3D Reconstruction of Buildings and Vegetation from Synthetic Aperture Radar (SAR) Images

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Abstract

3D models of a landscape are useful for the evaluation of remote sensing data or for landscape planning. In this paper, it is shown that a 3D reconstruction of buildings and vegetation can be obtained from the shadows in synthetic aperture radar (SAR) images. First, elevated objects like buildings and higher vegetation (e. g. trees), and shadow regions are segmented in the SAR image. Then the shadows are assigned to suitable elevated objects. Since it is assumed that the height of the ground is known from a digital elevation model (DEM) or from other sensors, the heights of the elevated objects can be calculated from the estimated radial shadow lengths and the system parameters. The wrong positions of elevated objects in SAR images can be corrected afterwards. Finally, triangulation and texturing methods lead to a realistic 3D model of the landscape including buildings and vegetation.

1 Introduction

Remote sensing of the earth's surface with synthetic aperture radar (SAR) has several advantages when compared to optical sensors: Since SAR is an active radar system, it can operate independent of time of day and weather conditions. Moreover, due to the forming of a synthetic aperture, which grows with an increasing distance, the resolution is nearly independent from the distance. On the other hand, the SAR principle results in errors in the SAR image, when the observed objects are moving [1] or when their height differs from a nominal, constant height. In the latter case non-linear effects like shadows and overlay occur and the objects appear at wrong positions.

For topographic mapping, some techniques applying interferometric SAR have been proposed (e. g. [2]). They need two antennas, which are associated with high hardware and computational effort. To reduce this effort, it will be shown that a conventional SAR system with a single antenna can be used to gain the 3D shape of elevated objects like buildings and vegetation (woods, bushes etc.). The height of the ground without elevated objects is already known and available in form of a digital elevation model (DEM) for many regions on the earth. In this paper, a method for 3D reconstruction of elevated objects is presented, which deals with SAR images obtained from a conventional SAR system and a DEM. This method evaluates the shadows behind elevated objects, when viewed from the antenna. These shadows occur due to the 2D imaging of the SAR antenna, measuring azimuth (along-track) angle and range rather than azimuth and elevation angle as by optical sensors [3].

The proposed method consists of three main steps, the segmentation of the SAR image, the height estimation, and the generation and visualization of the 3D model. These three steps are described in the following sections.

2 Segmentation of the SAR image

The segmentation of the SAR image is done using a segmentation algorithm based on Gibbs-Markov random fields [4]. This algorithm estimates the statistical properties of representative regions which have been interactively marked in a learning map. Each region marked in the learning map belongs to one class like elevated objects (woods, buildings), flat ground (field, streets) or shadows. Afterwards the SAR image is segmented by iteratively assigning the pixels of the image to the distinct classes, dependent on the assignments and properties in a neighborhood.

The segmentation relies on the first and second order statistics of the texture. It sometimes fails in distinguishing between shadows and streets or between field and wood which have similar statistical properties, respectively. The resulting partly erroneous segmentation is corrected by investigating the order of the different labels in the segmented image.

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3 Height Estimation of Buildings, Woods and Trees

A SAR system measures the reflectivity coefficient of locations that are described by only two coordinates. Consequently the generation of a SAR image includes the process of projection of the 3D shape of the considered landscape into the SAR image plane.

The projection of objects into the SAR image plane (x/y-plane with x - azimuth and y - ground range) is performed by circular projection. The axis of rotation is assumed to be equal to the linear flight path. By this the circular projections take place in parallel planes, which are called reconstruction planes and that are perpendicular to both the SAR image plane and the path of flight. The height estimation is a result of reconstructing the objects' cross-sections within the reconstruction planes.

As the projection is ambivalent [5] the objects are distinguished as elements of two groups taking into account their different projection characteristics:

- Objects without crown (buildings, woods)
- Objects with crown (trees)

In case of objects without crown shadow and object pixels are directly connected (Fig. 1). Objects with crown produce sets of shadow and object pixels along the y-axis, which are interrupted by ground pixels (i. e. field or street), due to the fact that the reflexions from the narrow trunk can be neglected. For the reconstruction of objects with crown an ideal tree model is applied, as shown in Fig. 2. Since the top of woods behaves similar to the roofs of buildings, woods are considered as objects without crown.

