

# SAR-BASED 3D-RECONSTRUCTION OF COMPLEX URBAN ENVIRONMENTS

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## ABSTRACT:

Within the paper the applicability of SAR imagery for 3D reconstruction of urban areas will be discussed. Since data collection for this purpose is usually based on stereo imagery or dense point clouds from airborne laser scanning, in the first part of the paper the main properties SAR systems will be compared to this standard airborne data collection. In this respect, advantages of SAR image collection like range and weather independence contrast with the usually lower quality of geometric and radiometric data due to the side-looking capability of this systems. This lower quality even increases the problems of automatic 3D data collection in urban areas compared to the evaluation of aerial images or LIDAR data. For this reason, our approach aims on the application of SAR imagery for change detection and semi-automatic building reconstruction. In order to fulfil this task, a user interface to generate 3D vector models is combined with a SAR simulator. By these means, simulated SAR imagery can be generated based on existing 3D city models and compared to real images for change detection. By interactive manipulation of the 3D object shapes, which are used as input data for the simulator, operators can be trained for the interpretation of SAR images. Additionally, this tool can be applied for semi-automatic building reconstruction.

## 1. INTRODUCTION

The development of algorithms allowing for an efficient collection of 3D urban data bases has become a task of increasing importance. Three-dimensional representations of urban environments by 3D city models are frequently applied for planning and simulation purposes. Additionally, these models provide the data base for visualisations in the context of virtual reality environments. This extensive and still increasing variety of applications results in very different requirements on data quality with respect to resolution, accuracy, and amount of detail for the 3D city models to be collected.

Of course these different requirements also have an influence on the particular approach to be selected for data collection. Whereas for example fully automatic data collection is most efficient, these approaches are only feasible for the reconstruction of relatively simple buildings. If, on the other hand, complex and detailed urban models have to be captured, up to now support by a human operator is necessary. For this reason, most existing tools for 3D building reconstruction are based on semi-automatic procedures.

Within almost all approaches, the 3D structure of built-up areas is either collected indirectly from stereo imagery, or provided by the evaluation of a Digital Elevation Model (DEM), which is usually measured by a LIDAR sensor. In addition to these data sources, the ongoing improvement of SAR sensors results in an increasing interest of applying this type of imagery for urban data collection. SAR systems are side-looking systems, which illuminate the area to be covered with radar waves. Since the trajectory of the sensor platform is measured precisely, the backscattered signals can be combined by exploitation of the Doppler-effect. This approach allows for the calculation of a so-called synthetic antenna, which is much larger than the real antenna. For this reason, the ground-

resolution of a SAR system is in principle independent from the distance to the object surface.

One possibility to exploit SAR imagery for the collection 3D city models is to generate a DEM from interferometric SAR. By these means, approaches originally developed for building reconstruction based on the evaluation of DEM from LIDAR measurement can be adapted (Soergel, 2001 and Gamba & Houshmand, 2000). Still, data processing has to take into account, that there are significant differences between DEM from LIDAR and InSAR, since both systems differ with respect to accuracy, performance and sensor geometry.

LIDAR systems usually collect data from nadir views by runtime measurement of reflected laser pulse. In contrast to that, InSAR is based on the evaluation of phase differences between SAR images captured from different positions. DEM data collection with LIDAR systems results in vertical accuracies of approximately 15cm (RMSE), whereas airborne InSAR provides only accuracies of 1m (Mercer, 2001). This results from the higher sensitivity to noise and the side-looking imaging geometry of SAR systems. On the other hand, the independence of the resolution to the distance from the object as well as the large swath width of modern airborne SAR sensors allows for a very fast and efficient data collection. This is especially advantageous, if large areas have to be covered in short time. As an example the DOSAR system has a range gate of up to 16k, which results in a swath width up to 20km depending on mode and flight parameters (Hoffmann & Fischer, 2002).

SAR data collection additionally benefits from the systems' ability to "look" through clouds, since microwaves can penetrate the atmosphere under almost all conditions. Thus, except from extreme rainfall, which especially can hamper spaceborne systems, the collection of SAR imagery is feasible for almost all weather conditions. Finally, the side-looking property and the range independence can be beneficial for some scenarios,

