ACCURACY ASSESSMENT OF BUILDING HEIGHT ESTIMATION FROM A HIGH RESOLUTION OPTICAL IMAGE COMBINED WITH A SIMULATED SAR IMAGE

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ABSTRACT:

Modern space borne SAR sensors like TerraSAR-X and COSMO-SkyMed are capable of acquiring images with a geometric ground resolution of one meter. Airborne sensors achieve even higher ground resolution. In such very high resolution SAR imagery single objects like houses and bridges become visible. However, effects due to the side-looking slant range acquisition principle of SAR, layover, foreshortening, and shadowing, complicate the interpretability of such data. Hence, one possibility is to combine extracted features from SAR imagery with features from optical images for the purpose of enhancing object recognition and reconstruction. In order to precisely combine features from both data sets within a unique statistical framework, the imaging properties and occurring effects have to be well understood. In this paper, simulations of a dense urban scene are compared to a real TerraSAR-X image.

1. INTRODUCTION

This paper presents first findings of a research project that investigates the analysis of dense urban areas by combining building hints on feature level from high resolution optical and SAR imagery. Three main topics are investigated that will contribute to an iterative building detection and reconstruction approach: building detection, building reconstruction and an accuracy assessment of the extracted features based on real data as well as on simulated data. In this paper, the focus is on the third topic since it is a prerequisite for integrating the detection and reconstruction steps into a unique statistical framework. In order to find out dependencies between SAR sensor parameters and feature detection accuracies in SAR imagery, simulated SAR images are used.

Buildings appear differently in corresponding optical images and SAR images due to the different viewing geometries of the sensors. Buildings in SAR images are usually characterized by bright lines due to multiple signal reflections between building walls and adjacent ground surfaces. However, such lines do not occur if the wall is directed in range direction or if it is occluded by, e.g., trees. Additionally, bright lines may be caused by other effects. Therefore, optical imagery can be exploited in order to extract additional features for supporting building detection hypothesis. A robust building detection approach for high resolution optical images based on an initial segmentation is used in this project (Mueller and Zaum, 2005).

Overlaying a SAR image and an optical image will lead to displacements which can be used for the extraction of height information (Inglada and Giros, 2004) and building reconstruction. Heights of elevated structures can either be estimated from one single SAR image or from the displacement between corresponding features of one SAR image and one optical image (Wegner and Soergel, 2008). In order to correctly overlay both images, the exterior orientation of the sensors has

to be known. Moreover, a Digital Terrain Model (DTM) is necessary in order to project extracted features from the optical and the SAR image to ground geometry.

Basically, the accuracy of the recognition and reconstruction procedure depends on the sensor parameters, particularly the off-nadir angle of the SAR sensor. For instance, an increasing off-nadir angle will lead to a bigger shadow region and to a decreasing layover effect. Thus, it is of interest to analyze the influence of different off-nadir angles on the height estimation accuracy of elevated structures.

The artificial SAR images in this presentation are provided by a simulator based on ray tracing techniques (Auer et al., 2008) which has been designed to deliver results with high geometric accuracy. Simulated SAR images have the advantage that various combinations of acquisition parameters can be investigated systematically. In addition, images can be simulated for individual buildings without any interference by e.g. vegetation. In this paper simulations accomplished with the previously introduced simulator are compared to a real TerraSAR-X image in the case of a dense urban scene in the city of Hannover, Germany. The "Schneiderberg" area contains several multi-story buildings with flat roofs and with gable roofs. In front of the buildings, with respect to the sensors perspective, no elevated vegetation occludes the building facades. One investigated street only has buildings on one side and, hence, the SAR sensor's view to the buildings is nearly unobstructed. Typical effects for SAR acquisitions like layover can be very well investigated under such conditions. A second street has buildings on both sides offering the possibility to investigate the interference of backscattered signals from multiple adjacent objects.

