OPPORTUNITIES OF URBAN ANALYSIS FROM HIGH-RESOLUTION SAR DATA

U. Soergel[a], E. Michaelsen[a], U. Thoennessen[a], U. Stilla[b]

[a]FGAN-FOM Research Institute for Optronics and Pattern Recognition, Gutleuthausstraße 1, 76275 Ettlingen, Germany
[b]Photogrammetry and Remote Sensing, Technische Universitaet Muenchen, 80290 Muenchen, Germany
soe@fom.fgan.de

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ABSTRACT:

State-of-the-art airborne SAR sensors provide spatial resolution on the order of a decimetre. In such data, many features of urban objects can be identified, which were beyond the scope of radar remote sensing before. In this paper, the impact of high-resolution SAR data on the analysis of urban scenes is discussed. An example for the new quality of the appearance of buildings in such data is given and interpreted. The fine level of detail opens the opportunity to reconstruct the structure of man-made objects (e.g. buildings). First results of segmentations of salient roof and facade structures, which become visible in such kind of data, are presented. The topics geocoding and data fusion using different kinds of reference GIS data are addressed. In order to limit the computational load, a combined multi-scale SAR image processing and analysis is advantageous.

1. INTRODUCTION

In general, topographic mapping of urban areas is based on sensor data acquired from airborne platforms in nadir view under good weather conditions, e.g. aerial imagery and LIDAR. An alternative part of the frequency spectrum of steadily growing importance in remote sensing is the radar domain. Synthetic aperture radar (SAR) sensors provide a two-dimensional mapping of the scene. However, the SAR principle requires an oblique and side-looking viewing direction [Schreier, 1993]. Consequently, occlusions and multi-bounce signal propagation occur frequently in urban areas [Dong et al., 1997]. Additionally, layover inevitably takes place at building locations. On the other hand, SAR has some very significant advantages compared to complementary sensors like aerial photography: because of the active scene illumination, SAR is independent of the daytime and the large signal wavelength provides almost insensitivity to weather conditions. These features suggest utilizing SAR for event-driven mapping tasks [Soergel et al., 2003a], which may be requested for traffic monitoring [Stilla et al., 2004], disaster management [Kakumoto et al., 1997], and damage assessment [Shinozuka et al., 2000] in case of a flooding or an earthquake [Takeuchi et al., 2000].

Commercial airborne SAR sensors typically provide data of spatial resolution on the order of a meter and currently developed space-borne systems will achieve similar values [Roth, 2003]. First results of experimental airborne SAR systems have shown that objects of size even below a decimetre can be resolved [Brenner and Ender, 2002]. In such data many features of urban objects can be identified, which were beyond the scope of radar remote sensing before. This seems to offer the opportunity to overcome some limitations of building recognition from SAR data in dense urban areas [Gamba et al, 2000; Soergel et al., 2003b].

In this paper, the impact of high-resolution SAR data on the analysis of urban scenes is described in the context of a retrieval of geometric features of objects. Examples for the new quality of the appearance of buildings in data of decimetre resolution are given and interpreted in Chapter 2.

Reflections of roof structures like eaves and ridges or facade structures like single windows appear for the first time well contrasted in the SAR imagery. In Chapter 3 segmentations of different kinds of building features like the roof edges and a grouping of regular point structures are demonstrated, in order to point out the potential of the reconstruction of man-made structures by SAR.

The topics geocoding and data fusion are addressed in Chapter 4. The fusion aspect is vital for a reliable analysis of high-resolution SAR data of urban scenes, because the interpretation of such data is a demanding task even for experts [Soergel et al., 2004]. The pros and cons of different types of symbolic reference data, e.g. 2D maps and 3D city models (prismatic and polyhedral building representation), are discussed.

The burden of the high computational load required for both the processing and the image analysis of high-resolution SAR data is discussed in Chapter 5. In order to tackle this problem, a scheme for multi-resolution processing and analysis is proposed.

