Bridge Detection in multi-aspect high-resolution Interferometric SAR Data

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Abstract

State-of-the-art airborne SAR sensors provide spatial resolutions in the order well below half a meter. In such data many features of urban objects can be identified, which were beyond the scope of radar remote sensing before. Core elements of urban infrastructure are bridges. An example for the new quality of the appearance of bridges in high-resolution InSAR data is given and interpreted. Due to the fine level of detail even smaller bridges are mapped to extended data regions covering large numbers of pixels. Therefore, in data of this quality the identification of bridge structure details is possible at least by visual interpretation. In this paper, the special appearance of bridges over water in high-resolution InSAR data is discussed. Geometric constraints for the mapping of bridge structures into the interferometric SAR imagery are given. These constraints can be exploited for the extraction of structural object information from the data. An approach for detection of bridges is proposed and first results demonstrated using orthogonal InSAR data sets of spatial resolution better than 40cm.

1 Introduction

Bridges are key elements of the man-made infrastructure. Monitoring of these important connecting parts of the traffic network is vital for many applications such as disaster management. In time critical events SAR can be the most suitable remote sensing technique for gathering useful actual data under certain circumstances such as bad weather or at nighttime. Therefore, the extraction of bridge constructions in SAR data is a topic of growing interest both in military and civil applications. Furthermore, in high-resolution SAR data of state-of-the-art sensors many more features of the bridge structure can now be observed, allowing better discrimination from other urban objects compared to coarser data.

The detection of objects like bridges does not only benefit from the higher resolution of amplitude SAR data. In addition, the capability of SAR to measure the 3D shape of the scene topography by interferometric processing offers valuable possibilities to distinguish bridges from other objects. For example, bridges are naturally higher than the surrounding ground and they coincide with an orthogonal orientated stripe of low coherence, if they span a river. Depending on the aspect certain object features may show up in the data or not. This is especially true for SAR that inherently requires oblique scene illumination. For example, in the case of bridges over water under certain viewing conditions different types of scattering events lead to the appearance of several bridge images at different range locations [2,3,4]. These images are mainly caused by layover, double-bounce reflection, and triple bounce-reflection occurring between bridge structure and water surface. The locations of such scattering events can be predicted from the given SAR viewing geometry and the bridge structure. On the one hand, such features can be exploited to derive information about the 3D structure of bridges from InSAR data.

On the other hand, SAR phenomena such as layover and occlusion burden the analysis. Hence, in order to achieve higher detection probability a multi-aspect analysis is advantageous. In this paper, a methodology for screening of large multi-aspect InSAR data sets for bridges is proposed and first results are presented. Subsequent fine analysis based on detection results and aiming at bridge reconstruction is scheduled for future studies.

The paper is organized as follows. In Section 2 the typical appearance of bridges in high-resolution InSAR data is discussed. Geometric constraints for the mapping of bridge structures into the SAR imagery are given. The methodology for the detection of bridges is outlined in Section 3. This structural image analysis approach is demonstrated for two InSAR data sets of the same urban scene, which have been taken from orthogonal viewing directions. The InSAR data have spatial resolution better than 40 cm in range and even finer in azimuth direction.

