SAR SIMULATION BASED CHANGE DETECTION WITH HIGH-RESOLUTION SAR IMAGES IN URBAN ENVIRONMENTS

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ABSTRACT:

Combined processing using different sensor types, i.e. for applications like change detection, requires a good geo-referencing. Furthermore the individual sensor properties have to be taken into account. SAR systems are side-looking and run-time systems. They suffer from occlusions and ambiguities especially in urban areas. Additionally layover and shadow effects disturb the geo-referencing of SAR images in urban areas, which is a prerequisite for a successful change detection. An improved geo-referencing can be achieved by simulating 3D-city models or street datasets using a SAR simulator and comparing the simulated image to the real image. Correspondences between simulated and real image can be used for geo-referencing the image according to the coordinates of the 3D-city model or street dataset. The geo-referenced dataset can afterwards be used for change detection analysis. SAR images represent a side-view of the three dimensional world. An automated change detection using SAR images should take this fact into consideration and therefore should use 3D-models as reference for the change-detection. These models are simulated and the simulated image is compared to the geo-referenced image, revealing changes between the simulated model and the real image.

1. INTRODUCTION

The urban environment is of the utmost importance for human society. In 2001, around 50% of the human population lived in cities and these numbers are still rising, especially in less developed countries (UNCHS, 2001). The dense placement of buildings in cities requires a good resolution of the remote sensing systems, to distinguish between the neighbouring buildings. Modern high-resolution airborne SAR systems reach very high resolutions up to 10cm (Ender & Brenner, 2003) and are therefore useable for remote sensing applications in urban environments.

Using SAR has some advantages, related to the capability of these systems to operate at day and night and under nearly all weather conditions. This is most beneficial for time dependant applications, like disaster management. But unfortunately SAR has also a lot of disadvantages, especially while using it in urban environments. These disadvantages are related to the run-time geometry and side-looking properties of the SAR system, leading to occlusions and ambiguities. In very dense urban environments, containing tall buildings, it is sometimes impossible to observe some areas at all.

For collecting data, it may therefore, be better to use other types of sensors. LIDAR, for example, is more suitable for building reconstruction and generating city models (Haala & Brenner, 1999), although it is possible to reconstruct buildings from InSAR (Sörgel, 2003). In case of an emergency, SAR is beneficial, especially for change detection applications combined with GIS data or remote sensing data from other sensors.

For change detection applications using different types of sensors, the data fusion is the main problem. To solve this problem, the individual sensor properties of the used sensors have to be taken into account. In the approach described in this paper, available 3D-city models are simulated using a SAR simulator. The simulated images, afterwards, are being compared to the real SAR images for geo-referencing and change detection purposes. The geo-referencing of the SAR data can be done using 3D-city models or GIS street data. In this approach, changes in the 3D-city model are detected by comparing the SAR simulated image of the 3D-model with the real SAR image. The simulated image represents the expected value. Differences between the expectations, derived from the simulation, and the real SAR image are supposed to be caused by changes. Although these differences may have other reasons, too.

2. SAR PRINCIPLE

SAR images differ from optical images not only in the wavelength but also in the geometrical properties. SAR images are run-time images and the SAR systems are side-looking systems. Due to this fact, it is difficult to combine SAR data and optical data, because of the different image geometries. Especially the layover and fore-shortening effects have to be taken into consideration while working on the fusion of SAR data and optical data.

