BRIDGE HEIGHT ESTIMATION FROM COMBINED HIGH-RESOLUTION OPTICAL AND SAR IMAGERY

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ABSTRACT:

Today's airborne (Memphis, AeS-1, Ramses) and space borne (TerraSAR-X, CosmoSkyMed, Radarsat) SAR sensors provide very high resolution imagery independent of daylight and cloud coverage. Space borne systems achieve geometrical resolutions of down to one meter while airborne sensors are capable of acquiring images with sub metric resolution. In this kind of data, urban objects like buildings and bridges become visible in much detail. However, due to the side-looking SAR sensor principle, layover and occlusion hamper the interpretation particularly in urban scenes. One possibility to overcome this drawback is the use of additional information from high resolution optical imagery. In this paper, first findings of a long term project using both optical and SAR imagery for the modelling and extraction of bridges are presented. The focus is on bridges because they play a key role as connecting parts of man-made infrastructure and are of high importance in case of rapid natural hazard response. Differences between bridges over water and bridges over land are explained. Furthermore, concepts for estimating bridge heights from of a single SAR image and by means of combined optical and SAR imagery are derived.

1. INTRODUCTION

Up-to-date airborne SAR sensors provide geometrical resolutions of well below half a meter. Because of the high level of detail provided by such imagery, the acquisition of urban scenes and furthermore the extraction of elevated objects like buildings and bridges becomes a promising application field. However, the SAR typical disadvantages, due to the sensor's side looking perspective, cannot be overcome easily. Effects like layover and occlusion are developed to their full extent particularly in urban areas. Such principal drawbacks can at least partly be alleviated by combining SAR imagery with spatial information, for example, retrieved from topographic maps or optical images. In this study, SAR images are interpreted in combination with optical images since they are usually available even for remote regions. However, the viewing geometries of SAR and optical sensors lead to different appearances of the same object in the corresponding images. Hence, simply overlaying images of these two different kinds of sensors will lead to displacements. The higher an object is elevated above the ground, the greater is the displacement between the imaged object in the SAR image and the imaged object in the optical image. Thus, elevated objects have to be modelled carefully taking into account both the SAR and the optical viewing geometry in order to come up with reasonably accurate results.

The focus of this paper is on the modelling and automatic extraction of bridges. Bridges are a key feature in urban infrastructure and have high importance especially in case of time critical events, such as natural hazards or political crisis. They are linking roads and railways, enabling rapid emergency response in regions, e.g., hit by flooding or land slides. It is of high interest to retrieve information about the bridges current condition in a crisis situation. Lack of daylight or clouds covering the region of interest often circumvent the acquisition of optical images. Due to their relatively long wavelength and the active imaging mode, SAR sensors capture images almost insensitive to the weather conditions and independently of daylight. By comparing optical images dating back to before the hazard and SAR images acquired during or after the hazard, automatic change detection can be conducted.

The following paragraphs will give an insight into first findings of a long term research project. SAR scenes of bridges over water and of bridges over land will be compared and SAR specific effects will be explained. Concepts for the three-dimensional extraction of bridges from one SAR image and one optical image will be presented.

2. BRIDGES IN INSAR AND SAR IMAGERY

The appearance of a bridge in a SAR image very much depends on the environment surrounding the bridge. Generally, two different kinds of bridges are thus distinguished: bridges over water and bridges over land. In the following two paragraphs, the differences between bridges over water and bridges over land are discussed.

2.1 Bridges over water

The characteristics of bridges over water in SAR imagery have already been discussed in detail for instance in (Robalo & Lichtenegger, 1999; Soergel et al., 2007; Cadario et al., 2008). Figure 1 (top image) shows an InSAR amplitude image of two bridges over water. The same two bridges are depicted again in an optical aerial image in Figure 1 (centre image). Usually InSAR allows for obtaining directly a three-dimensional model of the scene. However, calm water surfaces act like a mirror and hence the signal to noise ratio (SNR) is poor. Thus, water

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surfaces show poor coherence values leading to artefacts in the final Digital Surface Model (DSM). One possibility to more precisely estimate the water level is to determine the distance between the bottom of the bridge and the water surface. Knowing the absolute height of the bridge body, the height of the water surface can then be derived.