In the following section, the typical appearance of buildings in SAR imagery is explained. To this end, a TerraSAR-X mean amplitude map of a dense area in the centre of Berlin, Germany,

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is shown with focus on layover and shadow effects. Thereafter, a three-dimensionally modelled area in the city of Hannover is presented. A simulation using the "Schneiderberg" CAD-model is carried out with the TerraSAR-X parameters of a real acquisition of the same scene. The simulated images are then compared to the real TerraSAR-X image.

2. BUILDINGS IN HIGH RESOLUTION SAR IMAGES

Figure 1 shows a bird's eye view of the area surrounding the Alexanderplatz in Berlin, Germany, extracted from Google Earth. Several high buildings, marked with letters A to D, are surrounded by open areas of flat terrain composed of broad streets and plazas. Only a few small vegetation areas are present in the region of interest. Figure 2 shows the corresponding mean map created by averaging 21 high resolution spotlight TerraSAR-X images captured in VV polarization using an incidence angle of 47 degrees. It has to be considered that the image is in slant range geometry. Since random scattering and speckle effects are reduced due to the averaging process, reflection effects occurring at man-made objects are likely to be deterministic.

The difference between optical images and SAR images becomes evident comparing Figure 1 and Figure 2. Optical sensors basically measure directions and angles while the SAR sensor consists of measuring distances between ground objects and the sensor itself. Optical images contain spectral information of the imaged objects while SAR images do not due to their signal in the microwave domain. The angular resolution of the SAR sensor in elevation direction is rather poor. Hence, objects with different heights but the same distance to the sensor cannot be distinguished in the image. The combined analysis of features extracted from optical and SAR imagery may thus greatly improve the overall scene interpretation process. An optical image may also help to distinguish between different types of scattering contributions in SAR data. In the TerraSAR-X image in Figure 2 various effects can be recognised:

- Direct backscattering at rough surfaces at building facades as well as on the ground
- Double bounce phenomena occurring as linear features caused by the interaction between building walls and the surrounding ground, e.g. visible at buildings A, B, C and D
- Triple bounce phenomena visible as focused points which mainly appear at building façades facing the SAR sensor, e.g. visible at buildings B, C and D

Nonetheless, while dominant features can be well observed and explained, detailed interpretation is still complicated due to layover effects in range direction. Multiple backscatter signals of various adjacent buildings interfere and contribute information to the same pixels in the image thus complicating interpretation. Additionally, small objects are at least partly occluded by shadows from high buildings as well as by layover. For example, the façade of building B falls onto the neighbouring street. As a consequence, backscatter signal from cars cannot be distinguished from the façade's contribution to the final signal.

Moreover, distinguishing between double bounce lines and rows of corner reflectors is complicated despite the image resolution of below one meter in spotlight mode. However, such double bounce lines are of special interest for building recognition and reconstruction (e.g. Thiele et al., 2007; Xu and Jin, 2007) since they are strong building hints.

Characteristics of double reflection lines with respect to different aspect angles shall be shown by simulated reflectivity maps derived by illuminating a simplified model of a gable roof building as shown in Figure 3. The reflectivity maps are generated using a simulation tool based on ray tracing algorithms (Auer et al., 2008) which enables to assign different reflection levels, e.g. single, double or triple bounce, to separate image layers.