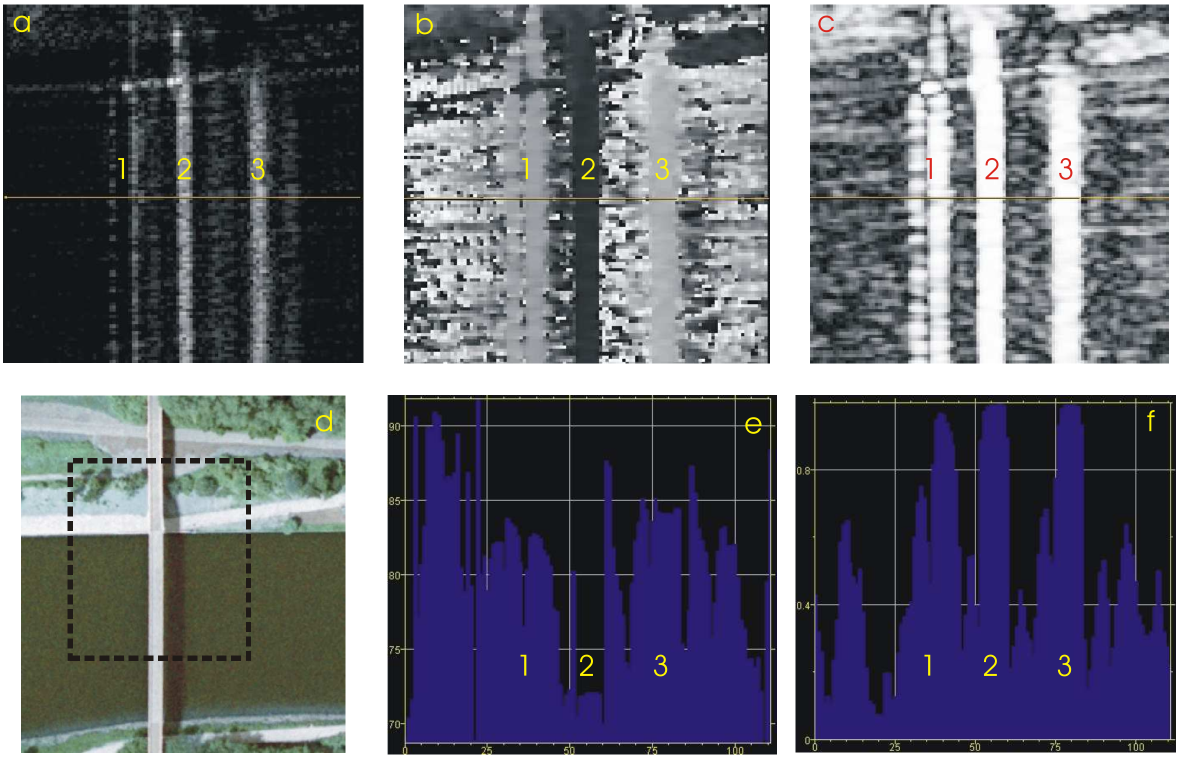

Figure 1 a-c) magnitude, height, and coherence images of an interferogram showing part of a narrow bridge over a river in slant range geometry, range is from left to right, spatial resolution approximately 38 cm in range and 18 cm in azimuth, off nadir angle 43 degree; d) aerial image of same bridge (dashed area corresponds to SAR data); e,f) elevation respectively coherence values along the horizontal profile in b-c).

2 Appearance of bridges in high-resolution InSAR data

Bridges over water illuminated from orthogonal direction (e.g. along the river direction) may cause multiple images in SAR data. Usually three parallel structures can be observed caused by direct reflection, followed by double-bounce reflection between bridge and water or vice versa, and finally triple reflection (water, lower parts of the bride and water again). Sometimes additionally superstructure elements and piles are also visible. This was already shown in the literature for SAR satellite amplitude imagery [2,3,4]. Here, the appearance of bridges in high-resolution InSAR data is discussed and geometric constraints are given. The test site is located in the city area of Dorsten, Germany. The single-pass X-band SAR data were acquired by the AeS sensor of Intermap [5]. Spatial data resolution is 38.5 cm in range and 18 cm in azimuth. After co-registration and further pre-processing, interferograms have been calculated from the given SAR imagery. The image chips shown in **Figure 1a-c** cover part of a narrow bridge spanning water, illumination direction is from left to right, the off nadir angle θ is approximately 43 degree. The mentioned triple stripe structure can be identified again in the magnitude, elevation, and coherence images. In SAR data of coarser resolution usually the structures show up as bright lines, now they appear as stripes of considerable width. In the magnitude image (**Figure 1a**) however the layover signal (structure *1*), causing the closest stripe to the sensor, is only partly visible, probably due to scattering at railing elements and mirror reflection on the road pavement. The former hypothesis is supported from the dashed structure of the related coherence (**Figure 1c**). Both in elevation and coherence images (**Figure 1b,c**) the layover stripe structure is better visible compared to the magnitude data. The entire width of the layover stripe Δs was estimated from the InSAR data to be approximately 5m in slant geometry that project to distance Δg of 7.3m in ground range according to:

$$\Delta g = \Delta s / \sin(\theta) \qquad (1),$$

with the difference Δs between first s_{lf} and last layover point s_{ll} (**Figure 2a**). This is well above the ground truth bridge width of 4m taken from the aerial image shown in **Figure 1d**. But considering the sketch in **Figure 2a,** this is not surprising, since layover on the water body is caused both by vertical and horizontal bridge structure elements. If additionally the identification of the signal of point s_{lc} located at the lower bridge corner is possible, at least the vertical bridge dimension h_b can be derived from the data by:

$$h_b = (s_{lc} - s_{lf}) / \cos(\theta) \qquad (2).$$

Reason for the second bright stripe (structure *2*) is double-bounce reflection s_{db} occurring at the corner reflector that is spanned from smooth vertical bridge facets facing the sensor and the water surface. This effect can be studied in **Figure 2b**.