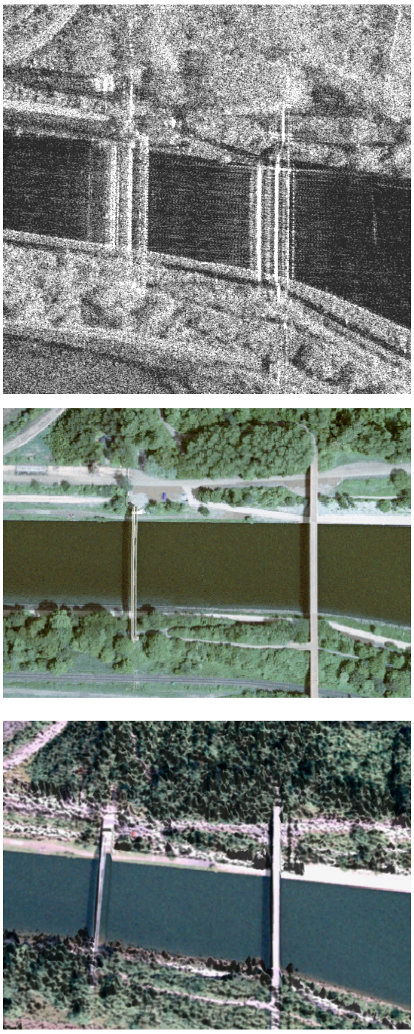


Figure 1: Test images of bridges near the city of Dorsten in southern Germany, (top) InSAR magnitude image pair taken in X-Band (illumination direction from right to left), (centre) optical aerial image, (bottom) 3D visualization of optical and InSAR data after fusion.

This technique becomes possible because the very calm surface of the canal leads to strong signal due to multiple reflections. In particular, double and triple-bounce effects are typical for bridges over water, illuminated perpendicularly by the sensor. Three lines can be observed for each bridge in SAR data of coarser resolution. In high resolution imagery such lines widen to stripes. The first stripe in illumination direction represents the height of the bridge body because most of the radar signal is backscattered directly from the bridge body. The second stripe is due to double-bounce reflection between the bridge and the water surface or vice versa. Triple reflection leads to the third stripe where the radar signal first hits the water surface, then lower parts of the bridge body, and finally the water surface again. The height h of the bridge over the water surface can be estimated by measuring the slant range distance Δs either between the first and the second or the second and the third line. Knowing the off-nadir angle θ of the SAR sensor, h is estimated:

$$h = \Delta s / \cos(\theta) \tag{1}$$

However, the exact horizontal position and outlines of the bridges cannot be easily derived due to the multiple bounce effects. This is done by fusing the three-dimensional InSAR scene with an aerial photo taken in nadir view. The double-bounce stripe in the InSAR data is replaced with the optical data and the water surface is replaced with the newly computed value (Soergel et al., 2007).

2.2 Bridges over land

Bridges over land appear differently in SAR imagery compared to bridges over water (Wegner & Soergel, 2008). Multiple parallel lines at a bridge, typical for bridges over water, do not occur in SAR images of bridges over land (compare Figure 1 (top) and Figure 2). This is due to the different reflectivity properties of water and land. Calm water strongly reflects the radar signal whereas inhomogeneous terrain and vegetation leads to almost diffuse reflection on the ground under the bridge body. In case of bridges over land, multiple bounce effects only occur at dihedral reflectors on the bridge body and where bridge pillars meet the ground. Hence, the bridge height cannot be determined directly from the distance of parallel lines and the off-nadir angle.