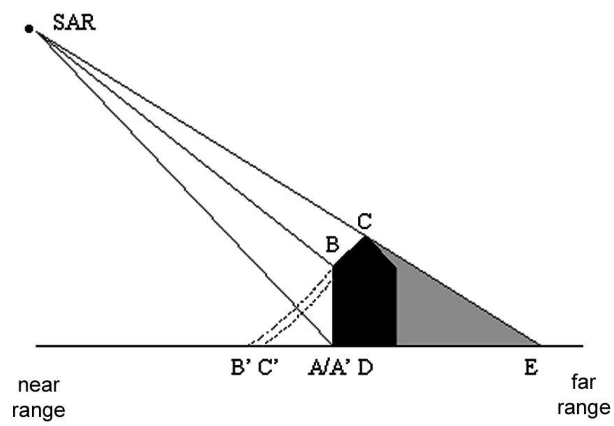

Figure 1. SAR geometry in range

In Figure 1, the SAR geometry is shown schematically using a single house as an example. For SAR processing, flat terrain is assumed, therefore the house is wrongly positioned in the image. Point A is imaged correctly in A’, whereas the points B and C are imaged in B’ and C’, closer to near range, as their real position. This effect is called layover and is caused by the run-time geometry of the SAR sensor. The range between A and E is the shadow area. Because of the displacement of point C in C’ the shadow is starting at point A and not at point D.
In dense urban environments the situation is getting more complex. As shown in Figure 2, occlusions and ambiguities make the interpretation of the data nearly impossible. In the RADAR shadow, no data is acquired at all. The layover area of buildings also occludes a lot of information. In fact it is hard, sometimes impossible, to tell which information is reflected from which building, thus making the interpretation of SAR images in urban areas very complicated.

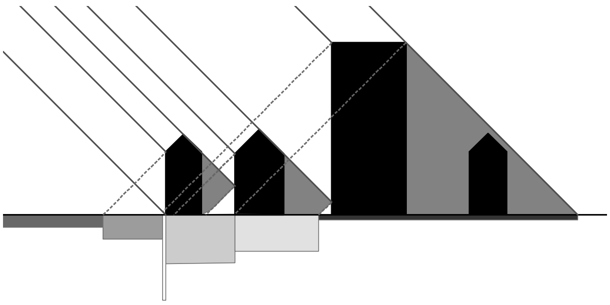

Figure 2. SAR geometry of an urban environment in range

3. SAR SIMULATION

A SAR simulator is a key tool for the interpretation of SAR images (Leberl & Bolter, 2001). Using SAR in urban environments, the simulator is also useful during mission planning, for choosing the optimal SAR acquisition parameters and avoiding occlusions in the area of interest (Sörgel et al, 2003).
For the presented approach, the SAR simulator is the key element. The complex interaction of different effects in SAR cannot be totally understood, but a SAR simulator helps understanding SAR images by simplifying the reality. Therefore SAR simulators are used for training purposes and are also quite helpful in change detection applications.

Figure 3. Subset of a DOSAR image of Karlsruhe

Figure 4. Simulated SAR image

Figure 3, shows a DOSAR image of the area of Karlsruhe. DOSAR is the multifrequency polarimetric airborne SAR system of the EADS Dornier GmbH (Hoffmann & Fischer, 2002). The flight direction is 90.05°, the off-nadir angle is 70°, the pixel resolution is 0.26m and the 3dB-resolution is about 0.57m. In Figure 4, the result of the SAR simulation of the 3D-city model of Karlsruhe is shown. Comparing Figure 3 and Figure 4, the great differences between the simulation and the reality are getting obvious.

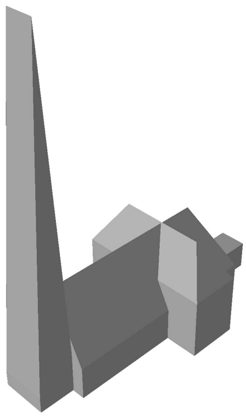

Figure 5. Model of the St. Bernhardus church

In Figure 5, the model of the St. Bernhardus church from the 3D-city model of Karlsruhe is presented. This model was reconstructed from LIDAR data and ground plans (Haala & Brenner, 1999). Due to problems during the data acquisition, the spire is not correctly modelled and the whole building is wrongly shaped. The error regarding the footprint of the building is around 1m in different directions. Anyhow such a model is good enough for the presented approach.
Using the SARView Light SAR simulator (basis version) of the EADS Dornier GmbH, this dataset was simulated according to the SAR parameters of the real SAR data acquisition flight (see Figure 11).
3D-city models are generalised and simplified representations of the reality. In addition they can be erroneous and incomplete. Every simulation based on these models can therefore be incomplete and wrong. Furthermore the SAR simulator is not able to handle all the possible SAR effects and even the real SAR

data itself might be faulty. Moreover strong corner reflectors and their side-lobes are able to disrupt every interpretation and unfortunately they can not precisely be forecasted. Normally the SAR processor should reduce the effect of side-lobes.

