EXTRACTION OF BRIDGES OVER WATER IN MULTI-ASPECT HIGH-RESOLUTION INSAR DATA

U. Soergel[1], H. Gross[2], A. Thiele[2], U. Thoennessen[2]

[1]Institute of Photogrammetry and GeoInformation, Leibniz Universität Hannover, 30167 Hannover, Germany
[2]FGAN-FOM Research Institute for Optronics and Pattern Recognition, 76275 Ettlingen, Germany

soe@fom.fgan.de

Commission III

KEY WORDS: SAR, Infrastructure, Building, Detection, Reconstruction, Urban

ABSTRACT:

Modern airborne SAR sensors provide spatial resolution in the order well below half a meter. In such data many features of urban objects are visible, which were beyond the scope of radar remote sensing only a few years ago. Core elements of urban infrastructure are bridges. In high-resolution InSAR data even small 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. The special appearance of bridges over water in high-resolution InSAR data is discussed. Geometric constraints for the mapping of certain bridge elements in interferometric SAR imagery are given. An approach for detection of such bridges is proposed. Information about the bridge structure is extracted in subsequent fine analysis. First results of the approach are demonstrated using orthogonal InSAR single-pass data sets of spatial resolution better than 40cm.

1. INTRODUCTION

In time critical events SAR can be the most appropriate remote sensing technique for gathering useful actual data under certain circumstances such as bad weather or at night-time. For example, satellite SAR has proven being suitable for flooded area detection and damage assessment purposes [Bach et al., 2005]. Due to climate change, flooding events of unfortunately even increasing devastation capability are more frequently observed in many places of the earth [International Charter, 2006]. Given the rather coarse resolution of operational SAR satellite systems, up to now the SAR analysis was mostly restricted to medium scale products, such as flood maps (e.g. Elbe flooding, 2006, [International Charter, 2006]). With the advent of high resolution SAR satellite systems and commercial airborne systems more detailed analysis at the object level becomes feasible. This was already studied for example in the context of building recognition [Soergel et al., 2003] and road extraction [Hedman et al., 2005] from SAR imagery.

Bridges are key elements of man-made infrastructure. Monitoring of these important connecting parts of the traffic network is vital for applications such as disaster management or in the context of political crisis, e.g. to evacuate inhabitants and to deliver goods and equipment.

In this paper, first results of a long-term project are presented, which aims at automatic detection and reconstruction of bridges in Interferometric SAR (InSAR) data of fine spatial resolution. Here, the focus is on bridges over water. In later project phases the investigation shall be expanded to other bridge types too. Compared to coarser SAR images in high-resolution SAR data of modern sensors many additional bridge structure features are observable, allowing better discrimination from other urban objects and higher level of detail in object recognition. Urban analysis does not only benefit from higher resolution of conventional amplitude SAR imagery. In addition, the capability of SAR to measure the 3D shape of scene topography by interferometric processing offers valuable features to distinguish man-made objects of different kinds [Soergel et al., 2003]. For example, bridges are naturally higher than surrounding ground and they coincide with an orthogonal orientated stripe of low signal amplitude and poor coherence, if they span a river. Additionally, the strong aspect dependency of SAR, due to the oblique scene illumination principle, leads to very interesting effects at bridges over water.

Under certain viewing conditions different types of scattering events lead to the appearance of several bridge images at different range locations [Raney, 1983; Raney, 1998; Robalo & Lichtenegger, 1999]. These images are mainly caused by direct backscatter, double-bounce reflection, and triple-bounce reflection involving bridge structure and water surface. The location of such scattering events is predictable from the given SAR viewing geometry and the bridge structure. On the one hand, such features are useful to extract 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 bridge detection in large multi-aspect InSAR data sets is proposed and demonstrated. Based on detection results information about the bridge structure is derived in subsequent fine analysis.

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 bridge detection and geometry extraction is presented 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 data have spatial resolution better than 40 cm in range and even finer in azimuth direction.

