan from two descending parallel tracks (Tracks 208 and 480) and an ascending one (Track 487) (more than 300 000 targets). (Color) PS ellipsoidal height with respect to a reference point.

IV. Photogrammetric Spot Heights

By courtesy of the Territorial Information System Office of Milan municipality, we can compare the PS height results achieved in Milan with about 250 000 spot heights retrieved by means of photogrammetric restitution [8]. To give an idea of the spatial resolution of such data, Fig. 5 shows a close-up near the Railway Central Station of Milan. The spot heights are plotted on an airborne optical image, and their color is function of the geodetic height ranging values between 120 and 136 m. The nominal accuracy of the elevation data is 20 cm. A very interesting property of these spot heights is that they have been selected among the points at street level (considering also subways and flyovers). The selection has been manually carried out by the Territorial Information System Office of Milan by means of *in situ* inspections. Indeed, observing the image shown in Fig. 5, on the left, some roads crossing Garibaldi railway and, on the right, the rail tracks on the back of the Central Station are easily recognizable. This property comes out very useful when comparing the height of the single SAR scatterer to the spot heights.

V. Cross Validation

We can chose two different strategies to compare PS and spot heights data. The first one is aimed to validate the digital terrain map retrieved with the PS technique as previously described. In other words, we check the assumption that we are able to select the targets that lie on the ground without *a priori* information. The second one achieves the purpose of assessing the accuracy of the height estimate of the single SAR target.

To reach the first objective, we resample the spot heights on the same grid of the PS DTM with a kriging process, as described in [3], 200 m of decorrelation distance. Then, we compute the difference between the PS and the spot heights DTMs pixel by pixel. Fig. 6 shows on the left the difference in planimetric coordinates. Note that the overlapping area between