Figure 1: Bird's eye view of Alexanderplatz, Berlin; © Google Earth; tall buildings marked by letters A - D
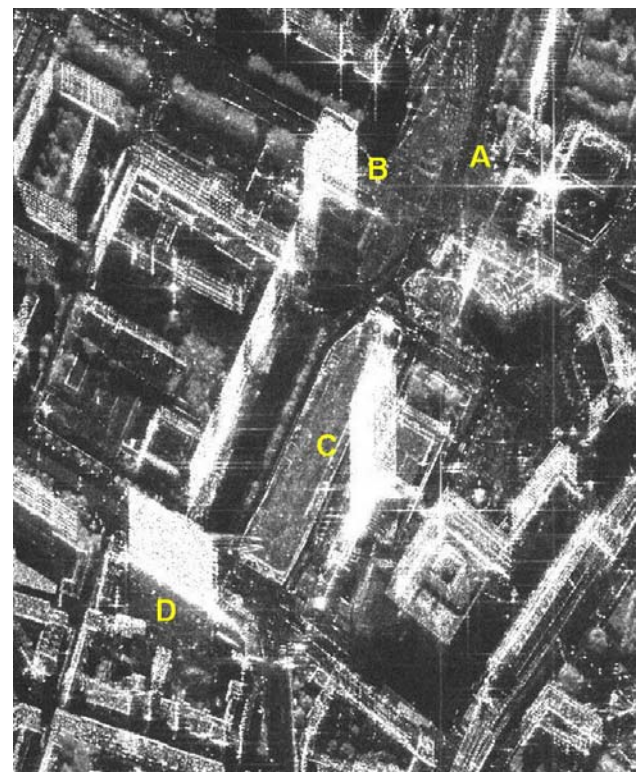

Figure 2: Mean map of 21 spotlight TerraSAR-X images captured in VV-polarization showing Alexanderplatz, Berlin; angle of incidence: 47°; azimuth from left to right; range: top-down

At first, the building ridge is oriented perpendicularly to the sensor's flight direction. Analysing the corresponding reflectivity map top-down in range direction, single bounce contributions of roof parts and walls are contained in a layover interval followed by a double bounce line which is located at the edge between the building wall facing the sensor and the surrounding ground (see left part of Figure 4) ahead of the double bounce line.
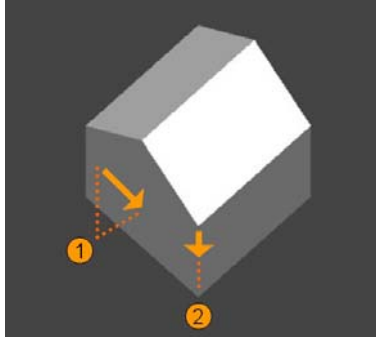

Figure 3: Building model with gable roof; strong diffuse backscattering behaviour assigned to roof surfaces; case 1 + 2: aspect angles used for simulation shown in Figure 4
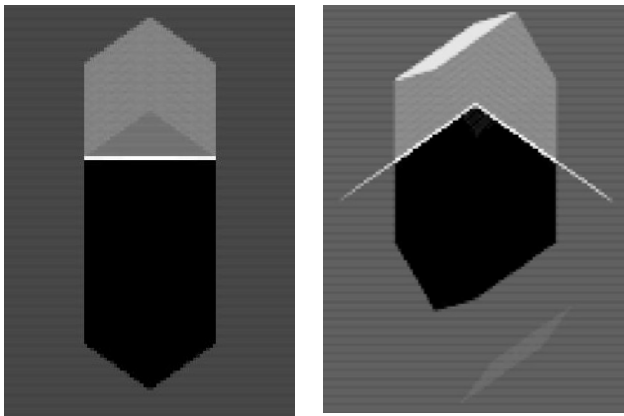

Figure 4: Resulting reflectivity maps for aspect angles of 0° (case 1; left) and 45° (case 2; right), respectively; angle of incidence: 45°; range: top-down

In the case of the ridge being rotated by 45 degrees with respect to the sensor's flight direction, diffuse single bounce backscattering is dominant for one roof part since its surface is hit steeper by incoming signals compared to the other roof part. Furthermore, two double bounce lines are visible (see right part of Figure 4) which also are located at the intersection lines between building walls and the plane beneath the building. These double bounce lines originate from radar signals following the path "sensor - building wall – ground in the background of the building – sensor" or vice versa.

