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S. Gernhardt; N. Adam; M. Eineder; R. Bamler

a Remote Sensing Technology, Technische Universität München, Munich, Germany
b Remote Sensing Technology Institute (IMF), German Aerospace Center (DLR), Oberpfaffenhofen, Germany

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Potential of very high resolution SAR for persistent scatterer interferometry in urban areas

S. Gernhardt\textsuperscript{a*}, N. Adam\textsuperscript{b}, M. Eineder\textsuperscript{b} and R. Bamler\textsuperscript{a,b}

\textsuperscript{a}Remote Sensing Technology, Technische Universität München, Munich, Germany; \textsuperscript{b}Remote Sensing Technology Institute (IMF), German Aerospace Center (DLR), Oberpfaffenhofen, Germany

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Persistent scatterer interferometry (PSI) has matured to an established method for detection of large-scale and small-scale deformation phenomena in urban areas and of man-made infrastructure. Deformation regimes originating from oil, gas, or water extraction, storage of gas underground, CO\textsubscript{2} sequestration, loading of dams and dykes, and mining activities are prominent examples for investigations that have been carried out successfully applying the PSI technique to ERS or ENVISAT data stacks.

Due to the sparse spatial distribution of persistent scatterers (PSs) and the moderate resolution of the mentioned satellites it has usually not been possible to track down the source of scattering in detail. The use of PSs was also opportunistic, that is, the PSI monitoring of individual buildings or specific parts of infrastructure was not always been guaranteed.

This situation changes dramatically if PSI is applied to very high resolution data obtained from modern radar satellites like TerraSAR-X or COSMO-Skymed. For example, TerraSAR-X is able to deliver images with a resolution of up to 1 m in azimuth and 0.6 m in slant range when operated in the so-called high-resolution spotlight mode with 300 MHz bandwidth. This kind of data provide much more details of single objects and at the same time much higher PS densities. Compared to ERS or ENVISAT type data, the PS density can increase by factors of 100–200 on the same area. This is caused by the physical fact that at higher resolution and shorter wavelength, small scatterers (e.g., trihedrals) show higher signal-to-clutter ratio. Often, several tens to more than a hundred PSs can be found on a single large building facade or roof. Thus, individual buildings and infrastructure can be monitored in terms of structural stress and seasonal deformation, which is also supported by the short revisiting time of only 11 days of TerraSAR-X.

Besides on resolution, the density of these points also depends on additional acquisition parameters like incidence angle or polarization and also on the three-dimensional (3D) structure of the given scene, as regions of layover areas and shadow are closely related to the geometrical configuration. The dependence of PS density on these parameters is discussed in this article utilizing results of PSI analysis of different high-resolution TerraSAR-X spotlight data stacks.

In addition to this increase of resolution, TerraSAR-X products benefit from a high absolute slant range georeferencing accuracy of 0.5–1 m, which supports a very precise absolute 3D localization of the PSs on the same order. Hence, the physical nature of a PS can be investigated in more detail helping the understanding of the scattering source of the man-made infrastructure. Results of 3D localization and deformation assessment on several test sites are presented in this article.

Keywords: high-resolution SAR; TerraSAR-X; persistent scatterer interferometry; surface deformation

1. Introduction

Synthetic aperture radar (SAR) data offer some advantages in comparison to the use of optical sensors, such as independence of light sources or weather conditions, and can be used for a variety of applications. Coherent combination techniques of multiple images allow for a three-dimensional (3D) reconstruction of the imaged objects and the detection of deformations up to millimeter level (Adam et al. 2009, Ferretti et al. 2007). But due to the side-looking geometry and the radar-specific speckle phenomenon, objects look differently in SAR images. The scenes are mapped by their range to the sensor, as can be seen in Figure 1, which shows a (speckle-reduced) temporal average of several acquisitions. Besides the apparent geometrical peculiarities (e.g., houses flipped toward the sensor), the effect of speckle is reduced in averaged images, and the mapped scene holds many clearly visible details. The given sample image has been acquired by TerraSAR-X satellite, which was launched on 15 June 2007. After the subsequent commissioning phase, the German radar satellite went operational on 9 January 2008. First results using TerraSAR-X data have already been presented by Eineder et al. (2009) and during recent conferences where the benefits for different applications of this new instrument could be demonstrated, like varying acquisition modes and the short revisiting time of only 11 days. Especially the possibility to acquire data based on almost the same geometrical parameters with such a high repeat rate facilitates setting-up interferometric stacks for persistent scatterer interferometry (PSI) about three times faster than with ERS or ENVISAT. These satellites