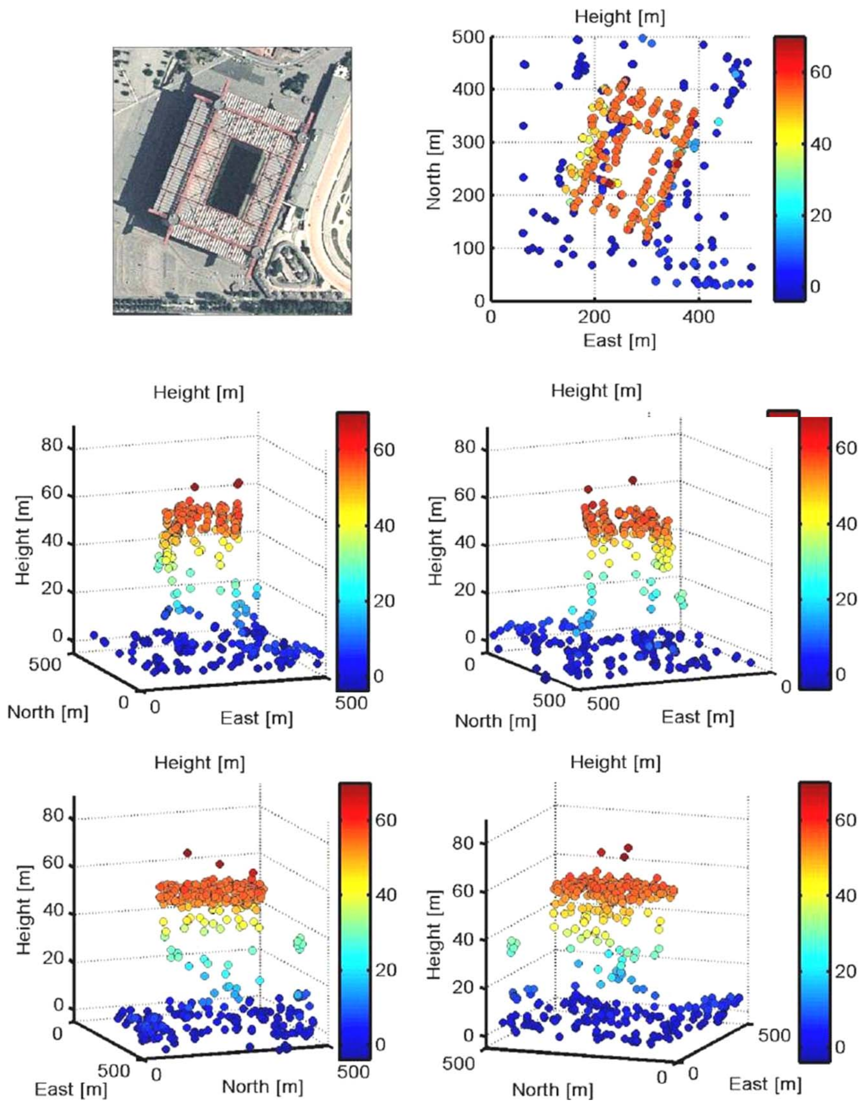

Fig. 3. PSs detected on the Meazza soccer stadium, San Siro, Milan, from three tracks. (Color) PS height. (Above) Optical photo and PS planimetric coordinates. The other four images are 3-D views.

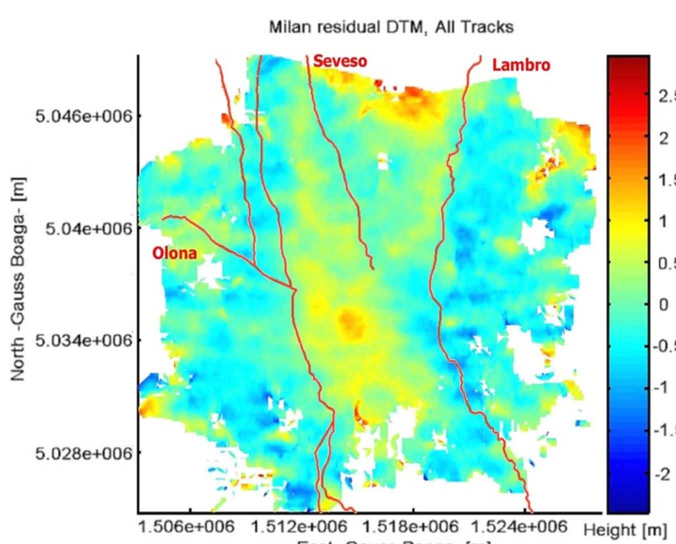

Fig. 4. Milan DTM retrieved from PSs on the ground detected from three tracks. A second-order surface has been removed to enhance the terrain details. (Red lines) Watercourses in Milan.

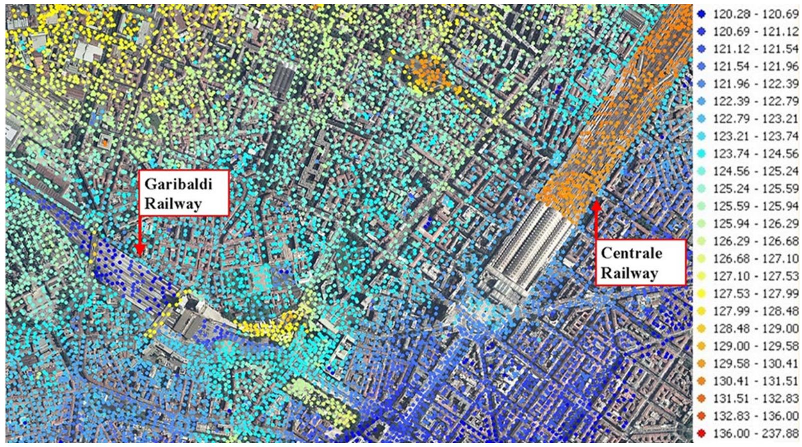

Fig. 5. Spot heights derived from photogrammetric restitution in Milan. (Color) Ellipsoidal height. The spot heights lie on streets, roads, flyovers, and rail tracks.