At both ends of the building, double bounce tails are obtained due to the assumption that the range history of double bounce effects of this kind depends on the height at which the building is hit by the signal during the double bounce process. Considering a building rotated by 45° as shown in Figure 3, signals specularly reflected at higher wall parts will hit the building's background farther away in both directions azimuth and range. Hence, the first and last contact along the processed synthetic aperture is likely to be different resulting in different zero Doppler coordinates in azimuth. Surfaces approximately oriented in direction of the sensor's flight path will cause short

double bounce tails while surfaces almost facing away will be characterized by long double bounce lines in the SAR image. Besides the aspect angle, the length of the double bounce lines also depends on the incidence angle used for capturing the SAR image and on the building height.

However, limitations to the approximation of this kind of double bounce effect have to be discussed. Generally, besides assumptions necessary for the simulation concept, estimation of the first and last contact along the synthetic aperture is not straightforward for urban scenes since most buildings are not only surrounded by rough terrain but also by other buildings or vegetation avoiding undisturbed interaction between building walls and nearby streets, open grass areas or plazas. The higher the wall area is hit by a signal the bigger is the size of the required area in the building's background which has to be free from disturbing objects. Thus, the length of double bounce tails depends on the height of the building effectively contributing to double bounce effects. Moreover, at least one surface participating at the double bounce process has to show a diffuse backscattering behaviour for receiving signal parts at the SAR sensor. As the simulation might tend to overestimate the length of double bounce tails, results extracted from reflectivity maps only should be considered as a hint where additional double bounce signals might appear in addition to double bounce lines located at the bottom of building walls.

In Sections 3 and 4 simulated reflectivity maps will be compared to real SAR data in the case of an urban scene.

Figure 5: Optical image showing area "Schneiderberg", Hannover, Germany; © Google Earth

Figure 6: Facades and roof structures of buildings facing the open grass area as visible in Figure 5; the photo was taken from the street "Schneiderberg" running from the lower right to the upper left in Figure 5

3. MODELING OF URBAN SCENE

For comparison purposes, an urban scene located in Hannover, Germany, has been selected including rows of gable roof houses, flat roof buildings and backyards (Figures 5 and 6) covered with vegetation or pavement. The focus is on buildings standing in the street "Schneiderberg" which is running from the lower right to the upper left corner in Figure 5. Figure 6 shows the facades of such buildings. The red building in Figure 6 is located at the junction in the centre of the left part of Figure 5. All facades are facing the open grass area and hence are unobstructed with respect to the signal from the TerraSAR-X satellite.

Figure 7 shows the 3D model of the "Schneiderberg" scene. It was extracted from LIDAR data and is used for the subsequent simulation process. At the present time, features like windows or balconies are not included in the 3D model but walls are approximated by flat surfaces. Since the area does not experience any significant height variations, the ground beneath the buildings is approximated by a flat plane. Vegetation objects like trees or bushes are neglected. Many details of the building facades and the roofs are not modelled in the current 3D model as it may be seen comparing the real building facades in Figure 6 with the building model shown in Figure 7. Details with a size in the order of the signal wavelength of the SAR sensor contribute backscatter signal to the final SAR image and thus are usually not negligible. However, the SAR image resolution of one meter allows the use of a 3D model without such details at the present stage of this project since all main structures are included. In order to model the scene "Schneiderberg" more precisely including details in the order of the signal's wavelength, the entire scene is currently acquired and modelled using close range photogrammetry.

For visualising the point of view of the artificial SAR sensor used for simulating reflectivity maps of the scene (Figure 8), the image shown in Figure 7 is captured using the same imaging geometry as for the subsequent simulation. Moreover, a virtual light source has been introduced at the position of the camera for detecting building surfaces oriented in direction to the sensor. Hence, direct backscattering effects are visible in the centre of the urban scene at roof surfaces facing the camera's line of sight. In the case of a SAR image captured from the same position in space, strong single reflection effects are expected at these surfaces. Moreover, strong double bounce effects are likely to appear at these buildings due to wall surfaces and the ground in front of the buildings forming dihedrals oriented towards the sensor.
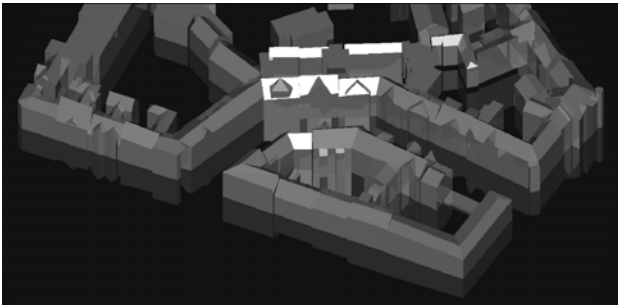