If the SAR processor is not suppressing the side-lobes sufficiently, it is also possible to suppress the side-lobes by a filtering in the frequency domain of the SAR image. Applying a wedge filter, according to the squint angle, in the Fourier image and comparing the original image with the filtered image, reveals the areas affected by the side-lobes. These areas have to be masked out in the future image interpretation steps. Unfortunately not all the areas are detected by this simple method and some areas may be wrongly masked out.

4. SIMULATION BASED GEO-REFERENCING

4.1 Model based geo-referencing using street vectors

The first step of a change detection is to combine different datasets. This is done by geo-referencing the datasets. SAR data is normally, at least, roughly geo-referenced, but this initial spatial reference is often not accurate enough for data fusion purposes. The initial reference of the DOSAR image of Karlsruhe, for example, has an offset of 150m.

In the approach described in this paper, one possibility to improve the spatial reference of the SAR image is using GDF-street data as ground-truth for automated geo-referencing. The other possibility is to use 3D-models of landmark buildings, but such 3D-models are often not available, whereas street network data is commonly available. These standard datasets are, e.g. provided for car-navigation systems. The street vectors are transformed to the UTM coordinate system. Afterwards the street vectors should be SAR simulated using a DEM of good quality, if available.

Streets in SAR images are normally quite dark, because the street surface is very smooth and reflects the SAR beam away from the sensor. Cars and signs are strong reflecting objects on or near the street, but they are not taken into consideration here. Therefore, it is assumed that streets should appear dark in SAR images and can be found by their structure.

The flight direction and the rough position of the image have to be known for further processing. In this example, we used the DOSAR flight over Karlsruhe mentioned above. The initial coordinates of this flight have an offset of about 150m. This spatial reference should be improved using GIS data. For this purpose GDF-street data, has been used. This data has an accuracy of around ±3m (Walter, 1997).

For geo-referencing the SAR image, corresponding points in the SAR image and in the street data have to be found. The corresponding points should be evenly spread over the image, to allow a stable referencing of the data. On the other hand, for the automated search method described in this paper, it is necessary to use points from areas containing many streets and junctions, to avoid ambiguities. Depending on the content of the SAR image this is a trade off, because streets and junctions are normally not evenly distributed. In this approach, a huge amount of distributed points are selected. From those, only the points with the most junctions in their search subset are being used.

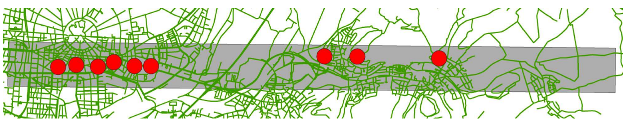

Figure 6. Footprint of the SAR image and the search areas

In Figure 6, the footprint of the SAR image, the GDF-data and the search areas are visible. Obviously the corresponding points are not very well distributed. This is due to the concentration of the algorithm on areas with many junctions and streets, mainly found in the city area. This results in points, which are not evenly spread. Another problem is the unfavourable distribution of the points. The selected points reside mainly on one line. This is due to the quite large search area used for the analysis. Therefore, the small strip-width forces the algorithm to search for corresponding points near mid-range.

To minimize the computational time, the resolution of the SAR image is reduced, in this example by the factor 5 in both x- and y-direction. Using this reduced image, the area around each search point is extracted and the streets in the corresponding areas are rotated in azimuth direction and are transformed to a binary raster representation.

The binary representation is used as search mask to analyse the reduced SAR image chips. The algorithm assumes, that streets are dark areas in the image, while the surrounding areas are bright. Therefore the sum of the pixel values of the real image in areas where, according to the street data, streets reside are divided by the sum of the pixel values where no streets reside. The pixel with the lowest calculated value in the search area is the point with the highest concurrence. This time consuming search method is working well in urban areas. Promising search results can be seen in Figure 7, showing the good automated matching, between the GDF-street data and the SAR image.