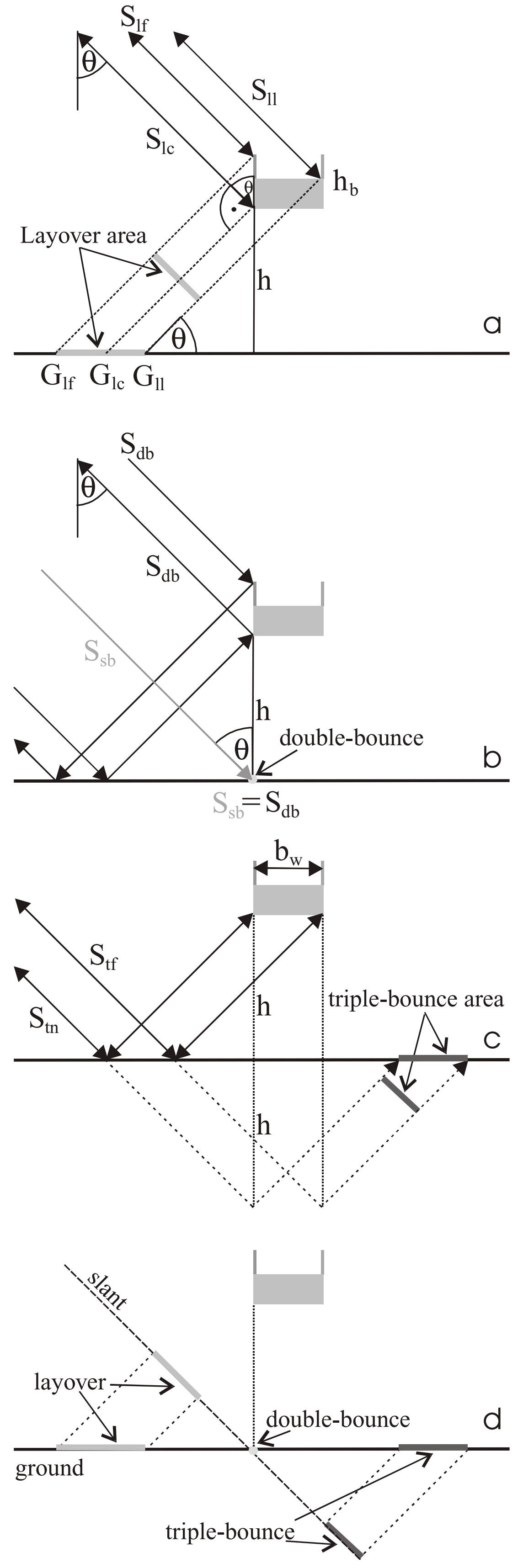

Figure 2 SAR Phenomena arising from viewing geometry at a bridge (grey) over water: a) layover, b) corner reflector double-bounce, c) triple-bounce, d) location of these effects in slant and ground geometry.

By theory all these double-bounce signals s_{db} should be integrated to the range cell s_{sb} that coincides with the nadir projection of the vertical bridge elements. But, due to additional different scattering events (e.g. at small bridge structures) and the non-perfect smoothness of bridge and water surface, the signal is usually spread out around the slant range value s_{sb} of a direct signal from the bridge footprint [4]. The width of this stripe seems therefore to be hardly predictable without very detailed 3D information of the bridge. Using Eqn. 2 the bridge height h can be estimated from the difference s_{sb} - s_{lc}.

Such estimate of height h of course can also be derived from the InSAR elevation data. The elevation values of the water itself were not useful for this purpose, because the almost specular reflection led to negative SNR of about -3dB that resulted in elevation data approximately evenly distributed over the possible span of unambiguous height of 20m. But, it turned out that the mean elevation value over the entire second stripe was a very good estimate of the water surface height. The standard deviation over this stripe was also very low. This observation is supported by the related mean coherence of 0.98 (**Figure 1f**). The bridge height h was estimated similarly using elevation values taken from the layover stripe (*1*). The difference of both estimates giving the distance between bridge deck and water was in this case 11m compared to 10,8m from ground truth (LIDAR DEM).