2. BUILDING STRUCTURES IN HIGH-RESOLUTION SAR DATA

The appearance of buildings in high-resolution SAR images is discussed using a subset of the test area Karlsruhe University campus (Germany). Fig 1a depicts an InSAR magnitude image of about one meter resolution, which was acquired with the AER-II sensor of FGAN in 1998 [Ender, 1998]. The very same part of the scene was mapped again in summer 2002 from the same aspect, this time with the new FGAN sensor PAMIR [Ender and Brenner, 2003]. The resolution of this multilook amplitude image presented in Fig 1b is slightly better than 20cm in range and azimuth (X-band, HH polarization, off-nadir angle 61°). The sensor is capable to provide even better resolution, below one decimetre in both directions.

Comparing the two SAR images, obviously in particular buildings look very different. Only a small number of scattering events occur and superimpose inside the small resolution cell of high-resolution SAR. Hence, much more building features like edges and point structures become visible, which were averaged with their surrounding background in SAR data of coarser resolution. This results as well in a larger dynamic range data especially in urban areas, in case of the PAMIR image of about 70 dB. Due to the presence of only a limited number or in the

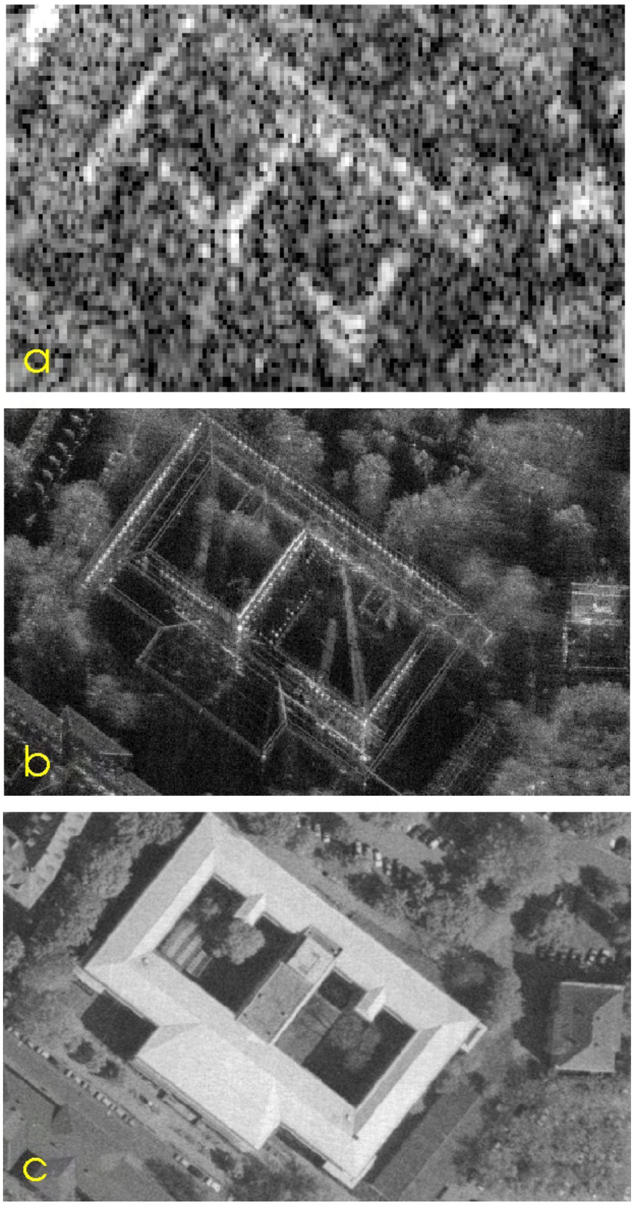

Fig1 a) AER-II image with one meter resolution, b) PAMIR image with resolution better than 20 cm, acquired in sliding spotlight mode, c) aerial image (30cm)

extreme case only a single scattering event inside one resolution cell, SAR polarimetry [Guillaso et al., 2003] is expected to be of growing importance, e.g. to determine the orientation of structures and to overcome the layover problem. An aerial image of the test scene is shown in Fig 1c. The PAMIR image and the aerial photo have about the same spatial resolution. Many features of the urban objects (buildings and vehicles) present in the scene can be observed in both images, but there are features, which appear in the SAR image but not in the aerial image and vice versa. Hence, a fusion of these complementing information sources for the analysis of urban structures seems to be fruitful [Tupin and Roux, 2004]. Furthermore, new opportunities for building recognition from SAR data arise from the high level of detail.