Figure 7. Search results overlaying a DOSAR image

But the method has some problems in rural areas with less contrast between streets and surrounding areas, which can be seen in Figure 8. Obviously there is some shift in the data on the left side, but the position is approximately correct. Gross errors exist in the second example on the right side. Apparently the position is totally wrong. The problem here, is not only the lower contrast. The small amounts of streets and junctions in the area, are causing the method to fail.

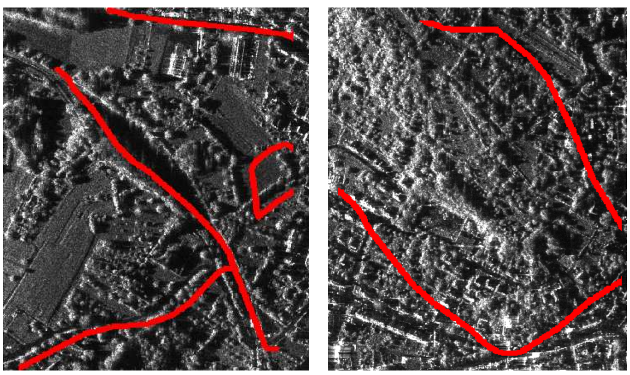

Figure 8. Erroneous search results overlaying a DOSAR image

It is therefore possible, that, as a result of a failed search, some corresponding points are placed in wrong positions. More points than needed for the transformation, should therefore be searched for. The analysis should concentrate on areas with many streets and junctions, because these areas offer a more robust determination.
After the analysis of all areas, the corresponding points are available in the reduced resolution. The final position is determined in the high-resolution image, using the same method. As the position of each corresponding point is roughly known, the computational time for searching in the high-resolution image is reduced considerably. After the required number of corresponding points are known, the transformation can be calculated. By analysing the transformation and the resulting errors, wrong correspondences can be eliminated.

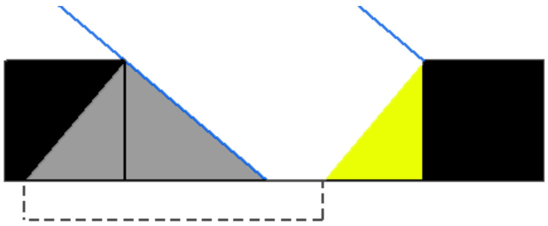

Figure 9. Supposed street position, shifted in near range direction

Due to the SAR imaging properties, the streets surrounded by houses, are displaced. The position of the dark areas in the image, supposed to be streets, is shifted in near range direction, due to the shadow and layover effects of the surrounding buildings.
The length of the shift in near range depends on the incident angle and the height of the surrounding buildings. If the buildings on both sides of the street have the same height, the shift can be calculated according to

$$shift = \frac{height}{\tan(off - nadir)}$$

Assuming a building height of 10m and an off-nadir angle of 70°, the shift in near range direction is ca. 3.6m. Using a pixel size of 0.26m, this is equivalent to 14 pixel. If all the buildings in the analysed area have nearly the same height, the streets are just shifted in near range direction. If the building heights in a given subset vary a lot, the search method described above may fail.