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since it allows a very flexible mission planning. Within the paper airborne data collection will be discussed. In addition to that, the future availability of high-resolution spaceborne systems like TerraSAR with a ground resolution up to 1m will further increase the interest in the application of SAR imagery. The limited quality of height data from InSAR data can result in considerable problems of DEM-based building reconstruction especially in complex urban areas. Potential and limitations of InSAR for building reconstruction is for example discussed by Stilla et al (2003). As an alternative, SAR imagery can be applied for 3D object reconstruction, if the system is supported by a human operator. In that case, similar to manual or semi-automatic approaches based on airborne imagery, interfaces have to be provided. By these means, the human capability in image interpretation can be exploited efficiently. Humans can easily perceive the three-dimensional structure of objects like buildings from aerial images since they are very well trained in the interpretation of optical imagery. In contrast to that, the different geometry of SAR sensors can result in an unusual visual impression especially for complex three-dimensional structures. For this reason, additional training is required in order to qualify a human operator for the reconstruction of objects like buildings from SAR imagery. For this purpose, a system for simulation of SAR imagery based on existing 3D models can be used.

SAR imagery in urban areas can, for example, be simulated based on DEM from LIDAR measurement (Soergel et al, 2002). In contrast to this, we use 3D vector data for this purpose. This allows the operator to easily manipulate the shape of the respective objects. Thus, the influence of different shapes to the appearance of 3D object structures in SAR images can be studied.

In the first part of the paper, the geometric properties of SAR data collection in complex three-dimensional scenes is briefly discussed and results of SAR simulation based on existing 3D city models are compared to real data. This comparison of simulated data to real imagery can also be used for change detection from SAR images in urban environments. A SAR simulator not only allows experiments with defined and known objects, it is also a key tool for the evaluation of SAR imagery. Within the final part of the paper this will be exemplarily demonstrated by applying the simulator for semi-automatic building reconstruction based on real SAR imagery.

## 2. SAR PRINCIPLE

Since SAR systems are run-time systems, the position of a pixel in the captured image depends on the distance between the sensor to the imaged object. The brightness of the pixel is determined by the backscattered energy. Thus, this SAR image intensity depends on the roughness and the dielectric constant of the depicted material. Additionally, the shape of the depicted object has a major influence to the brightness. Thus, especially if an object consist of similar material, its appearance in an SAR image mainly depends on its shape as well as the sensor and platform parameters.

As already discussed, we are aiming on an operator assisted data collection, which is based on the evaluation of a single SAR intensity image. For simple objects consisting of the same material and by additionally assuming plain or known ground height, the three-dimensional object shape can be calculated based on the depicted shadow and the layover areas.

The easiest example for determine the form of an object from a single SAR image is a wall.

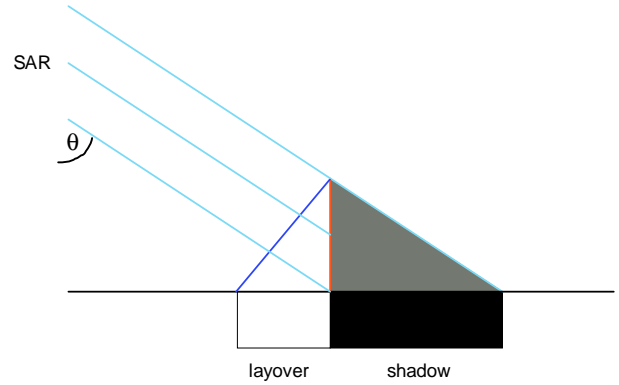


Figure 1: Layover and shadow of a wall

As depicted in Figure 1, the height of the wall can be calculated from the length of it's shadow by

$$height_{object} = \frac{length_{shadow}}{\tan(\theta_{off-nadir})} \quad (1)$$

To achieve more stable results, additionally the length of the layover should additionally be applied. Resulting to

$$height_{object} = length_{layover} \cdot \tan(\theta_{off-nadir}) \quad (2)$$

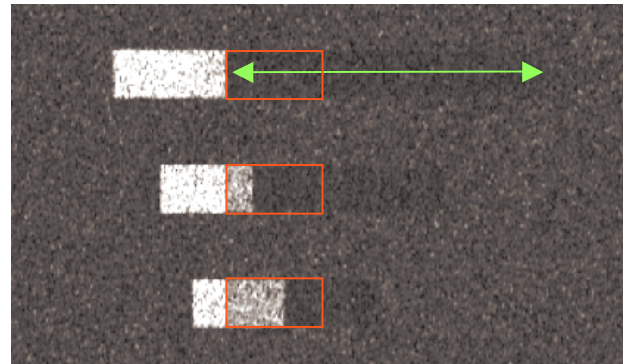


Figure 2: Simulated flat buildings with different heights (EADS Dornier GmbH)

Figure 2 demonstrates, that the situation is already getting more complex for flat buildings. In Figure 2 three flat buildings are simulated using the SARView Light SAR simulator (basis version) of the EADS Dornier GmbH. For the simulation lambertian reflection was assumed, with a SAR sensor position left to the objects. The buildings have the same length and width and their footprints, marked in red, reside on the same x-position. The buildings only differ in their height. In the resulting image the positions of the buildings move toward the sensor depending on the height of the object. The green arrow in Figure 2 shows the displacement of the highest building. Because of this displacement the height of the object cannot be calculated using (1) or (2).