As mentioned above not every feature in the SAR data can be understood by comparing it with the aerial image. Hence, for the discussion of some interesting features a photo is used, which was taken in oblique view from a neighboured tower. The photo and a SAR image of part of the building complex are illustrated in Fig 2a,b. To ease the interpretation, the SAR image is shown rotated, according to the viewing geometry of the photo. The eaves (1, 2) and the ridge (3) of the roof can clearly be identified as linear structures in the SAR data, even inside the layover region in the lower image part and at the rear roof areas. The roof faces appear dark, because they are made of metal plates and the signal is mainly reflected away from the sensor. Despite the presence of some deciduous trees in front of the building, which were full of leaves at the time of the SAR data recording, the double-bounce scattering between facade structures and the ground in front can be observed (4). This bright linear feature is the starting edge of the layover area that ends at the projections of the front eaves.

Very interesting are linear structures of equidistant point scatterers (5) located at the front building walls facing towards to the sensor. Their most probable sources are slightly elevated metal stripes connecting the metal plates on a small roof between the middle and the top floor. On the terrace (6) in the middle of the building complex some small concrete pillars (yellow, respectively black pointers in Fig 2c,d) and a railing that encloses the terrace are located. These objects are mapped to salient point structures in the SAR image. In case of the railing, which is hardly visible in the photograph even after large magnification, the strong signal is mainly caused from its vertical metal poles.

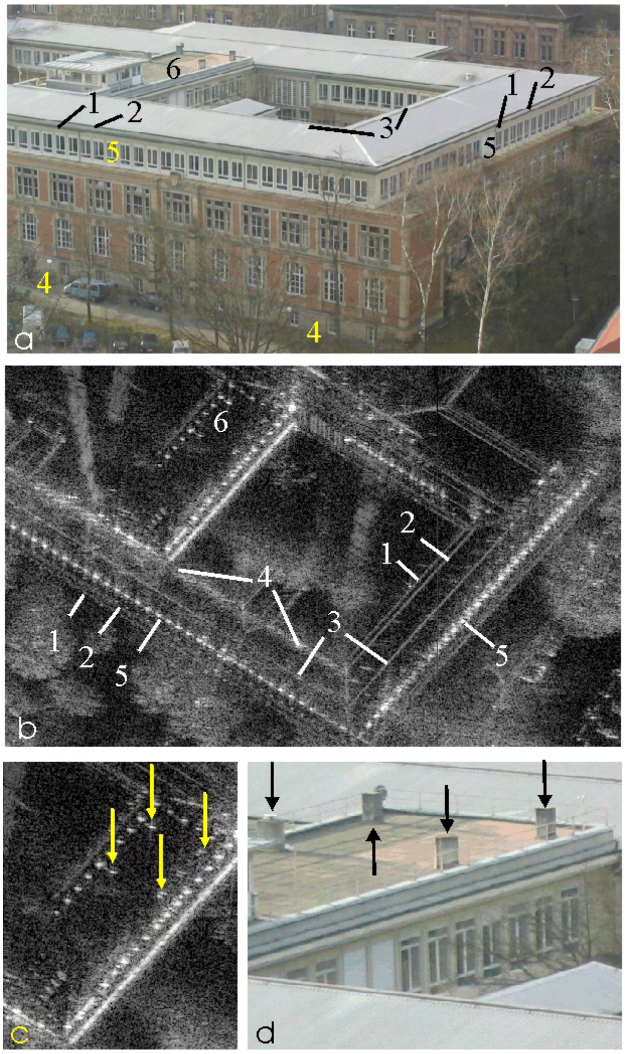

Fig.2 a,b) photograph and SAR image of one part of the building complex (numbers see text), c,d) detail structures on the terrace (6)