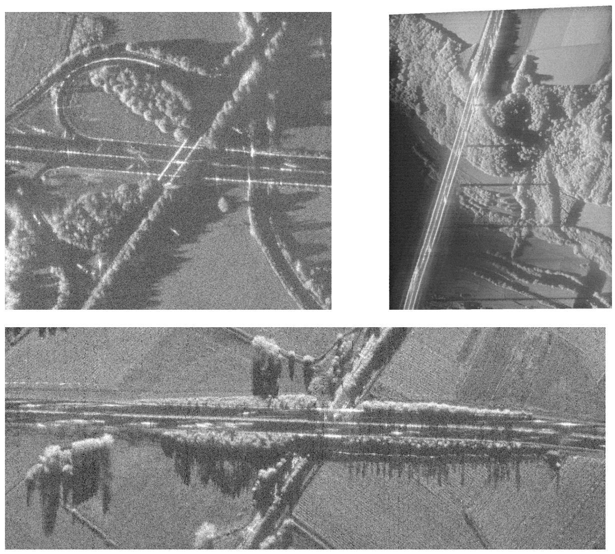


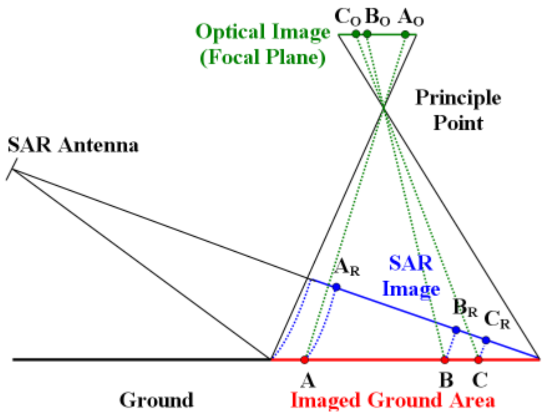
Figure 2: SAR test images of highway bridges acquired by the MEMPHIS sensor in ka-Band, (top left) SAR image of a bridge near Manching (illumination direction from left to right), (top right) SAR image of a bridge near Schwäbisch Hall (illumination direction from left to right), (bottom) SAR image of a bridge near Wolnzach (illumination direction from top to bottom).

However, other features have the potential to provide additional information about the imaged scene. The three images in Figure 2 show three different bridges in Southern Germany. A relatively short bridge crossing a freeway is displayed in Figure 2 (top left). Most of the radar signal on top of the bridge is reflected away due to the smooth surface of the tarred road.

Therefore, the road appears dark in the image and almost no insight can be deduced from direct backscatter. However, although the bridge surface itself cannot be seen nicely, the width of the bridge may be derived from two parallel bright lines. They are due to double-bounce effects from the guardrails on top of the highway bridge. Such guardrails are typical features of highway and freeway bridges. They also appear in the top right image and the bottom image in Figure 2. The top right image shows a freeway bridge crossing a deep valley close to the city of Schwäbisch Hall. In addition to two guardrails on each side of the bridge, a third guardrail can be seen in the middle of the bridge, separating the two opposed driving directions. A typical SAR effect, useful for modelling bridges over land, is occlusion. A shadow of the bridge body and the pillars is observable in the top right image of Figure 2. Its shape depends on the bridge body, the height of the bridge above the terrain and the undulation of the terrain. The greater the distance between the bridge body and the bottom of the valley becomes, the further away is the shadow from the bridge (assuming a constant height in the occluded area). This shadow distinguishes objects elevated above the ground from non-elevated objects. It describes the bridge as a three-dimensional object, discriminating it from roads.

3. BRIDGE HEIGHT ESTIMATION FROM OPTICAL AND SAR IMAGERY

The three-dimensional modelling of a scene using one optical image and one SAR image is possible due to the different perspectives of the sensors (Figure 3). Optical sensors usually acquire images with off-nadir angles smaller than 30°. SAR sensors are side looking and e.g., military airborne sensors acquire imagery with off-nadir angles up to 70°. Hence, two different perspectives of the same object on the ground allow for the estimation of height values. Additionally, SAR sensors measure distances whereas optical sensors measure angles. Hence, the points A, B, and C in Figure 3 are projected to A_O,



B_O, and C_O by the optical sensor while they are imaged to A_R, B_R, and C_R by the SAR sensor.