Figure 7: 3D model of area "Schneiderberg"; point of view corresponds to line of sight of artificial SAR sensor used for the simulation shown in Section 4; bright areas: direct backscattering from roof surfaces oriented in direction to the sensor

Weak diffuse scattering and strong specular scattering characteristics are chosen for ground surfaces, while moderate diffuse and high specular scattering characteristics are assigned to building surfaces in order to emphasize multiple reflection effects which are analyzed in the following Section.

4. REAL DATA VS. SIMULATION

The previously introduced 3D CAD-model of the "Schneiderberg" area was used as input to the simulator. All parameters were set corresponding to the parameters of the TerraSAR-X acquisition shown in Figure 9. The incidence angle was set to 44.789°, the aspect angle to 7.4° (with respect to the north direction), and the pixel size to 0.5 m x 0.5 m.

Three different images in slant range geometry were calculated: an image containing all backscattered signals (Figure 8 top), one image showing only single bounce contributions (Figure 8 centre), and one image displaying double bounce contributions (Figure 8 bottom).
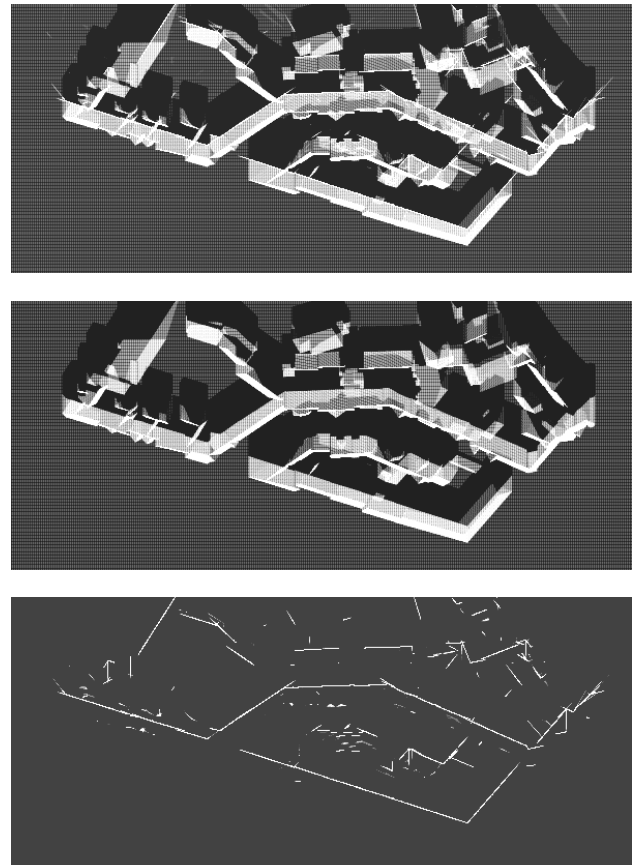

Figure 8: Simulated SAR images of the 3D model scene of area "Schneiderberg" (range direction from bottom to top); top: all backscatter contributions; centre: single bounce backscatter; bottom: double bounce backscatter

The double bounce lines (Figure 8 bottom) are of particular interest since they are characteristic features used for building recognition and building reconstruction. Such bright lines are also visible in the TerraSAR-X image (Figure 9). Range direction is from bottom to top and azimuth direction from right to left. Some lines seem to be blurred and are visible less clearly than in the simulated image. This effect is partly due to

the TerraSAR-X data processing including filtering with a Hamming window which was not done during the simulation procedure. Moreover; the simulation concept tends to overemphasize focusing of double bounce effects occurring due to diffuse backscattering from surfaces. In a real world case, backscatter signals from vegetation and other objects interfere with the backscatter signal from the buildings. For example, cars are parked in front of the buildings in the "Schneiderberg" street as it may be seen in Figure 6. Such objects are not included in the 3D CAD-model and hence the double bounce lines appear more clearly in the simulated image.