3. SEGMENTATION OF BUILDING FEATURES

Traditionally the recognition of the detailed geometric structure of urban areas from remote sensing data was restricted to aerial imagery and LIDAR. Such approaches in general exploit knowledge about frequently observed features of man-made objects like straight edges, right angles, symmetries and regular or parallel alignment of object groups [Stilla and Jurkiewicz, 1999]. Until now, building recognition from SAR suffered mainly from the coarse level of detail of building features in the data [Soergel et al., 2003b]. As discussed in Chapter 2, in high-resolution SAR data many of such features became visible, which can now be incorporated into the analysis. Hence, it seems to be worthwhile to adapt existing methods e.g. for building recognition to SAR data. This will be sure a research topic for the next future when more of such data becomes available. Here, the potential of such an analysis is demonstrated by some examples for object primitive segmentation and object grouping. The assembly of more complex objects starting from primitives is carried out by a production system. The production net shown in Fig 3a illustrates the workflow.

Because only a very limited number of high-resolution SAR data sets are available up to now, no adapted segmentation methods for such imagery are established yet. Instead standard tools were used for the investigations presented in the following. First, in a pre-processing step cropping of small numbers of very strong scatterers and choosing the 40dB of the signal starting from this threshold prune the large dynamic range of the data. Then the signal is mapped to byte format by non-linear operations.

Primitive line objects *L* are derived from edge [Burns et al., 1986] and line segmentations [Steger, 1999]. From this set of objects *L* long line objects *LL* are built by production p1. Small gaps between neighboured collinear primitives *L* are bridged in this step. The objects *LL* shown in Fig. 3b represent the subset of all objects *LL* that are orientated along the two right-angled main directions. These main directions were derived by local histogram analysis with an estimated accuracy of a few degrees. The major building outlines and a number of roof structures have been detected in this manner. The next step is the assembly of objects angle *A* from adjacent perpendicular objects *LL* with production p5. Production p6 looks for suitable couples of such objects *A*. Suitable are those couples that are hypotheses for U-shaped structures. Centrelines of such couples are hints to symmetry axes of building structures. Clusters of such hypotheses are identified by production p6, which results in so-called objects symmetry *Sy*. In Fig 3d the built objects *Sy* are illustrated in black. Three of four detected candidates coincide with real symmetry axes of the building. The outlier is caused by some detected angle structures *A*, which show a slightly different orientation compared to the building.

With a different approach a grouping of rows *R* of equidistantly spaced point scatterers (production p4) was carried out, using a perceptual grouping algorithm. As a first step salient point scatterers *P* are detected by a hot spot filter [Michaelsen et al., 2004]. Adjacent objects *P* are clustered to objects scatterer (*Sc*). In order to prevent exhaustive search, the grouping direction was restricted to the main orientations of the long lines *LL*. This constraint exploits the knowledge that facade structures and roof superstructures are often oriented in parallel to the building outlines (production p2). The result is depicted in Fig. 3c: salient point scatterers are represented as red crosses and the resulting groups of scatterers are superimposed as yellow lines. The main groups of such scatterers at the facade and on the terrace have been detected.