Figure 3: Comparison of optical and SAR sensor geometries

3.1 Displacement of elevated objects in optical imagery

One database containing optical imagery covering the entire Earth with reasonably high resolution is GoogleEarth. Ortho-rectified optical images from both space borne and airborne sensors are available free of charge. In case rapid change detection is needed during the occurrence of a natural hazard, imagery from GoogleEarth can be used as a reference. Since the optical images are ortho-rectified, distortions due to terrain undulation are significantly decreased. However, elevated man-made objects stay distorted because they are not included within the digital elevation models (DEM) that are used for the rectification process. Such DEMs only contain points on the bare ground. This effect is shown in Figure 5 while an overview of the entire bridge is given in Figure 4. Figure 5 shows a section of a long railroad bridge, crossing a valley. The terrain height of the valley bottom is varying as it can be seen in Figure 4 (left) and from the distance between the shadow and the bridge in Figure 5. The further away the shadow is situated from the bridge, the deeper is the valley.

Figure 4: Images of a railroad bridge made of concrete-steel near the city of Zellingen in southern Germany, (left) oblique photo taken out of the aircraft with a consumer grade camera, (right) optical image from GoogleEarth.

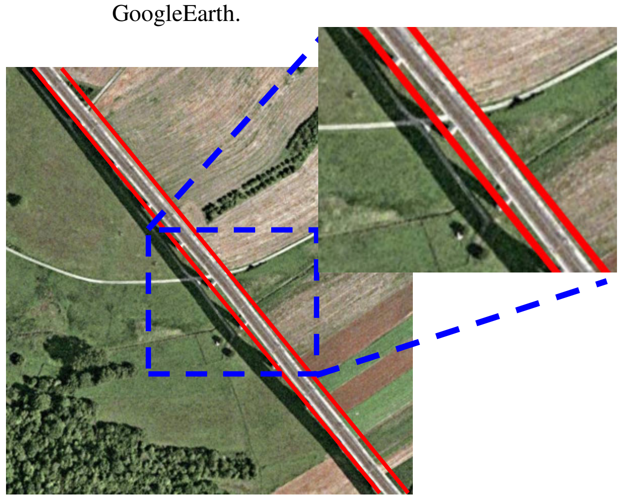


Figure 5: Blow-up of a GoogleEarth from Figure 4; compared to the two parallel red lines, the distortion of the bridge in the ortho-rectified image can be observed.

The distortion of the railroad bridge in Figure 5 becomes obvious by comparing the alignment of the two parallel red lines with the bridge body. The greatest distortion occurs at the highest elevation of the bridge above the valley bottom. Since the image was taken from the south-west, maximum distortion occurs towards the north-east.

A first rough estimate for the height h of the bridge (knowing the altitude of the sun φ) is achieved by simply measuring the length of the shadow s in the image (Equation 2).

$$h = \tan(\varphi) \cdot s \qquad (2)$$

3.2 Displacement of elevated objects in SAR imagery

In SAR imagery, the ortho-rectification process leads to similar effects as in optical imagery. Elevated objects stay distorted in the image if they are not included in the DEM the image is rectified with. However, the lasting distortion is more severe because SAR sensors acquire imagery with high off-nadir angles. Additionally, the SAR technique consists of measuring distances and hence the bridge body is imaged closer to the sensor than the bottom end of its pillars (layover effect). Therefore, three-dimensional objects that are not accounted for during the ortho-rectification process show more distortion than in corresponding optical data. This effect can be exploited in order to obtain height values of elevated objects both from a single SAR image and from combined optical and SAR imagery.