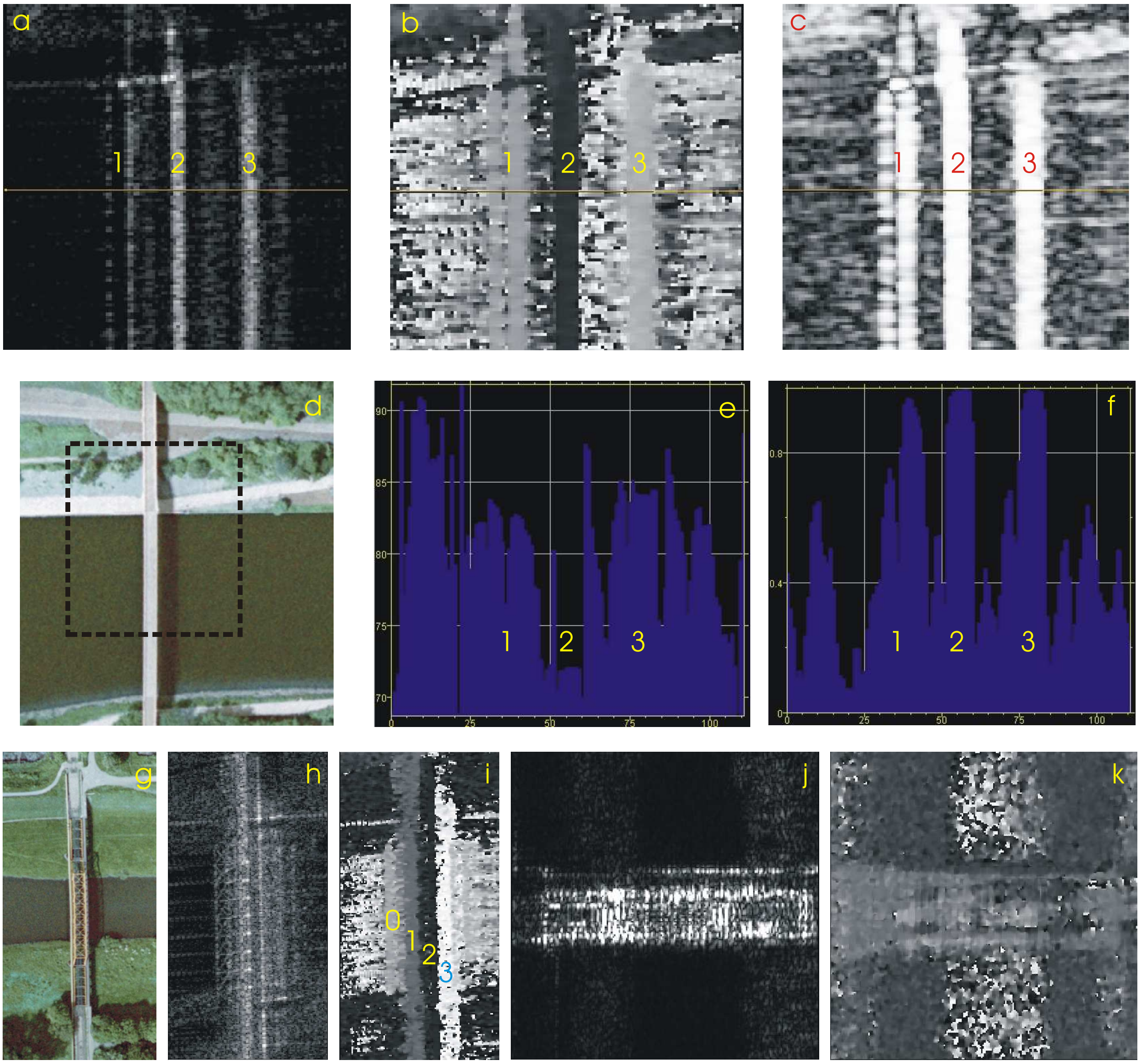

Figure 1 InSAR data sets with spatial resolution approximately 38 cm in range and 18 cm in azimuth, off nadir angle 43 degree, range is always from left to right: a-c) magnitude, elevation (DEM), and coherence images of an interferogram showing part of a narrow bridge over a river in slant range geometry; d) aerial image of same bridge (dashed area corresponds to SAR data); e,f) elevation and coherence values along the horizontal profile in b-c); g-h) railway bridge: g) aerial image; h,i) amplitude and elevation data of same aspect as a-c), number 0 corresponds to layover from bride superstructure; j,k) amplitude and elevation of railway bridge in orthogonal view.