Figure 9: TerraSAR-X image in ground range geometry of the "Schneiderberg" area (range direction from bottom to top)

In the single bounce image (Figure 8 centre) an effect typical for gable roofs becomes visible which may also be detected in the TerraSAR-X image. Since the side of the gable roof facing the SAR sensor and the incoming signal enclose an angle of nearly 90°, i.e., all points on the roof have approximately the same distance to the sensor. This effect can nicely be seen at the building roof appearing very bright in the 3D-model in the centre of Figure 7. Its inclination is approximately the same as the viewing angle of the SAR sensor and thus the signal is almost mirrored back to the sensor. As a consequence, the roof appears very bright in the SAR image as it can be seen in the centre of the TerraSAR-X image.

Moreover, the entire roof side is mapped to one single line in the SAR image due to approximately the same distance of all roof parts to the sensor. It appears particularly bright because all signals from the roof plane fall onto a narrow line. Furthermore, such line falls towards the sensor (layover) since the distance between roof and sensor is shorter than such between the double bounce line and the sensor. Hence, two parallel bright lines, one due to single backscattering from the roof and one due to double bounce scattering focused at the intersection line where the building wall meets the ground, can be observed in the lower part of the TerraSAR-X image shown in Figure 9. The lower line originates from the roofs of the buildings shown in Figure 6. Double bounce scattering occurs where the building walls meet the ground. Knowing the width of the building and the approximate inclination of the roof plane, the height of a building can be determined by measuring the distance between such two parallel bright lines in the slant range image (Thiele et al., 2007a).

However, as previously described, two parallel bright lines may be not visible in dense urban areas due to obstruction and interfering signals from adjacent objects. In order to achieve reliable recognition and reconstruction results, such lines should be analysed in combination with features from optical images.

Figure 10: DEM of the "Schneiderberg" area overlaid with the corresponding vector model with height values from 0 to 23.8 meters (rescaled for visualization)

5. SUMMARY & OUTLOOK

A 3D CAD-model of a dense urban area with different kinds of buildings was generated and used as input to SAR image simulation. Various kinds of effects like double bounce lines and direct reflection from gable roofs, useful for urban scene interpretation, were explained based on simulated imagery and a real TerraSAR-X image.

The simulation proved to be very helpful for the investigation of such effects. However, it has to be considered that simulation only approximates the real SAR case. Both, geometrical distribution as well as image radiometry may be under- or overestimated. The 3D model used for the simulation presented in this paper will be improved in the future in order to enable more detailed simulations. Many effects that can be observed in real SAR images occur due to backscattering at small structures in the order of the signal wavelength. For example, gable roofs are covered with roofing tiles leading to additional single bounce backscattering at the edge of the roofing tiles. In addition, such tiles are typically less inclined than the roof in order to rest attached to the roof. Since the SAR signal is backscattered from the roofing tiles, a slightly smaller roof inclination has to be assumed for further studies. Superstructures of the roofs as well as balconies have not been included so far but these details are currently added to the 3D model using close range photogrammetry.

Future work will comprise a detailed analysis of the statistical properties of extracted line features. Double bounce lines will have to be further investigated in order to exploit them for building recognition and reconstruction purposes. Statistical measures based on extracted double bounce lines will be introduced in a statistical framework as a basis for recognition and reconstruction. In Figure 10 a DEM derived from the 3D model of the "Schneiderberg" overlaid with a vector model is shown. In the future, the vector model will be projected to slant range geometry using the DEM. For instance, this will allow for the comparison of the position of the double bounce lines in the azimuth-range plane with the position of the intersection line where building walls meet the ground.

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