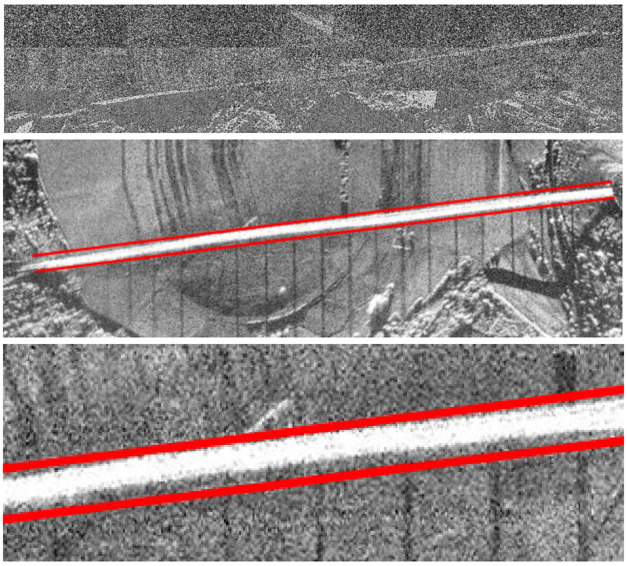


Figure 6: SAR image of the railroad bridge near Zellingen acquired with the airborne MEMPHIS sensor in ka-Band (illumination direction from top to bottom), (top) SAR image ortho-rectified with DEM, (centre) bridge distortion becomes obvious compared to the parallel red lines, (bottom) the blow-up of the centre image shows that the bridge distortion follows the terrain undulation

In Figure 6, a high resolution SAR image of the Zellingen bridge scene, already shown in optical imagery in Figure 4 and Figure 5, is displayed. It was acquired in Ka-Band by the airborne sensor MEMPHIS, like the images shown in Figure 2. The bridge appears particularly bright in the image because it is a railroad bridge. Strong backscattering and multiple bounce effects occur at the steely railroad tracks and at the superstructure of the bridge. Occluded areas due to the bridge body and the pillars can nicely be seen. This shadowing effect can be exploited for several purposes. First, the shadow distinguishes a three-dimensional object from a two-dimensional object. Hence, a shadow is helpful for a classification and detection process in order to distinguish between roads (2D) and bridges (3D). Second, the shadow can be used in order to derive bridge height estimates directly from a single SAR image as it will be explained in detail in the following paragraph.

3.3 Bridge height estimation from a single SAR image

Assuming a flat wave front as well as locally flat terrain, the height of an object imaged by a SAR sensor can be directly derived from the image. Figure 7 displays the basic SAR imaging principle. Let object P with elevation h be the railroad bridge from Figure 6. Its true horizontal position on the ground is P'. The SAR sensor (SAR) acquires the scene with incidence angle α_1. Due to the distance measuring radar technique, object P is imaged to point PS in the SAR image. Since the bridge top P is closer to the sensor than P', it comes to a layover effect, i.e., P is imaged closer to the sensor (to point PS) than P'. Hence, the distance between P' and PS is due to layover.

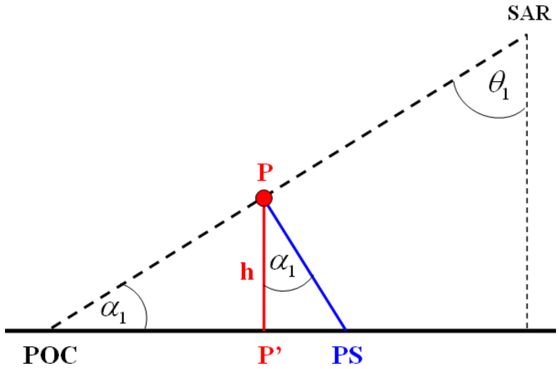


Figure 7: Height estimation of an elevated object from a single SAR image

Elevated Object P not only leads to layover but also to occlusion. It occludes the entire area between P' and POC leading to a shadowing effect. This occluded area between P' and POC corresponds to the shadow of one of the bridge pillars in Figure 6. In case the true bridge position P' is known, a simple Pythagoras formula (3) can be applied in order to obtain an estimate for the height h of the bridge.

$$h = \sqrt{\overline{POC\,P'} \cdot \overline{P'PS}} \tag{3}$$

However, the true bridge position P' may not always be known and the bridge height has to be determined directly from the distance between POC and PS (D). Knowing the depression angle α_1 (= 90° - off nadir angle θ_1) of the SAR sensor, the bridge height can then be obtained with trigonometric formulas (7).

$$\overline{POC\,P'} = h / \tan \alpha_1 \tag{4}$$

$$\overline{P'PS} = h \cdot \tan \alpha_1 \tag{5}$$

$$D = \overline{POC\,P'} + \overline{P'PS} = (h \cdot \tan \alpha_1) + (h / \tan \alpha_1) \tag{6}$$

$$h = D \frac{\tan(\alpha_1)}{\tan^2(\alpha_1) + 1} = D \frac{\sin(2\alpha_1)}{2} \tag{7}$$

3.4 Height estimation from combined SAR/optical data

As it will be shown in this paragraph, estimates for the heights of elevated objects can also be deduced from combined optical and SAR data. Simply, the distance between the displaced bridge in the optical image and the displaced bridge in the SAR image has to be measured.