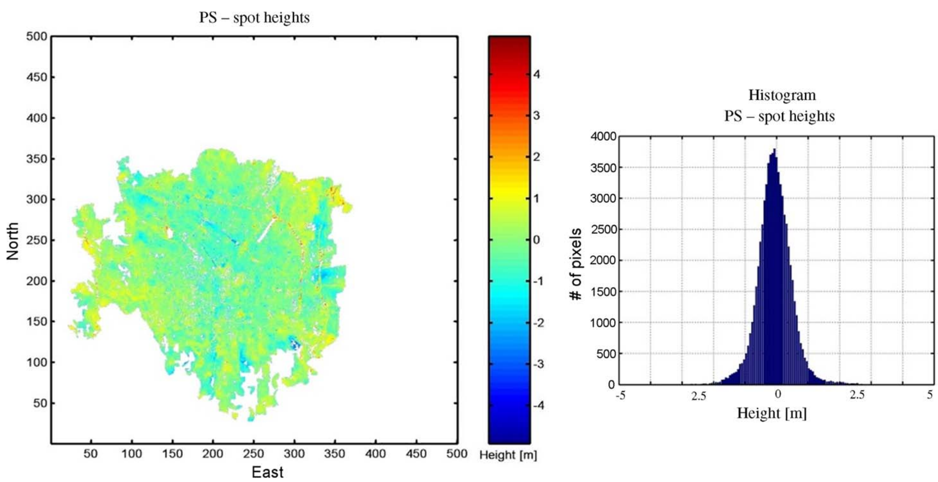

Fig. 6. Difference between PS and spot heights DTM. (Left) In planimetric coordinates. (Right) Histogram of the difference values.

PS and spot height is about one half the PS area. It is worth observing the quality of orbital corrections and geocoding (no slope is evident). In addition, the difference mean value is close to zero, owing to detected poles used as tie points. Few regular features can be recognized with outlier height values, due to the different spatial resolution between the two measurements. On the right of Fig. 6, the histogram of the differences is reported. The standard deviation between the two measures is on the order of 10 cm. It is now interesting to make the same comparison with the freely available SRTM data. The result is shown in Fig. 7. Again, on the left, the difference is plotted in planimetric coordinates, and on the right, the histogram of the difference values is reported. As known, the accuracy of the SRTM height is about 10 m [9]. Moreover, Fig. 7 shows that SRTM data interpolate the height values and do not extract the terrain level. On the contrary, Fig. 6 shows the validation the proposed technique for DTM generation by means of PS data.

The second goal is achieved by finding for each PS the spot height with planimetric coordinates nearest to it. Then, the height difference between them is computed, and the histogram of the difference values is shown in Fig. 8. The first information we get from Fig. 8 is the width of the peak. The accuracy of the height estimate of the single target is less than 1 m. The second information is that many urban PSs (about half of the total) are at the same level of the spot heights (± 1 m). But, these spot heights were selected among those staying at street level. This means that many PSs are on roads and streets and reveals again the multibounce nature of many urban SAR targets (dihedrals, poles, trihedrals [10]).

VI. Physical Considerations

It is worth stressing the importance of the obtained results. The resolution of the SAR system (ERS case) is 20 m $\times$ 5 m on the ground. Considering a normal baseline range of 2 km, the height of the resolution cell is about 10 m [3], [4]. Thus, a PS could be formed by the interaction of elementary scatterers randomly distributed within a 1000-m^3-volume cell. The ensemble of elementary scatterers then shows an electromagnetic barycenter, whose height is estimated by the PS technique. Under such a condition, the estimated height would be affected by a random error due to the unknown virtual position of the electromagnetic barycenter. The real height estimate would then be biased, and the theoretical precision of 30 cm derived in Section II would not correspond to an actual accuracy. But what is being observed from the data, in accordance with the study on the physical nature of the targets [4], [10], is that only a little part of PSs derives from the combination of many scattering centers. Many PSs are basically dihedrals, trihedrals,