To calculate the height of the flat buildings the SAR imaging parameters, the terrain height around the object, the length of the shadow and the object width and length have to be used. Knowing these parameters also the displacement caused by SAR properties can be calculated and thus the height of the object.

can be easily interpreted by a human operator and should of course be used for reconstruction, if available.

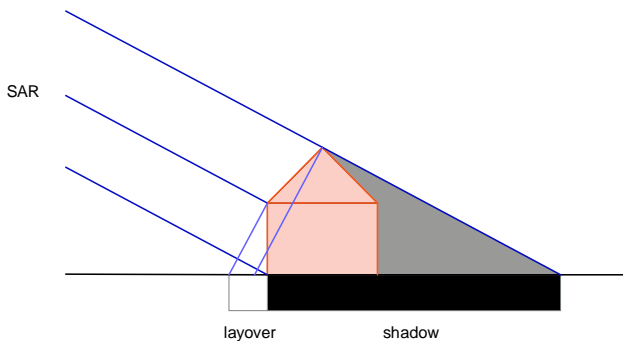


Figure 3: Layover and shadow of a building

In Figure 3 the object displacement is depicted once again schematically. In this case, due to the gable-roof form, the building will appear smaller in the resulting image, because in the resulting image only the layover part will be interpreted as building. This part is displaced comparable to the displacement seen in Figure 2.

Trying to calculate the height assuming a cube will lead to erroneous results. Fortunately, such an error can be detected using the shadow length and the layover length for the calculation. By these means the depicted building can be distinguished from a cube or a wall.

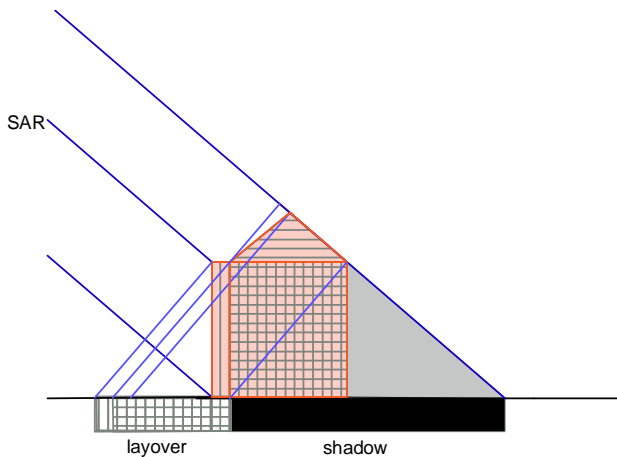


Figure 4: Different types of simple house forms show different layovers and shadows

In Figure 4 two buildings are shown, a flat-roofed building and a gable-roofed. The gable-roof building is striped horizontally and the flat-roofed building is striped vertically. Both buildings have the same shadow length, although they do not have the same height. To discriminate between both forms, the length of the layover has to be used. Combining both information, layover- and shadow length, the shape of simple buildings can be reconstructed. Figure 4 also shows that the layovers do not differ too much in their length, therefore it is possible but difficult to discriminate between the two different shapes. This can become even more difficult for real images.

As it is demonstrated in Figure 5, depending on the orientation of the building it is also possible to deduce the 3D shape of a building from the 2D shape of its shadow. Such information

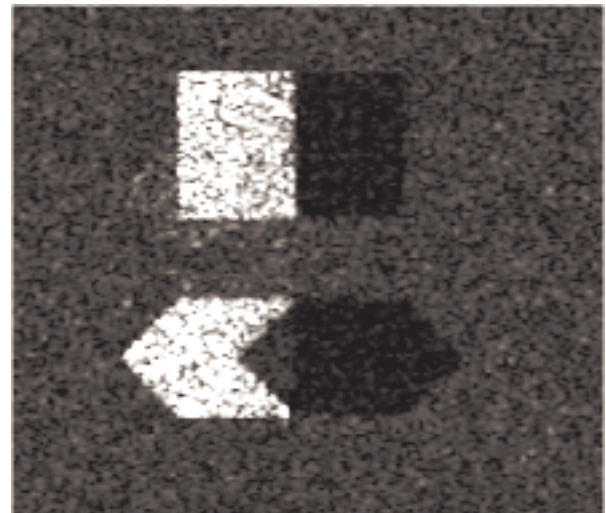


Figure 5: Simulated SAR image of two buildings (EADS Dornier GmbH)