\textsuperscript{*}Corresponding author. Email: stefan.gernhardt@bv.tum.de
in contrast offered a resolution of only approximately 25 m in range and 5 m in azimuth, which makes it very difficult to investigate the nature of strong persistent scatterers (PS) in this – comparatively large – resolution cell. Now, using TerraSAR-X in high-resolution spotlight mode (at 300 MHz bandwidth), images with resolutions of up to 1.1 m in azimuth and 0.6 m in range are available at the German Aerospace Center (DLR) (Fritz et al. 2008, Breit et al. 2010). This high resolution leads to an enormous increase in the number of PSs, as has already been shown in Adam et al. (2008), now resulting in many PSs appearing on single objects. As data can be acquired from the same area of interest using different orbits, position and number of PSs are likely to vary between stacks of data sets based on different incidence angles and also on ascending and descending tracks.

For investigations on the influence of different parameters on PS density, six data stacks covering the area of downtown Berlin have been set up and the findings of the analysis will be presented in this article, which include comparisons of the number of PSs extracted in each stack and the variation of PS densities in different subregions of the data. Hence, based on the desired spreading and concentration of PS, the essential acquisition parameters for this region – and comparable ones – can be chosen in advance. In addition, examples on PS localization are shown and results of a deformation assessment covering the central train station of Berlin is discussed in detail.

2. Data basis

For each of the following examples, one stack, that is, a time series of images with equal look geometry, resolution, and polarization of SAR data has been investigated. One special scenario depicts the area of Berlin, Germany, for which more details on the data are given. The area of interest is the inner city of Berlin, with a focus on the main railroad station. Between February 2008 and November 2009, six different stacks of data takes (all in VV polarization mode) have been acquired. The characteristics of the stacks are listed in Table 1. The number of images ranges from 25 to 35.

<table>
<thead>
<tr>
<th>Beam number</th>
<th>Incidence angle</th>
<th>Track type</th>
<th>Area (km²)</th>
<th>Number of data</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>30°</td>
<td>Ascending</td>
<td>50.0</td>
<td>25</td>
</tr>
<tr>
<td>57</td>
<td>42°</td>
<td>Ascending</td>
<td>40.9</td>
<td>25</td>
</tr>
<tr>
<td>85</td>
<td>51°</td>
<td>Ascending</td>
<td>32.9</td>
<td>29</td>
</tr>
<tr>
<td>42</td>
<td>36°</td>
<td>Descending</td>
<td>42.5</td>
<td>35</td>
</tr>
<tr>
<td>70</td>
<td>47°</td>
<td>Descending</td>
<td>35.0</td>
<td>33</td>
</tr>
<tr>
<td>99</td>
<td>55°</td>
<td>Descending</td>
<td>33.5</td>
<td>34</td>
</tr>
</tbody>
</table>

Figure 1. Temporal mean image of TerraSAR-X data. Sensor look direction: left to right; flight direction of satellite: bottom-up. Buildings appear flipped left toward the sensor due to imaging geometry and characteristics of radar sensor (range-related imaging). Bright pixels on street (at rotary) represent cars stopping at traffic lights, which have obviously been on red during many of the acquisitions.
These six stacks can be separated into two groups: ascending and descending tracks, each consisting of three stacks of different incidence angles: 30°, 42°, and 51° for the ascending beam numbers 28, 57, and 85 and 36°, 47°, and 55° for the descending beam numbers 42, 70, and 99, respectively. The covered area ranges from 33 to 50 km², whereas steep angles produce larger coverage than flat ones. For the given investigations related to Berlin, each stack is processed separately to obtain estimates of position and deformation parameters for all occurring PS.