2. APPEARANCE OF BRIDGES IN HIGH-RESOLUTION INSAR DATA

Bridges over water illuminated orthogonal to their orientation (i.e. along the river direction) may cause multiple images in SAR data. Usually three parallel structures are observed at increasing range locations: first direct backscatter from the bridge (more precise: layover of bridge and water signal), followed by double-bounce reflection between bridge and water or vice versa, and finally triple reflection (water, lower parts of the bridge and water again). Sometimes additionally superstructure elements and piles are also visible. This was already shown in the literature for SAR satellite amplitude imagery [Raney, 1998]. In SAR data of coarser resolution usually the structures show up as salient bright lines in sharp contrast to surrounding water surface. From the ground range distance Δg_s of first to second or second to third stripe and off nadir angle θ the bridge height h can be estimated [Raney, 1983; Robalo & Lichtenegger, 1999] according to:

$$h = \Delta g_s / \tan(\theta). \qquad (1)$$

In SAR data of finer spatial sampling however the structures are not line-like anymore but appear as stripes of considerable width, which has to be considered for geometric analysis. Additionally, in the case of InSAR data further information is available in form of interferometric elevation and coherence.

In the following, the appearance of bridges in high-resolution multi-aspect InSAR data is discussed and geometric constraints are given. The test site is located in the city area of Dorsten, Germany. It contains several water canals. The single-pass X-band SAR data shown in Figure 1 were acquired by the AeS sensor of Intermap Technologies [Schwaebisch & Moreira, 1999]. 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. From the interferogram the coherence is obtained and, after phase-unwrapping, the InSAR elevation (DEM). The image chips depicted in Figure 1a-c cover part of a narrow bridge spanning water, illumination direction is from left to right, off nadir angle θ is approximately 43 degree. The mentioned triple stripe structure shows up again in the magnitude, elevation, and coherence images. In the magnitude image (Figure 1a) however the bridge's layover signal (structure *1*) is only partly visible, probably due to scattering away from sensor at railing elements and mirror reflection on the smooth paving. 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 manually from the InSAR images to be approximately 5m in slant geometry that project to distance Δg of 7.3m in ground range according to:

$$\Delta g = \Delta s / \sin(\theta), \tag{2}$$

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 backscatter 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:

$$h_b = (s_{lc} - s_{lf}) / \cos(\theta). \tag{3}$$

Assuming s_{lc} to coincide with the border between dashed and solid layover parts, vertical height h_b is estimated to 2.6m, which seems to be plausible for such small bridge.
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. The signal propagation according to this effect is sketched in Figure 2b. By theory all these double-bounce signal contributions s_{db} should integrate into the range cell that coincides with the direct reflection or single-bounce backscatter path length s_{sb} from the nadir projection of the vertical bridge elements on the water surface:

$$s_{sb} = s_{db}. \tag{4}$$

But, due to additional different scattering events (e.g. at small bridge structures) and non-perfect smoothness of bridge and water surface, the double-bounce signal is usually spread out around the slant range value s_{sb} of a direct signal from the bridge footprint [Robalo & Lichtenegger, 1999]. The width of this stripe seems therefore to be hardly predictable without very detailed 3D information of bridge geometry and material properties.