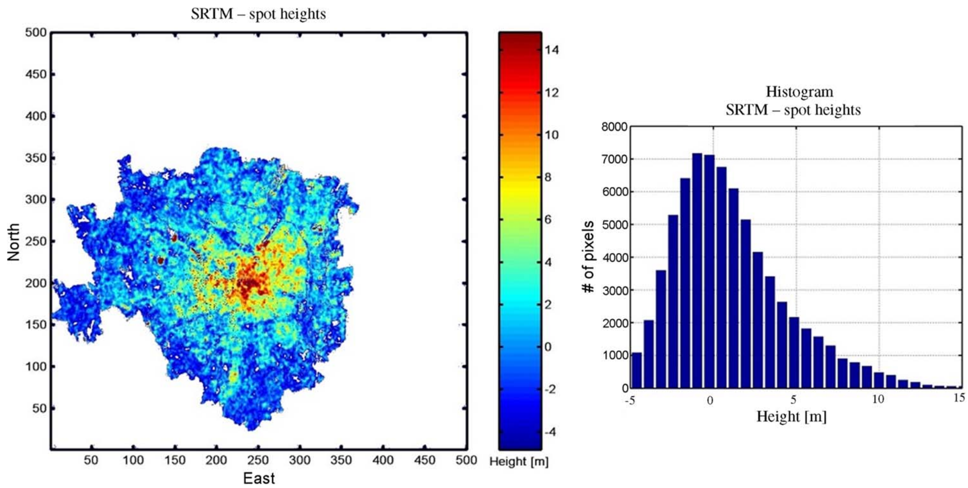

Fig. 7. Difference between SRTM and spot heights DEM. (Left) In planimetric coordinates. (Right) Histogram of the difference values.

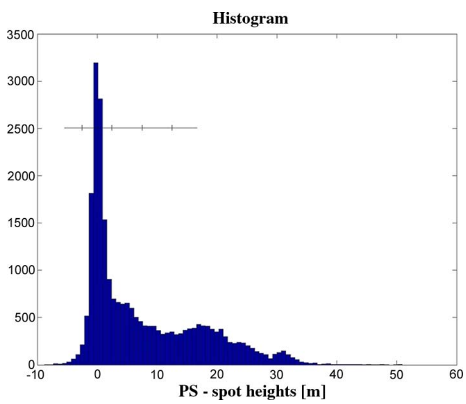

Fig. 8. Histogram of the PS elevation referred to the closest spot height. The width of the main peak is the variance of the estimate of the PS height ($\sim$1 m). Most PSs are at street level.

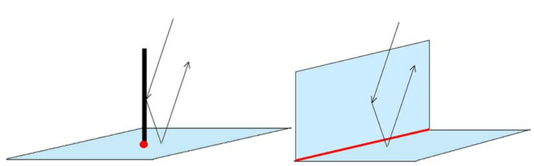

Fig. 9. Examples of PS at street level in urban sites: poles and dihedrals. The electromagnetic barycenter of such targets is the intersection between the ground plane and the vertical structure (a point for a pole and a line for a dihedral). The PS technique estimates the height of the target electromagnetic barycenter.

or poles. The barycenter of such targets is the intersection between the ground plane and the vertical structure, as shown in Fig. 9. Thus, the height estimated by the PS technique has a physical correspondence. The results of the comparison between PS and spot heights (in particular, Fig. 8) confirm such interpretation. In case of poles (whose barycenter is pointwise), the PS analysis, being capable to localize a target within 1-m^3 cube, realizes a physic superresolution [3] of a factor 1000 with respect to the initial resolution. Finally, these considerations stress again the importance of knowing what kind of targets the radar looks at, to correctly interpret the data [11].

VII. Conclusion

In this letter, for the first time, a validation of the PS height estimate has been provided by means of photogrammetric data. Moreover, the capability of detecting targets on the ground and, consequently, to generate accurate DTMs with the PS technique has been assessed. Derived from photogrammetric restitution, 250 000 spot heights have been compared with more than 300 000 PSs detected from three different orbits (two parallel descending and one ascending) around the city of Milan, showing submetric correlation.

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