3. Persistent scatterer densities

At first, PS candidates have to be selected from the image stacks. This can be accomplished by choosing a threshold for the temporal amplitude dispersion index, as implemented in the original PSI algorithm presented by Ferretti et al. (2001). Another possibility uses the spatial signal-to-clutter ratio (SCR) as an appropriate selector (Adam et al. 2004). The latter has also been used in the investigations presented here, whereby the threshold was left unchanged for all stacks, allowing mutual comparison. The detected points serve as a basis for the adjacent estimation of deformation parameters using the PSI-GENESIS InSAR software system of the DLR. For a detailed version of every single processing step, the interested reader is referred to Kampes (2006) and Meyer et al. (2007). In the following sections, the influence of different imaging parameters on the density of PSs is described in more detail.

3.1. Dependence on incidence angle and polarization

The availability of six data stacks covering different incidence angles and track types allows for investigating the influence of viewing geometry on the number of PSs. Unfortunately, it is not possible to acquire data in different polarizations at the same time in the very high resolution (VHR) mode of TerraSAR-X. However, some data sets in HH polarization for each of the six stacks have been gathered and the following comparison is carried out on a smaller number of images for the VV cases (in contrast to the given numbers in Table 1), comparable to HH stack sizes. Figure 2a and b illustrates the trend of PS densities due to increasing incidence angles for both types of polarizations within different regions of Berlin. A first look on the total number of selected points normalized by the covered areas shows that the PS densities slightly increase starting with steep incidence angles up to about 42°–47° and decrease again for higher angles. This is valid for common urban areas with buildings of medium height and no dominant orientation of the facades in parallel to any flight directions of the sensor (see Figure 2a). This behavior can be explained by considering many PSs to be created by di- and trihedral reflections from every floor within buildings. If the incidence angle exceeds a certain threshold, unique for each geometrical configuration including certain buildings’ height and distance to other constructions, the sensor cannot ‘see’ these scatterers anymore due to shadowing caused by other buildings, and many PSs get lost. In addition, resolution in vertical direction gets worse with rising incidence angles and PSs from different floors of the buildings may not be separable anymore. In the Berlin case, this seems to happen for incidence angles around 45°. Geometry is in general the key element affecting PS density numbers. The second example (cf. Figure 2b) shows the trends for another region, containing many facades aligned in parallel to ascending flight direction.

Figure 2. Variation of PS densities with incidence angles for HH and VV polarizations. (a) Selection covers part of Berlin inner city with houses of medium height. No main orientation of facades. (b) Selection covers part of Berlin inner city with larger houses. Facades’ main orientation in parallel to ascending flight direction.
upper floors on facades perpendicular to the sensor’s viewing direction still increases at shallow angles.

Comparison of the density values for HH and VV shows a slight advantage of HH polarized data. In this case, approximately 5–10% more PS can be obtained, locally up to 20%. But for the whole scene there is no strong preference for one of the two polarizations. PSI can be carried out successfully using both types of polarization, as enough PSs should be available (many thousands of points per square kilometer), for which deformation estimation parameters can be derived.

3.2. Dependence on resolution

Many PSs are structures acting as dihedral or trihedral reflectors. Assuming a background clutter of 4 dB normalized radar cross section and a PS detection threshold of 6 dB above clutter, then in ENVISAT/ASAR-type data an ideal full trihedral metal structure of about 30 cm side length is required to be detected as a PS. With TerraSAR-X high-resolution spotlight mode and the same incidence angle, any full trihedral structure of 8 cm side length will be detected as a PS. These types of structures (e.g., corners of window frames) are typically plenty on modern building facades and can be well resolved due to the high resolution. Therefore, we can detect many PSs at a single building and are able to estimate deformation of the building itself. Our first experiences with TerraSAR-X high-resolution spotlight data show typical PS densities of up to 120,000 PS/km², that is, one PS per area of 2 x 2 m. The increase of PSs with resolution is dramatic (cf. Figure 3) because the VHR fits well with the typical spatial scales of constructive elements at buildings.