Very interesting is also the third structure (*3*) resulting from triple-bounce reflection between water, the lower bridge part, and water again. **Figure 2c** illustrates the effect: because of the longer signal path the signal is mapped to a position behind the true bridge location in range direction. Geometrically the signal seems to stem from a virtual bridge replica produced by mirroring the real bridge at the water surface. Assuming the absence of substructures below the bridge's core, the width of the bridge can be estimated exploiting this type of signal. Using the difference of near and far stripe borders, here called s_{tn} respectively s_{tf}, as Δs (here: 3m) in Eqn. 1 yields 4.5m for the bridge width, which is close to 4m according to the aerial image. However, the interferometric elevation values of such stripes were in some cases far too high in the final product, possibly due to erroneous treatment during phase unwrapping processing, because initial phase values indicate to elevation well below water level. This behaviour is object of further studies.

In **Figure 2d** the mentioned effects are summarized and their location in slant and ground range SAR images is given.

3 Bridge detection approach

Bridge detection is based on a structural image analysis approach. The aim of the algorithm is screening of large data sets for potential bridge locations. For reasons of robustness and computational load the automatic detection is carried out in sub-sampled data. High-resolution data would be required for subsequent fine analysis, not discussed here. Bridges are modeled as stripe-like objects. The appropriate range of the geometric stripe features length and width is derived from knowledge about the typical size of such infrastructure. Here, the focus is on bridges over water. Hence, the object traversed orthogonally by the bridge (the river) is modeled to be darker than the bridge and exhibiting a far lower coherence on average. At the beginning of the investigations it was assumed, that the average elevation of the water would match its real height, despite the lower SNR compared to other objects. However, this was not the case, probably due to absence of wind leading to almost mirror-like water surface resulting in dominant noise influence and an elevation mean only slightly below bridge level. Therefore, the threshold for the elevation difference to the bridge was set to a small value and the main feature exploited for river detection was low amplitude.

Figure 3 illustrates snapshots of amplitude images of the same bridge from two InSAR data sets taken from orthogonal directions. In increasing hierarchical order from left to right image analysis results are superimposed. In a pre-processing step de-speckling was achieved by Gaussian smoothing tailored to the requirements of the subsequent primitive line segmentation [1]. From the initial set of lines object hypotheses of type river stripe and bridge stripe are assembled according to the related object model. In lower hierarchical stages usually large numbers of hypotheses are generated of which only a small subset is actually related to objects of interest. In higher level reasoning steps these false hypotheses are sorted out successively. The two sets are scanned for crossing stripes with suitable crossing angle. The results for the example bridge are shown on the right in **Figure 3**. In both datasets the bridge was found. In the case of perpendicular SAR illumination the bridge's height over water can be assessed using the double-bounce signal in the manner described in the previous section. In the other case (upper part in **Figure 3**) this procedure is not possible resulting in height underestimation because of the noise floor in the water signal. Finally, fusion of the individual results is carried out.

4 Conclusion and future work

Modern SAR sensors achieve such high spatial resolution that even rather small bridges are mapped with considerable level of detail. Therefore, more detailed analysis of such objects is now possible. Interferometric processing even reveals many additional object features supporting bridge extraction. However, the constraints arising from the sometimes multiple appearance of bridge structures in the data have to be considered carefully.

In this paper the focus was on bridges over water. In further investigations other types of bridges shall be considered. At present, the detection is carried out independently in each InSAR data set. In the future the image analysis shall be combined in earlier recognition stages to enhance results by mutual evidence support and the elimination of blunders. Finally, a subsequent bridge reconstruction will be investigated.

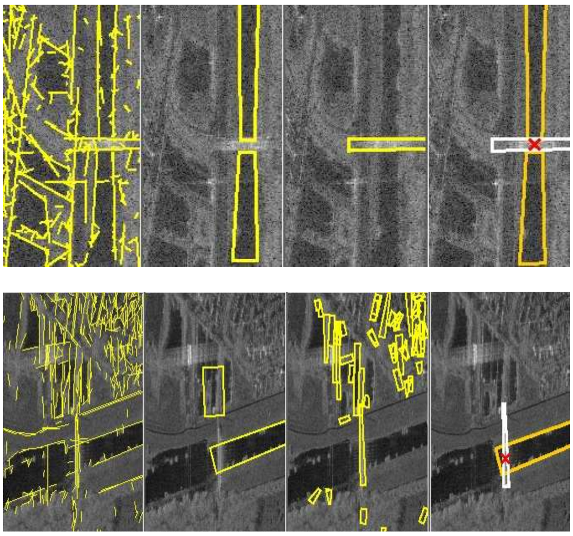

Figure 3 Detection of same bridge in InSAR data of two orthogonal aspects. From left: line primitives, river stripe hypotheses, bridge stripe hypotheses, bridge object crossing river objects.

5 Literature

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