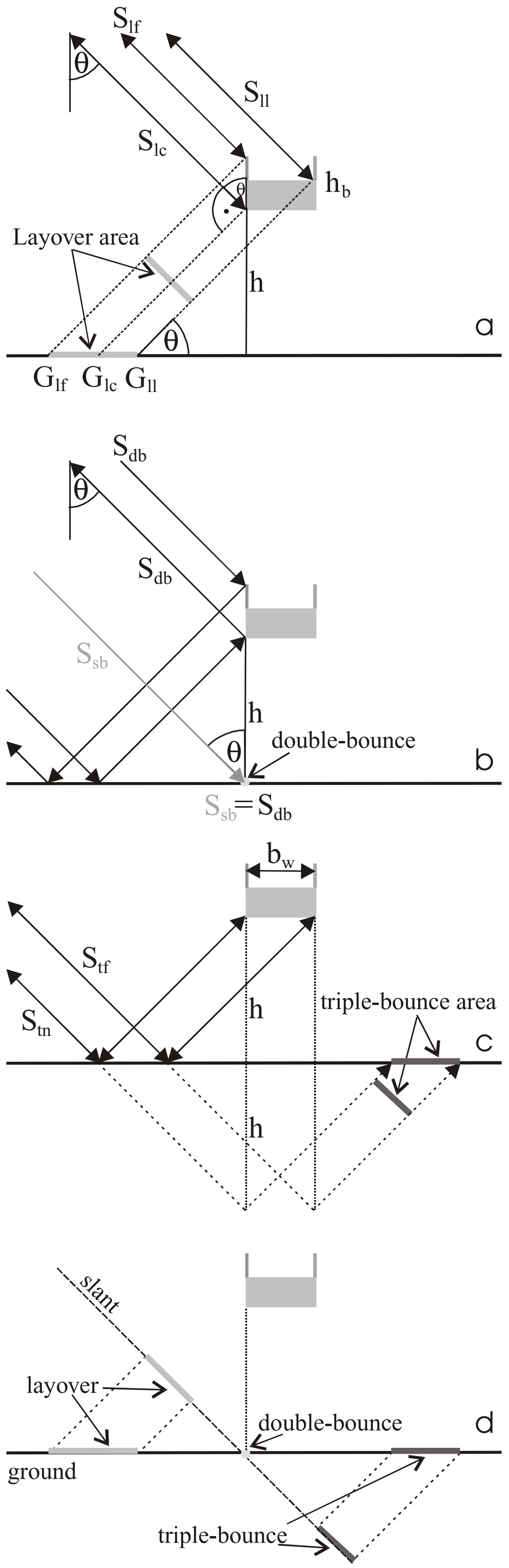

Figure 2 SAR Phenomena arising from viewing geometry at a bridge (grey) over water: a) layover, b) corner reflector double-bounce, c) triple-bounce, d) location of these effects in slant and ground geometry.

Analogous to Equation 3, the bridge height h can be estimated from the difference s_{db} - s_{lc}:

$$h = (s_{db} - s_{lc}) / \cos(\theta). \quad (5)$$

Such estimate of height h of course can also be derived from the InSAR elevation data. At first glance, the most straightforward way for this task seems to use the interferometric elevation value difference between bridge and surrounding water. However, elevation values coinciding with water surface were not useful for this purpose, because almost specular signal reflection led to negative SNR of about -3dB, resulting in elevation data approximately evenly distributed over the possible unambiguous elevation span 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 elevation data standard deviation over this stripe was also very low. This observation is supported by the related mean coherence magnitude $|\gamma|$ of 0.98 (Figure 1f). According to

$$SNR = \frac{|\gamma|}{1-|\gamma|}, \quad (6)$$

this coherence value translates to SNR of 49 or approximately 17dB. The bridge height h over water was estimated using elevation values taken from the layover stripe (structure *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 bridge image (structure *3*) resulting from triple-bounce reflection between water, the lower bridge part, and water again. Figure 2c illustrates this effect: because of the longer path length 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 b_w can be estimated exploiting this type of signal. Analogous to Equation 2, bridge width b_w is given by the difference of near and far triple-bounce stripe borders, here called s_{tn} and s_{tf} respectively:

$$b_w = (s_{tf} - s_{tn}) / \sin(\theta). \quad (7)$$

This estimate yields 4.5m for the width of this bridge b_w that is close to 4m according to the aerial image.

Interestingly, the interferometric elevation values of such stripes were in some cases far too high in the final DEM 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. From the sketch and the image examples discussed above it becomes clear that in high-resolution InSAR data the stripes are not evenly spaced in range and show different spatial extension. Hence, simple height determination according to Equation 1, which yields good results for data of coarser resolution, seems not to be appropriate for data of finer spatial sampling.