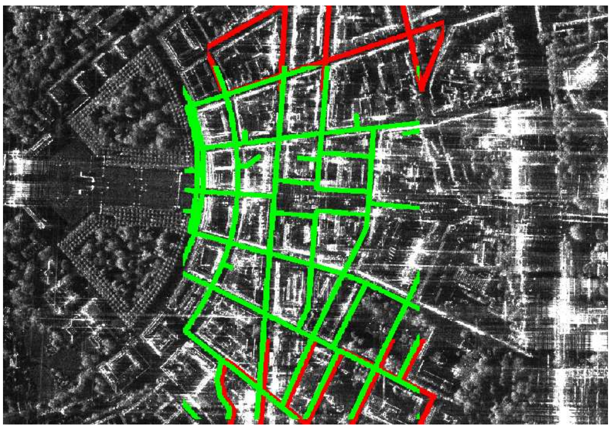

Figure 10. Three search results overlaying a DOSAR image

In Figure 10, the shift can be seen in the results. Three neighbouring search areas are presented and there is some shift in range direction between these regions. This shift is mainly caused by the effect shown schematically in Figure 9. Additionally the analysis does not provide a very high accuracy itself.
Due to the near range shift of streets in urban areas, the position in range will be wrong for a lot of the subsets. Even worse, the shift is changing according to the environment. In inner city areas, the shift is very high, due to the high-rise buildings there. On the other side, streets without neighbouring buildings will have no such shift at all.
An accuracy of the overall spatial reference of around 6m is achieved by the method described above. This error is caused by the inaccurate street data, as well by the shifting of the streets as shown in Figure 9. Erroneous corresponding points are furthermore causing a lot of problems. Considering the high errors caused by shiftings and by inaccurate data, it is not easy to automatically find the erroneous corresponding points.
Therefore the overall accuracy is not high enough to use this geo-referencing method for automatic change detection applications. But it can be useful for manual change detection and it may be used as rough geo-referencing method for the whole image, which should be refined during the change detection process for a local area.

4.2 Model based geo-referencing using landmark buildings

The geo-referencing can be more accurate if a 3D-city model alternatively to GDF-street data is being used. Special landmark buildings of the 3D-city model are being used for the method described in this paper. Landmark buildings are unique buildings with special properties, which are separated from the neighbouring buildings, to avoid them from merging together in the SAR image. The buildings have to be selected by an operator. It is also possible to find such buildings automatically, by analysing the GIS data. After the building has been selected it has to be simulated according to the sensor parameters of the real SAR image. The SAR simulated image of the selected model should look quite similar to the building in the real SAR image.
The first analysis step is not performed based on a raster representation of the data, but on the vector representation, because the upcoming search can be calculated much faster using vector data. For this purpose, the model of the landmark building is simulated without any speckle and the resulting image is transformed in a vector representation (see Figure 11).

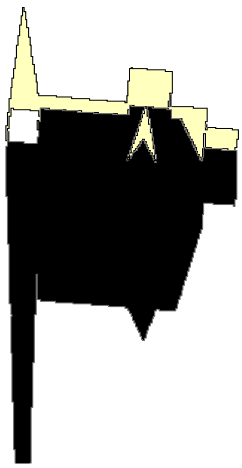

Figure 11. SAR simulation of the St. Bernhardus church as vector representation

From the real SAR image three pyramid layers are calculated and afterwards segmented, using an adaptive threshold method (Levine & Shaheen, 1981). The segments are transformed to vector polygons. Starting from the pyramid level with the lowest resolution, the polygons, which represent peak areas, are analysed. Neighbouring polygons representing peak areas, grow together. Analysed polygons, with area sizes not exceeding a maximum area and not undershooting a minimum area, are selected and the search is continued in these polygons on the next higher resolution pyramid level. The thresholds of the maximum and minimum area sizes are derived from the simulated model. Those thresholds are getting more exact in pyramid levels of higher resolution. Using this simple method, only a few polygons are left as possible building positions.

These positions are afterwards analysed using a pixel-wise comparison of the simulated and the SAR image. The pixel with the highest concurrence is considered as the real position of the landmark building. For each building or object searched in the image, one coordinate pair can be determined.

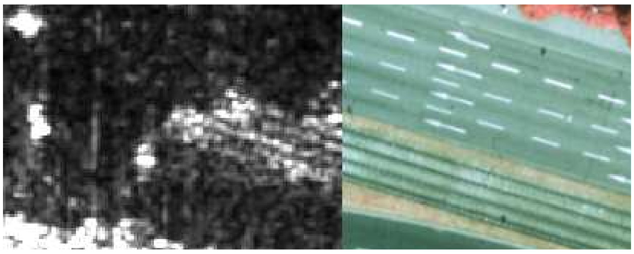

Figure 12. DOSAR image (left) and orthoimage (right)

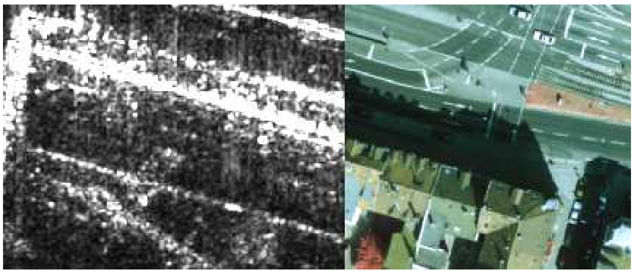

Figure 13. DOSAR image (left) and orthoimage (right)