### 3. SAR-SIMULATION IN URBAN AREAS

The simulated SAR images in Figure 2 and Figure 5 were generated using the SARView Light SAR simulator (basis version) of the EADS Dornier GmbH. Due to the complexity of the SAR imaging process, the application of a simulator is a key tool for the evaluation of this type of data (Leberl & Bolter, 2001). Since a simulator allows a lot of experiments with defined and known objects, it is important for learning and training purposes. Additionally, simulators are frequently used as a test tool during software development. In principle, simulated SAR imagery can also be applied for change detection and semi-automatic object reconstruction.



Figure 6: City model from Karlsruhe. Reconstructed using LIDAR data.

Figure 6 depicts a section of an existing 3D city model of Karlsruhe. In this example, the available data is restricted to three-dimensional representations of the buildings, no trees,

streets or other objects are contained in the model. Figure 7 shows the simulated SAR image, which is generated based on this model. This simulated image can be compared to a real SAR image of the same area. For this reason Figure 8 shows an image captured by the DOSAR system from the EADS Dornier GmbH.



Figure 7: Simulated SAR image based on given 3D city model

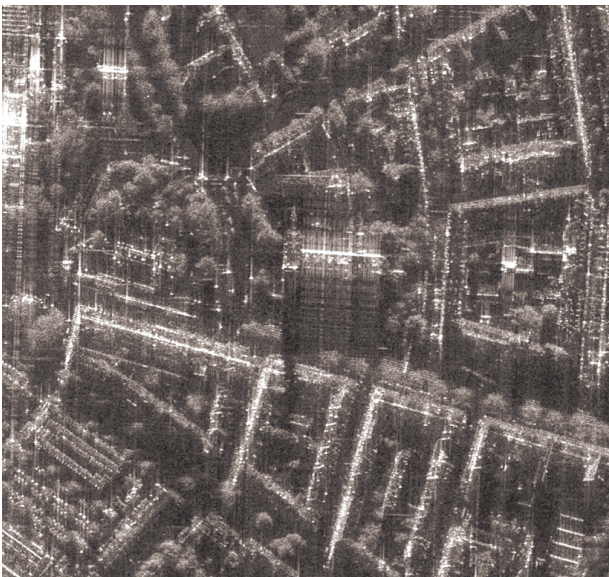


Figure 8: DOSAR image of simulated area (EADS Dornier GmbH)

For simulation of Figure 7 identical material and lambertian reflection was assumed, additionally only building objects were considered. Despite these limitations, the resulting simulated image is very useful during a operator based interpretation of the real SAR image. In principle, a comparison between both images can be applied for change detection purposes. Still, even by comparing the visible impression of Figure 7 and Figure 8 it becomes obvious that automatic change detection without high error rates is almost impossible from this type of data. Despite the difficulties from the SAR properties, like for example speckling and extreme reflections, the incompleteness of the city model used for simulation is a huge problem.

Due to ambiguities, uncertainties and occlusions within the SAR image, unique interpretations might not be feasible. For this reason automatic building reconstruction in dense inner city areas from a single SAR image is almost impossible. Still, the geometric properties of SAR images as described above can be used for a semi-automatic approach.

#### 4. SEMI-AUTOMATIC RECONSTRUCTION

For this purpose, the available simulator is integrated to an iterative process. In the first step the human operator makes a first guess on the size and shape of the depicted building objects. This first assumption is based on the appearance of the object in the SAR image and on the experience of the interpreter. A graphical user interface allows for the selection of simple building primitives and an interactive manipulation of their parameters.

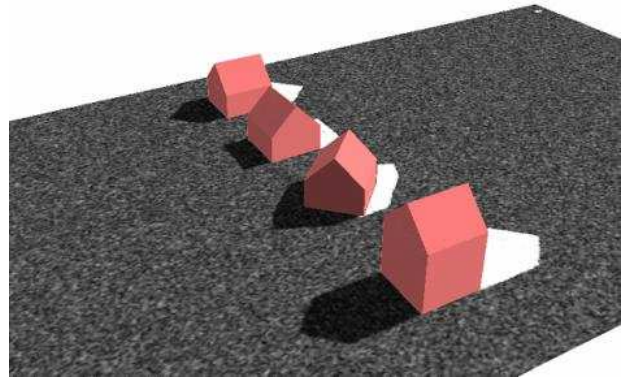


Figure 9: Three-dimensional visualisation of simple building models and simulated SAR imagery

Figure 9 shows an example of a 3D visualisation of the generated building objects, which are presented to the operator. Based on these models, a SAR image is simulated. For this purpose, a SAR sensor configuration has to be additionally selected. As demonstrated in Figure 9, the resulting image can then be presented in combination with the building objects. While the shape parameters are changed by the operator interactively, both the 3D presentation of the buildings and the simulated SAR image are readapted. Additionally, as depicted in Figure 10, the simulated image can be replaced by a real image.