4. PS localization and deformation assessments

In this section, some examples of localization results as well as deformation estimates from the PSI processing of different test sites are presented.

The first example is provided in Figure 4, which shows the PSs in their 3D positions on Hotel Bellagio, Las Vegas, USA (height of the points is color-coded from blue to red, i.e., 0–150 m). In general, the geocoded points can be imported in Google Earth™ software, which shows that often the dimensions of the 3D models available differ from reality. Many PSs are available at the facade of the buildings; however, there are regions of the facades where no PSs show up on the 3D model. Hence the models used in Google Earth™ are of wrong sizes. In addition, sometimes the model database seems not to be up-to-date, as other buildings can be seen from the PS point clouds, whereas the corresponding 3D model is missing. These suspicions have been confirmed by independent aerial photographs. This simple example demonstrates that the amount of PS in high-resolution spotlight data is sufficient to verify existing geo-data sets.

Figure 5 is another example demonstrating PS densities obtainable from TerraSAR-X. Again, the PS points are color-coded with respect to their height. The area covers the Las Vegas Convention Center, which consists of several huge halls with flat top roofs that provide stable point scatterers. From the picture, one can already recognize different parts of the building with their respective heights.

Another interesting test case is the central railroad station of Berlin, shown in Figure 6. In the center, two main buildings are constructed across the rail tracks. The latter is covered partly with a roof; besides a tower of triangular cross section is visible. The construction mainly consists of steel and glass, whereas the rail tracks to the left and right

![Figure 3](image_url) - Left: PS density as a function of spatial resolution. Right: Two areas with different urban development in Berlin are selected. Area 1 has a high building density and area 2 is a typical urban area.
are built on bridges of concrete and steel. A detailed analysis of several phase histories of PSs on the object finally showed a periodic displacement of the individual points.

For PSI processing a seasonal deformation model with a period of 1 year in combination with linear trends has been introduced. One sample phase history of relative deformation values including the estimated displacement functions between a PS on stable ground and one on the top of the main building is shown in Figure 7, which exemplifies very clearly the apparent deformation signal. The radar image of the area around central train station is shown in Figure 8.

Construction details of the steel building can be recovered from this amplitude image, whereas most of the bright points represent potential PS candidates. For these points, the parameters amplitude and temporal offset of the sine function are estimated and the obtained seasonal amplitudes are color-coded as visualized in Figure 9. The identified PSs are overlaid on the radar mean map (temporal mean image).

In the upper image, one ascending case is illustrated with a viewing direction from left to right. Below, data from a descending orbit has been evaluated and the viewing direction is opposite of the previous case (right to left). As only the line-of-sight (LOS) deformation component is measured by PSI, blue color indicates movement toward the sensor, whereas red color denotes displacement in the opposite direction. The separation of horizontal and vertical displacements can be achieved by considering observations from different directions, as available in this case. Evaluation of the two images imply that left and right of the main part of the building, the halls and bridges, experience a horizontal seasonal deformation, which shows up in an expansion to both sides (central part of both halls is stable; location indicated by white bar), whereas the central part is primarily moving in a vertical direction. In addition, a very interesting section can be found in the upper right corner, indicated by a sudden change in colors: two parts of the tracks are moving toward each other in summer time. Here an expansion gap is present, which has been approved by ground truth inspection. The origin of the detected periodic deformation signal could be related to thermal expansion during summer time and shrinking in
winter time of the steel construction. The central part shows an amplitude of about 8 mm (vertical displacement), that is, 16 mm total movement between winter and summer peaks. An investigation of the dependence of deformation amplitudes and height above ground of the PSs reveals a linear correlation of both parameters. A vertical expansion $\Delta L$ of the construction up to 16 mm on a length $L$ of approximately 45 m (height of the main building) can be induced on a steel construction by a temperature difference $\Delta T$, which can be calculated using the temperature coefficient of steel $k$:

$$\Delta T = \frac{\Delta L}{kL} = \frac{0.016 \text{ m}}{12.2 \times 10^{-6} \text{ K}^{-1} \times 45 \text{ m}} = 29.1 \text{ K} \quad (1)$$

Temperature histories of Berlin between February 2008 and December 2009 feature mean differences in high and low temperature of 33°C and 29°C, respectively. The assumption of thermal expansion of the building therefore can be confirmed.