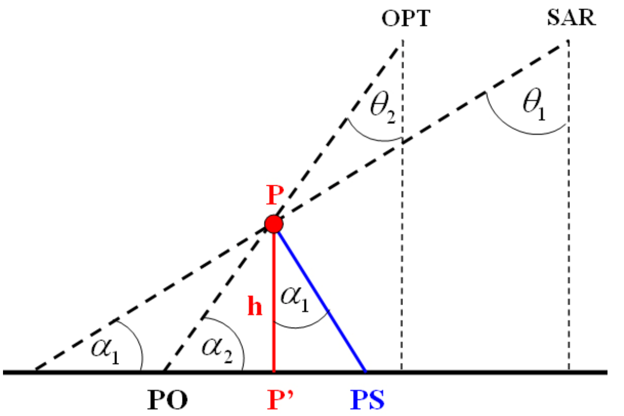


Figure 8: Height estimation of an elevated object by means of combined optical and SAR imagery

In Figure 8 an elevated object P with height h is imaged by both an optical sensor (OPT) and a SAR sensor (SAR). The two sensors acquire the object with two different off nadir angles θ_1 and θ_1. The corresponding depression angles are α_1 and α2. Object P is projected to two different locations in the images due to the different viewing geometries of the sensors. On the one hand, the optical sensor measures angles and hence P is imaged to point PO in the optical image. On the other hand, the SAR sensor measures distances from a side-looking perspective. Therefore, P is projected to point PS in the SAR image (layover). Object P's displacement can be expressed as (8) in the optical image and as (9) in the SAR image (assuming a flat wave front). The measured distance D between the displaced object P in both images is the sum of the two separate displacements in the optical and in the SAR image. Adding the two separate shifts leads to equation (10). Finally, the elevation of object P can be estimated with (11) (Inglada & Giros, 2004).

$$\overline{PO\,P'} = h/\tan\alpha_2 \tag{8}$$

$$\overline{P'PS} = h \cdot \tan\alpha_1 \tag{9}$$

$$D = \overline{PO\,P'} + \overline{P'PS} = (h/\tan\alpha_2) + (h \cdot \tan\alpha_1) \tag{10}$$

$$h = D\frac{\tan(\alpha_2)}{\tan(\alpha_1)\cdot\tan(\alpha_2)+1} \tag{11}$$

These equations have shown that only three parameters have to be known in order to estimate the height of an elevated object from combined optical and SAR imagery: the incidence angle of each sensor and the distance between the displaced object in the optical image and in the SAR image. None-the-less, equation (11) also allows for the estimation of three-dimensional surface models in case no DEM is available. In such a case the images would have to be registered using a local transformation. A disparity map could be drawn and the terrain heights could be deduced from the displayed shifts. Again, for such kind of application a locally flat earth has to be assumed between the projections PO and PS of object P.

4. SUMMARY AND FUTURE PERSPECTIVES

A comparison of bridges over water and bridges over land has shown that the appearance of bridges in SAR imagery strongly depends on their environment. Due to multi-path signal propagation at bridges over water, a height value can be determined directly from a single image. Such multiple bounces do usually not occur at bridges over land. First concepts of this long term project now have shown that a three-dimensional modelling of elevated man-made objects is possible from a single SAR image and from combined optical and SAR data.
In a next step the equations shown in this paper will be used in order to obtain estimates for the railroad bridge near Zellingen (Figure 4, 5, and 6). A field campaign will be done in order to measure precisely the bridge height at each pillar. Hence, estimates obtained from the imagery can be compared to the real heights and thus be evaluated.
So far all displacement measurements are done manually. Further steps of this project will be the integration of automatic feature extraction and object based image registration techniques. The bridges will be modelled on object level.

5. ACKOWLEDGEMENTS

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