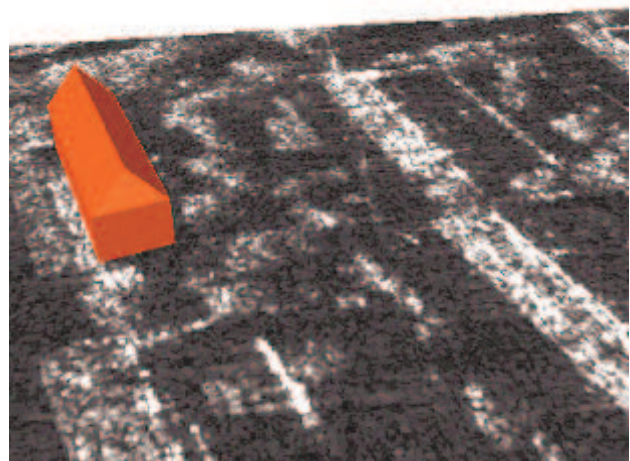


Figure 10: Reconstructed building overlaid to real image

This direct link between the model, the simulated SAR image and the real SAR data is very important for the operator. Having this close relation the system is also ideal for training purposes. By changing parameters the operator can directly learn from the resulting effects in the simulated SAR image. Additionally, the comparison between simulated data and real image is used within the semi-automatic reconstruction approach. For this purpose, the GUI is applied to refine the shape parameters of the initial building object. This refinement followed by a comparison between simulated and real image then is repeated till the best fit between simulated data and real image is achieved.

Of course, this approach is not restricted to building objects. Using an object database the operator has a large variety of objects to choose from. Even with all the above mentioned limitations the experienced operator can explain a lot of the effects seen in a SAR image by using the simulator and comparing the simulated results with the real image.

## 5. CONCLUSION

Due to features like the day/night operation capability, the all-weather usability and the stand-off capability SAR imagery is becoming a data source of increasing interest. For a number of applications like monitoring or damage assessment during catastrophe management these advantages are very important, especially compared to the limitation while collecting a LIDAR DEM or stereo imagery. Additionally, the range independence of SAR sensors allows high resolutions also for spaceborne platforms.

However, one problem while using SAR is the difficult interpretation of this type of data. One reason is the side-looking property of a SAR system, additionally, speckling effect and the large wavelength result in further problems during visual interpretation. These problems not only hamper the visual interpretation, they also result in difficulties for processes like automatic classification compared to optical images.

As discussed within the paper the availability of a SAR simulator is very important in order to enable the reconstruction of buildings from single intensity SAR images. The combination of 3D models, simulator and real images allows a huge improvement in the interpretation of SAR images and enables semi-automatic reconstruction approaches. The quality of the building reconstruction can be further improved using additional data. As an example, by using SAR images from different locations and angles, a lot of occlusions and ambiguities can be solved. By these means even automatic processes become feasible. To improve the reconstruction process, the application of InSAR data may be very useful and should be considered. In this way a DEM can be generated and used for 3D object reconstruction.

Another possibility is using a full-polarimetric SAR system. Using such a system a new range of information about the object is available. The polarimetric response can be used to discriminate between odd-bounce and even-bounce reflections by target decomposition (Cloude & Pottier, 1996). This differentiation is very useful for furthermore refining the reconstruction of buildings. Double-bounces occur often in built-up areas and are quite typical for those regions. Looking at a single house, the double bounce area is related to vertical walls and therefore this information can be used to discern between vertical walls and horizontal roofs which may look very similar using just one polarisation.

Having a look-angle larger than 30° and a small terrain-roughness surrounding the building the returned radar signal is

very sensitive to the orientation of the building (Franceschetti et al, 2002). This information can then again be used as additional information for building reconstruction, if fully-polarized SAR data is available. Polarimetric SAR data also provides information about the slope and the surface roughness (Schuler et al, 2002) which may also be useful.

So, despite all limitations of SAR data for 3D object reconstruction, in our opinion there is a huge potential of applying this data source for this type of application.

## 6. ACKNOWLEDGEMENTS

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