In the same InSAR dataset a railway bridge spanning water is almost perfectly orientated in same direction. This object features typical construction structures often observed at railway bridges, such as superstructures made of connected metal bars crossing in vertical and horizontal directions. The horizontal structures are directly visible in the aerial image (Figure 1g) taken from nadir view and the vertical ones can at least be guessed from sun shadow on water and shore. Similarly, but caused by totally different mapping processes, the superstructure pattern appears in the InSAR data. Especially from the magnitude image (Figure 1h, illumination direction from left again) the human observer may extract details of these structures. Despite layover, which causes signal mixture of vertical and horizontal metal bridge structures, the horizontal X-structures are at least partly visible in the layover signal, not only in the water region but also in the grassland area. However, the interpretation of the amplitude data is not straightforward, mainly because of dominant scattering events (e.g. at metal bars of the superstructure) superimposing adjacent areas even far apart the origin of such strong backscatter. The mentioned superstructures cause in the InSAR elevation data a fourth salient signal stripe, appearing as bright or elevated zone on the left in Figure 1i (structure *0*, structures *1,2,3* same as in Figure 1a-c). Then the sequence follows as described for the other bridge: layover of bridge's trackway, double-bounce area, and triple-bounce area. The very same bridge is shown again in Figure 1j,k, this time illuminated from orthogonal aspect along trackway direction. Even though the single-pass acquisition of both tracks was only 10 minutes apart, the bridge mapping is now totally different only due to the altered aspect angle. Superstructures orientated perpendicular to the illumination direction lead to strong scattering, revealing some insight in the bridge's geometry.

3. BRIDGE DETECTION APPROACH

Bridge detection and feature extraction are carried out in two subsequent modules. Knowledge about the typical size of bridges is coded a priori in a bridge model that can be further specified according to information of features of the scene of interest. In the general case, including bridges over roads and bridges crossing valleys of the landscape, both steps base on structural image analysis. For example, bridge hypotheses are detected using crossing stripe-like objects (one for the bridge and the other for the bridged obstacle), which fulfill certain model requirements and have been built hierarchically from edge or line primitives [Soergel et al., 2006]. But, for the special case of bridges over water such approach is not appropriate for two reasons. Firstly, despite man-made river regulation, rivers exhibit often rather curved structure together with sometimes remarkable and abrupt change of contours, e.g. due to natural riverbank variation. An example is given in Figure 3a on the right depicting an amplitude image of a canal of different shape on both bridge sides. Furthermore, river shape may change significantly because of seasonal effects influencing the water level. Secondly, the sharp bridge contrast to the water background allows a simplified detection strategy.

The strategy applied here is described using the images shown in Figure 3. First step is segmentation of dark amplitude image areas based on a threshold that can be estimated from histogram analysis. Of course besides the desired water area all other dark areas (e.g. caused from smooth surfaces such as asphalt) are extracted in this manner and the bright bridge structures are still missing (Figure 3b). By a sequence of morphological erosion and dilatation steps undesired small objects are removed and bridge gaps are closed. The remaining image region (white in Figure 3c) is now the expectation area for bridges over rivers. The morphological operation sequence has to be parameterized according to a given river and bridge model (i.e. search for narrow or broad rivers or bridge, respectively). Here, in general it is assumed that the bridge is narrower compared to the river