As shown, the use of VHR SAR data of TerraSAR-X (using 300 MHz bandwidth) for PSI yields a vast increase in the number of PSs, compared to medium-resolution data. The geocoded PSs now allow for a better physical interpretation and understanding of these points. In medium-resolution data it is not easy to localize the scattering source in real world. Now, the enormous amount of PSs leads to dense geocoded point clouds, which reveal the locations of scattering sources clearly. The availability of a detailed digital surface model (DSM) helps to better understand the nature of PSs. In Figure 10, the PSs obtained from one stack in Berlin are shown, including a DSM of the area at Potsdamer Platz. The PSs show up very nicely at the facades of buildings, especially originating from rows of windows. Several PSs are hidden by the surface in this image, as the points are located at corners or ridges and the 3D surface is not sufficiently modeled at vertical walls. Nevertheless, most of the PSs can be assigned to certain features of the buildings. An overview of all PSs obtained from the given stack of SAR data is imaged in Figure 11. The city structure is mapped nicely, covering all areas with buildings. Therefore, deformation monitoring of (single) structures within urban areas is feasible applying PSI to this new class of VHR SAR data.

5. Conclusion

This assessment provides an insight into PS densities obtained for the city of Berlin, Germany, acquired from different incidence angles and track directions with TerraSAR-X. It has been shown that incidence angles in
the mid-range, that is, approximately 40°–47°, are advantageous for urban PSI. Such incidence angles provide PSs from facades and from the top of the buildings. In contrast, larger incidence angles reduce the PS density due to increased shadow areas and a reduced height resolution. This results in a loss of storeys of buildings, which are likely to generate many of the PSs. Finally, the most appropriate incidence angle depends on the actual test site characteristics, for example, the building heights, the distances between them, and their orientation, shape, and material.

From comparison between ascending and descending tracks, it could be shown that the main orientation of the buildings has significant influence and should be considered for maximizing the number of scatterers in the scene. The optimal orientation of building facades is parallel to the flight track. Polarization has to be considered only if the maximum number of potential PS candidates has to be extracted from the data, as PS densities between HH and VV polarizations differ only marginally. The most important parameter in terms of PS densities is resolution.

High-resolution spotlight data from TerraSAR-X provide an enormous increase in number of PSs, mainly at facades and roofs of buildings. This fact enables new applications like deformation assessments of single buildings and monitoring of structural stress. An encouraging example has been presented by the nonlinear displacement estimation of the Berlin central railroad station, which experiences seasonal deformation due to thermal expansion of the steel structure. The movement could be separated into horizontal and vertical components by evaluating stacks of different viewing directions. Of course, temporal sampling of 11 days at minimum and the necessary introduction of a priori deformation models depict certain limitations on movements and must be considered for deformation assessments using PSI. However, the recently available class of VHR SAR data enables the possibility of single object observations as well as large-scale ground deformation monitoring. In addition, the density and accurate 3D positions of the PSs account for a better understanding of the nature of these points.

Figure 9. Estimated seasonal amplitudes. Ascending track (upper image) and descending track (lower image) allow for separation of vertical and horizontal components of deformation. Blue color indicates movement toward the sensor, red color away from the sensor. Main buildings in the center are moving vertically, tracks and halls left and right of the central part show mainly horizontal displacements (stationary parts indicated by white bars). Constructional gaps are validated at purple dashed bars.
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References

Figure 10. Geocoded PS (green dots) on DSM at Potsdamer Platz, Berlin. Especially on buildings from middle to right, structure of windows on facade becomes evident.

Figure 11. Geocoded PS from one stack of VHR SAR images of TerraSAR-X. City structure of Berlin is clearly visible from PS of man-made structures.
Breit, H., et al., 2010. TerraSAR-X SAR processing and products. 

Eineder, M., et al., 2009. Spaceborne spotlight SAR interferometry with TerraSAR-X. 