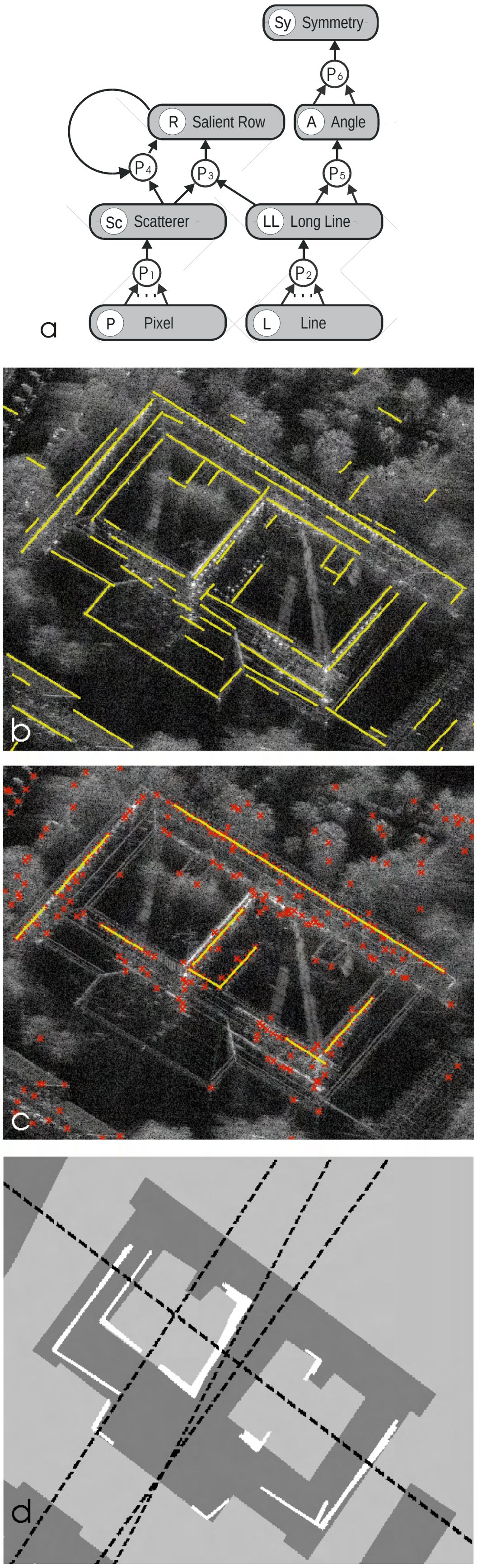

Fig.3 a) production net, b) edge and line structures in the two right-angled main directions, c) detected salient point scatterers (red) and groups of those orientated along the main directions, d) angle structures and symmetry axes (black).

A further building reconstruction was not carried out for the moment, because the data was restricted to this single amplitude image and for the separation of buildings from other urban objects in general multi-aspect elevation data sets are required. However, in an upcoming measurement campaign in fall 2005 the PAMIR system will be capable for InSAR measurements. Based on these data the feasibility of building recognition will be investigated.

Typical building faces are large compared to SAR resolution cells in the decimetre scale. The surface roughness of many of these objects (e.g. concrete walls, windows) is small with respect to the SAR signal wavelength. In such cases, the building face might cause the dominant scattering event present in a large number of neighboured resolution cells. Therefore, polarimetry is expected to become a key technique for object classification [Guillaso et al., 2003] and the determination of object orientations in urban areas.

4. FUSION WITH GIS DATA

The interpretation of SAR imagery in dense urban scenes without supporting context information is a difficult task even for experts. However, context information is usually not available for all areas at the same level. The benefit from integrating GIS data in the analysis will be discussed for different levels of available data in the GIS: 2D maps, prismatic and polyhedral 3D city models.

4.1 2D map data

In the simplest case the availability of a vector map containing a layer with building footprints is assumed. According to the sensor parameters and the carrier navigation data, the building footprints can be transformed into the SAR geometry and superimposed on the images. The lack of height information leads to a shift of the transformed footprints like shown in Fig. 4c (red polygons). However, this shift between the footprint and the building contours in the image visualizes the layover area for an interpreter. These areas could be e.g. treated in a special manner or excluded from further interpretation. If available, a road layer is useful for the discrimination of roads from cast shadow of buildings.