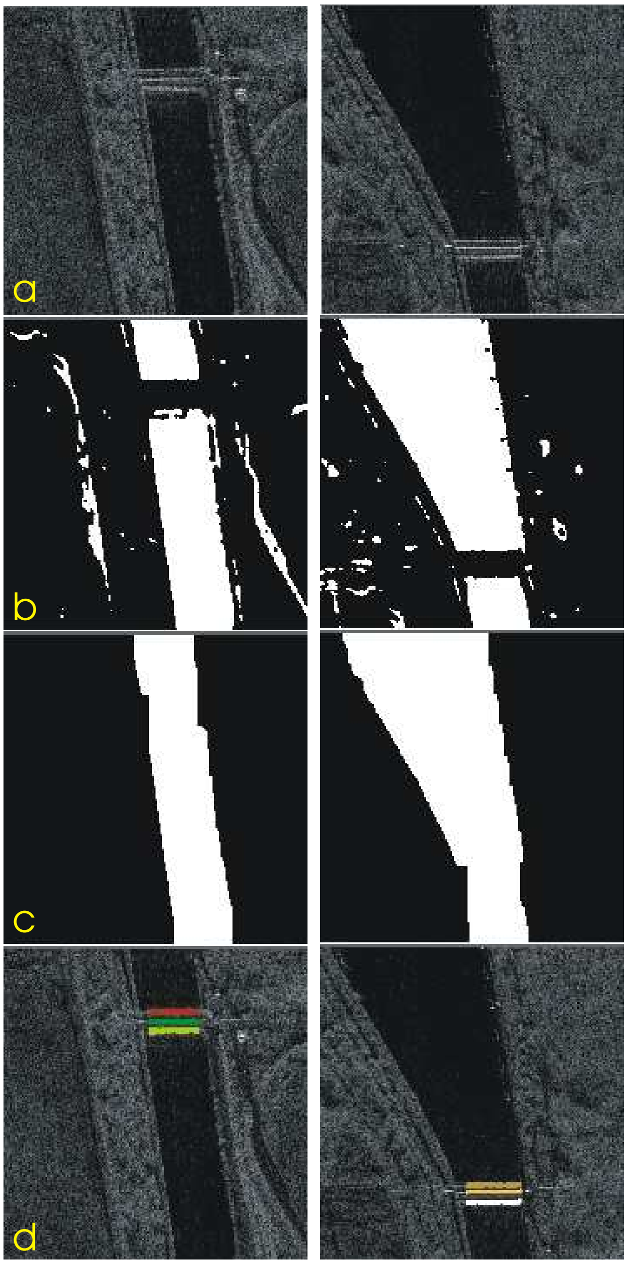

Figure 3 Detection of two parallel bridges in InSAR data, range direction top-down. From top: a) amplitude images, b) Result of threshold operation (dark regions shown in white), c) result after morphological operations, d) detected typical triple stripe image structure of both bridges.

or canal. The expectation area can further be scaled down by a logical "exclusive or" operation with the initial threshold result (i.e. Figure 3b ⊕ Figure 3c) and subsequent morphological noise reduction.

The aim of the algorithm described so far is screening of large data sets for potential bridge locations. For reasons of robustness and computational load the described procedure is carried out in sub-sampled data. Subsequent analysis is based on high-resolution data.

The next step consists of the detection of possible bridge structures in the InSAR data restricted to the segmented expectation area. As discussed in the previous section, depending on viewing aspect and river orientation the very same bridge might appear as single or multiple stripe structure in the imagery. In the remainder of this paper the more interesting latter case is focused on. Compared to magnitude and elevation data the coherence image is most suitable for detection of the triple stripe structure (Figure 1a-c). For the detection of individual stripes the Steger operator [Steger, 1998] is used. This operator requires the stripe width as parameter. The admissible range of this parameter is adjusted according to the given bridge model. Furthermore, the expected bridge orientation can at least be roughly estimated from the main direction of the detected water body in proximity of the bridge (assuming preferred orthogonal crossing of bridges over water). The extracted stripe structures for the two bridge examples are shown in Figure 3d. The analysis up to now was carried out separately for every viewing direction of the given InSAR data. The individual results can be fused to improve evidence. This topic shall be investigated thoroughly in future work.

4. FINE ANALYSIS

The fine analysis is based on the geometric constraints discussed in Section 2. The first step is to decide whether neighboring stripes belong to the same bridge or not. This is sometimes hardly possible, if bridges are located close to each other. In the test area this problem does not arise. According to the given bridge model, plausible minimum and maximum values of the separation in range of the stripes can be roughly estimated from Equation 1.

As discussed before, the bridge's height over water can be estimated in different ways from SAR and InSAR data. Results are shown in Table 1 and compared to LIDAR data as ground truth. B1 refers to the right column and B2 to the left column in Figure 3. The SAR and LIDAR data have not been collected at the same time, but since the scene contains canals and not rivers the water height is expected to be kept quite constant from authorities in order to ensure smooth shipping traffic. Except for the LIDAR reference data all estimates are rounded to integer values.

	Ground truth	Height from amplitude		Height from elevation	
		1 2	2 3	manual	automatic
B1	10.8	9	11	11	11
B2	11	11	9	11	11

Table 1 Results of bridge height over water estimation.