In Figure 12 and Figure 13 the good geo-referencing of the data is visible. The area around the St. Bernhardus church was referenced using the model of the church shown in Figure 5, which is quite erroneous. The result is comparable to a manual referencing. Even experienced operators have problems finding corresponding points using SAR and optical data. The railtracks fit quite well, also the buildings do fit well. The kerb shows some misplacement.

The accuracy which can be achieved is difficult to determine, because, not many points are directly comparable. The estimated accuracy is around 1.5m in the vicinity of the church, which is equivalent to 6 pixel of the SAR image or 3 times the 3-dB resolution of the SAR system.

5. CHANGE DETECTION

The exact geo-referencing of the different datasets is a prerequisite for the change detection. The building block used as example for the change detection is shown in Figure 14. The model has been modified. The black building is not real. It is too high and the shape of the roof is wrong. In Figure 15, the difference between the SAR simulation of the original and the modified model of Figure 14 can be seen.

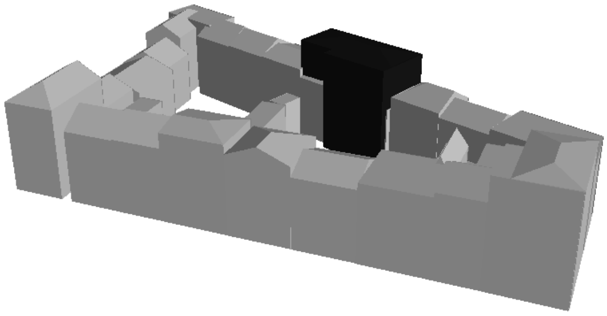

Figure 14. Changed 3D-model

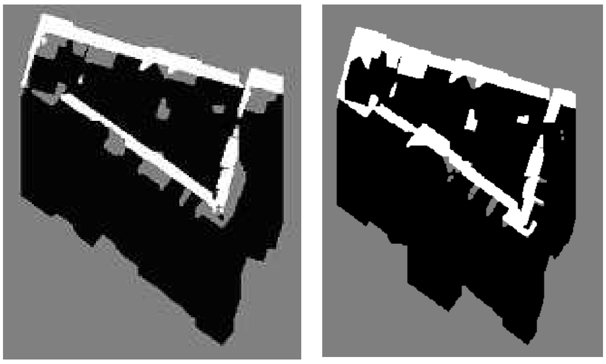

Figure 15. Simulated image of the original 3D-model (left) and of the modified 3D-model (right)

After the automated geo-referencing, the position of the building block is known. Because of topographical distortions, or if the automated geo-referencing was not very accurate, it is necessary to determine the position of the analysed building block again. This is done using just the pixel-by-pixel comparison in a small subset. Sometimes this pixel-by-pixel method is not necessary or working, for example if huge changes occur. In this case a good initial geo-referencing and a DEM is needed to determine the accurate position of the building block.

The simulated image of the 3D-model should afterwards be compared to the real image. Areas with high-values in the real SAR image, but low values in the simulated image may indicate the existence of new objects. Otherwise areas with low-values in the real SAR image and high values in the simulated image may indicate missing objects. The length of the layover and shadow areas are determined by the height of an object. Changes in the shape of those areas can be a result of the change in the shape of the analysed objects.