4.2 Prismatic 3D city model

Using height information, the accuracy of the projected building structures is enhanced. Fig 4a illustrates a prismatic 3D city model representing the height of the eaves. Fig. 4c shows in yellow the transformed roof contours superimposed on the slant range image. The location of the projected roof outlines is now correct. Comparing the red and the yellow polygons in Fig 4c the layover region becomes obvious: the area of the shift between the two projections contains the by layover superimposed signal from the roof, the facade, and the ground in front. This shift visualizes also the geocoding error using a digital terrain model (DTM).

4.3 3D city model

As discussed in Chapter 2, the appearance of buildings in high-resolution SAR data is governed by large extent from roof structures. Those are represented in a so-called polyhedral 3D city model. In Figure 4b a 3D view of the building of interest is depicted, which contains the major building parts and roof faces. Figure 4d shows the edges of the roof structures of the

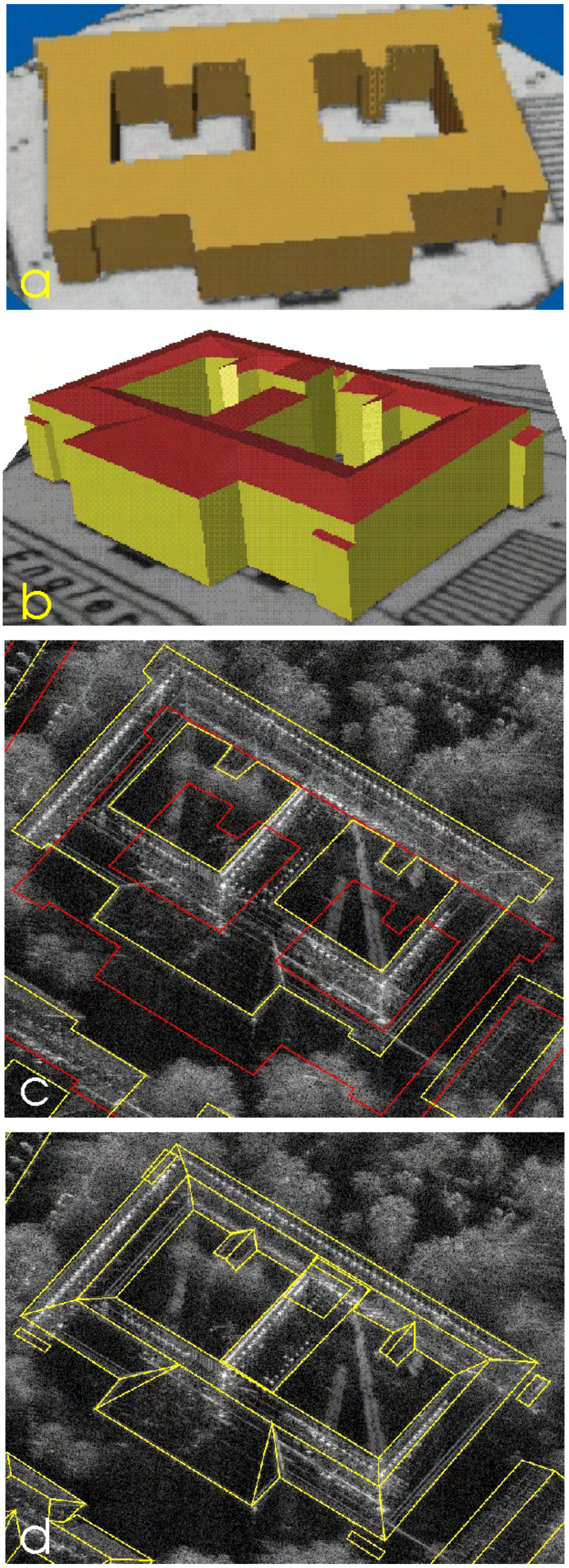

Fig.4 a,b) prismatic and polyhedral 3D city models, c) projection of the building footprints (red) and the roof eave structures into the SAR geometry, d) like c) using the polyhedral 3D city model. axes (black).