First, bridge height extraction from amplitude data is discussed. With respect to Equation 1, the problem arises to choose the correct range locations for the estimate. Here, manually the middle stripe range positions have been used and two estimates were carried out for stripes one to two and two to three. The accuracy of results varies with up to 2m error.

Another possibility to determine the bridge height is the elevation data. 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 height was estimated from the difference of the layover and the double-bounce signals. This was done twice: manually and from the automatically detected stripe structures. The results are close to the reference values. In the case of the exploitation of the automatically

detected stripes only elevation pixels coinciding with coherence values larger than 0.9 were used to calculate the mean over the extracted stripe. Furthermore, the coherence is used as weight in the averaging process [Soergel et al., 2003] to increase the accuracy of this estimate. Without consideration of the coherence results would be severely degraded.
Of course from such few examples as presented here no statistical sound overall assessment of the methodology is possible. However, the achieved accuracy encourages further investigation in this direction in future studies.

5. 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 comprehensive 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. Height estimate based on InSAR elevation data seems to be more robust compared to analysis of amplitude SAR data alone. First results of the proposed approach for bridge detection and geometry extraction are promising.
In this paper the focus was on bridges over water. The morphological water segmentation might fail in the case of narrow rivers or creeks. In order to detect such thin water bodies a line based approach will be developed. In further investigations other types of bridges shall also be considered (e.g. spanning roads, railway tracks, or valleys).
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. Furthermore, context information given for example by a road network extraction [Hedman et al., 2005] will be incorporated to support the analysis.Finally, automatic reconstruction of bridge extensions in terms of length and width will be investigated.

REFERENCES

Bach, H., Appel, F., Fellah, K., de Fraipont, P.: Application of flood monitoring from satellite for insurances, Proc. of IGARSS, 2005, CD, 4p.

Hedman, K. Wessel, B., Soergel, U., Stilla U.: Automatic Road Extraction by Fusion of Multiple SAR Views. In: M. Moeller, E. Wentz (eds). 3rd International Symposium: Remote sensing and data fusion on urban areas, URBAN 2005. International Archives of Photogrammetry and Remote Sensing, Vol. 36, Part 8 W27, 2005, CD, 5 p.

International Charter Space and Major Disasters: list of recent floodings: http://www.disasterscharter.org/new_e.html flooding of river Elbe, Germany and Czechia, April 2006: http://www.disasterscharter.org/disasters/CALLID_116_e.html

Raney, R. K.: "The Canadian SAR Experience", Chapter 13 of Satellite Microwave Remote Sensing, edited by T.D. Allan, Ellis Horwood Ltd., Chichester, 1983, pp 223-234. (see also: http://ccrs.nrcan.gc.ca/radar/ana/confed_e.php).

Raney, R. K.: "Radar Fundamentals: Technical Perspective." In Henderson, Floyd M., and Anthony J. Lewis, ed., Manual of Remote Sens-ing 3rd Edition: Principles and Applications of Imaging Radar, Vol 2. American Society for Photogrammetry and Remote Sensing, 1998, pp 9-130.

Robalo, J. and Lichtenegger, J.: "ERS-SAR Images a bridge", ESA, Earth Oberservation Quarterly, December 1999, pp. 7-10 (see also: http://esapub.esrin.esa.it/eoq/eoq64/bridge.pdf).

Schwaebisch, M. and Moreira, J.: "The High Resolution Airborne Interferometric SAR AeS-1". In: Proceedings of the Fourth International Airborne Remote Sensing Conference and Exhi-bition, Ottawa, Canada, 1999, pp. 540-547.

Soergel, U., Cadario, E., Gross, H., Thiele, A., Thoennessen U.: "Bridge Detection in multi-aspect high-resolution Interferometric SAR Data". Proc. of 6th European conference on synthetic aperture radar, EUSAR, 2006, CD, 4p.

Soergel, U., Thoennessen, U., and Stilla, U.: "Reconstruction of Buildings from Interferometric SAR Data of built-up Areas." Proc. of PIA, International Archives of Photogrammetry and Remote Sensing, Vol. 34, Part 3/W8, 2003, pp. 59-64.

Steger, C.: "An Unbiased Detector of Curvilinear Structures." IEEE Trans. Pattern Analysis Machine Intelligence, Vol. 20, No. 2, 1998, pp. 113-125.