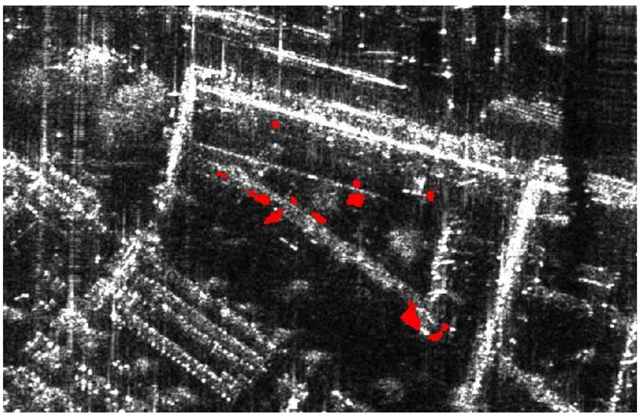

Figure 16. Detected changes of the building block overlaying a DOSAR image

In Figure 16, the automatically detected changes of the building block can be seen. Obviously not only the artificially implemented changes are visible. Furthermore, some objects inside the building block, are not modelled correctly in the 3D-city model. The biggest change is visible at the south-east corner of the building block. The roof of this building is wrongly shaped in the city model (see Figure 17).

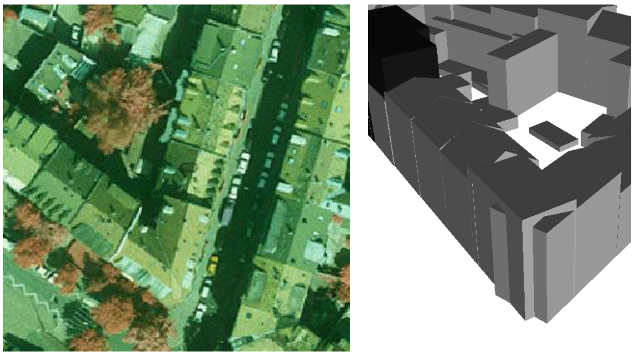

Figure 17. Orthoimage (left) and erroneous shaped 3D-model (right)

The errors and the incompleteness of the 3D-city model results in a lot distortions in the change-detection process. The real SAR image differs in many ways from the simulated image. For example, objects not contained in the model, may interfere the analysis. In Figure 13, this problem can be seen. The layover area of the building is influenced by the backscatter from the kerb near the building. In this case, those areas are overlapping and this is no problem. For an even taller building, the kerb in the middle of the street would have merged with the layover area, indicating a much larger layover area and disturbing the analysis.

Altogether the change detection based on SAR simulated images of 3D-models works pretty well using high-quality 3D-models. The main problem of change detection applications using SAR and other types of data is the geo-referencing. By simulating the 3D-models and using the simulated image as basis for the geo-referencing, a highly-accurate geo-referencing is possible. The change-detection works well after the successful geo-referencing, but still errors in the model itself are remaining. For example, the detected changes in Figure 16 are mainly based on errors in the used 3D-city model.

6. CONCLUSION

A prerequisite of every change detection operation is the geo-referencing of the different datasets. Combining SAR data with data acquired by different sensors, the geo-referencing of these different data types is problematic. SAR systems are side-looking systems with run-time geometry. Therefore the SAR geometry of SAR images differ a lot from optical images or GIS datasets. The different imaging properties have to be considered.

A SAR simulator can be used to transform the 3D-models into the SAR image space. Comparing the real SAR image and the simulated SAR image of the 3D-model, a meaningful change-detection is possible. This comparison can be used to automatically geo-reference SAR images to SAR simulated images of 3D-models. Using GDF-street data the initial geo-referencing of the SAR image could be improved from an offset of about 150m to around 6m. Using 3D-models the offset could be reduced to 1.5m, although the used model was quite erroneous.

For a successful change detection using SAR images, it is most useful to rely the detection on 3D-data instead of using 2D-data. The side-looking property of a SAR system makes it most important to regard the 3D-shape of the analysed object. The simulated image of the 3D-models, created by a SAR simulator, can be compared to the real SAR image and as a result of this comparison changes may be detected automatically. The final result of the change detection depends on the quality and completeness of the 3D-model simulated for the comparison. Furthermore errors in the real image and during the SAR simulation can disturb the result of the change detection.

The side-looking sensor principle of SAR is unfavourable for urban environments, compared to aerial imagery or LIDAR. Unfortunately in those environments any detection can be prevented by occlusions and disturbed by ambiguities. Under some circumstances no change detections is possible at all, using SAR. For time-critical applications SAR is anyhow still the best alternative, especially during the night or under bad weather conditions.

7. ACKNOWLEDGEMENTS

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