model superimposed on the SAR image, using the same transformation than before. Compared to the prismatic model, the cause of many additional linear features in the SAR data becomes now evident. The projected ridges and edges of the modelled roof patches coincide with their counterparts in the SAR data. In the case of imperfect geocoding a fine adjustment can be carried out by matching the transformed building model lines and segmented linear structures in the SAR image, like those shown in Fig 3a. Additionally, polyhedral 3D city models can be used as reference data for the simulation of multipath signal propagation [Soergel et al., 2004]. However, many of the building features visible in the SAR image are not modelled in the 3D reference. The detection of changes of the urban structure using SAR seems to be a realistic option for the future. Additionally, existing 3D models could even be supplemented by integration of features provided in high-resolution SAR data.

5. MULTI-SCALE PROCESSING AND SCREENING

In general, an increased geometric resolution results in higher computational load for the SAR image formation and the subsequent image analysis. However, often only a subset of the scene is in the focus of interest. For example, special events like flooding or earthquakes are often restricted to comparable small areas. Disaster monitoring [Shinozuka et al., 2000] and damage detection [Kakumoto et al., 1997] using SAR data has become a major research topic in recent years, because of the independency of SAR from weather conditions and time of day. In order to lower the computational burden and to speed-up both image generation [Brenner, 2002] and analysis, a multi-scale processing is appropriate. This proposed concept is discussed in the context of a building analysis here.

If GIS data is available, the region of interest (ROI) can be immediately identified using this data e.g. in the way described in the previous chapter. Otherwise, the ROI have to be identified from the SAR imagery alone.

It is advantageous to carry out the image processing and analysis in a coarse to fine manner. First, a low-resolution overview image is generated with a fast but sub-optimal processor. In a subsequent screening process, regions of interest are identified in the overview image. Afterwards, these regions are re-processed in higher resolution. Three resolution levels are considered here. Finally, a focused image analysis is carried out in the full resolution subset of the data.

The strategy for the determination of the ROI depends on the task and the image resolution. A separation of settlements from other classes of terrain like forest and field can be achieved by classification even for considerable coarse image resolutions, e.g. those of ERS. For example, the coefficient of variation, which is often exploited for speckle filtering, is usually high in settlement areas [Lee and Jurkevich, 1989]. Another method is the detection of clusters of dominant point scatterers [Gouinaud et al., 1996] that are frequently caused by triple-bounce at building corners. The further analysis in a medium resolution stage is restricted to areas classified as settlements in the first step. The higher the resolution gets, the more the focus is shifted from radiometric image properties to geometric object features. The feasibility of a building detection for this scene in InSAR data with one-meter resolution was already demonstrated [Soergel et al., 2003b]. The result from this medium resolution data steers the further analysis at the highest level of detail, exploiting the knowledge that buildings often form clusters and are aligned linearly along roads. Hence, the subsequent fine analysis is not restricted to the already found building candidates, but extended to their neighbourhood. Additional features segmented in the image of highest resolution offer the possibility to enhance the evidence and to improve already detected buildings, to find further ones and to discard false positives.

6. CONCLUSION

State-of-the-art high-resolution SAR sensors provide a detailed mapping of man-made objects, which could not be achieved by radar remote sensing only a few years ago. Structural image analysis approaches were up to now either tailored for extended targets or the extraction of rather coarse scene descriptions. Based on the new high-resolution data, a much finer level of detail of the object recognition seems to be possible. Polarimetry is expected to be of growing relevance for the analysis of urban areas. The geocoding accuracy should match the resolution of the SAR data and therefore the height reference data must represent the buildings. Precise geocoding is a prerequisite e.g. for the fusion of multi-aspect SAR data or the fusion of SAR data with complementing data of different kind. For many applications only a subset of the scene is of interest. In such cases, multi-scale processing and analysis are useful to speed up the analysis.

SAR data with decimetre resolution contains often object details not represented in a given 3D model of the scene. Hence, the 3D model can be enhanced analysing the SAR data.

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