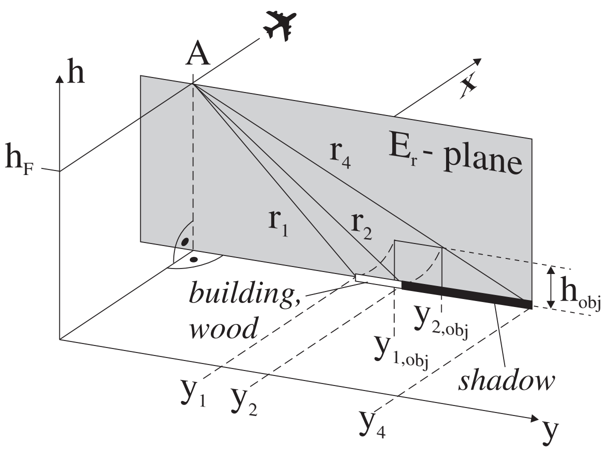

Figure 1: *Reconstruction of objects without crown*

The sets of object and shadow pixels are searched along the columns of the SAR image, i. e. in range direction. The joined appearance of both a set of shadow and object pixels allows the reconstruction of either objects with or without crown.

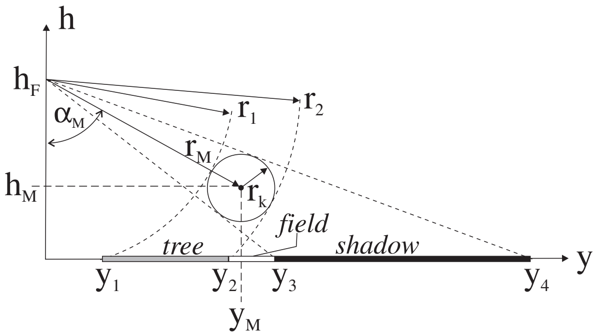

Figure 2: *Reconstruction of objects with crown*

Figures 1 and 2 show the assumed objects' cross-sections in the reconstruction plane E_r of each group. All buildings are supposed to have a plane roof, whereas trees are assumed to have a spherical crown. The flight height h_F is given by the parameters of the SAR system. The near and far end of both the set of object and shadow pixels, denoted by $y_{1,2}$ and $y_{3,4}$, respectively, are determined out of the segmented image, where $y_2 = y_3$ is valid in case of objects without crown. From these parameters for each point on the y-axis a circle can be calculated in order to invert the circular projection, which arose from the SAR imaging. The parameters that describe the objects' cross-sections in the reconstruction plane can be derived from trigonometric equations (see below). In both cases the SAR image plane is supposed to be equal to the earth's surface. The same principles can be applied even if the earth's surface is not planar, on condition that a height map of the ground is available (e. g. a DEM).

For objects without crown the three parameters that describe the cross-section $y_{1,obj}$, $y_{2,obj}$ and the object height h_{obj} are estimated as (see Fig. 1):

$$
\begin{aligned}
h_{obj} &= h_F \left(1 - \frac{r_2}{r_4}\right), \\
y_{2,obj} &= y_4 \left(1 - \frac{h_{obj}}{h_F}\right), \\
y_{1,obj} &= \sqrt{2 h_F h_{obj} + y_1^2 - h_{obj}^2} \;.
\end{aligned}
$$

For objects with crown we get the ground range y_M, the radius of the crown r_k and the height of the center of the crown h_M as (see Fig. 2):

$$
\begin{aligned}
y_M &= \frac{r_1 + r_2}{2} \sin \alpha_M, \\
r_k &= \frac{r_2 - r_1}{2}, \\
h_M &= h_F - \frac{r_1 + r_2}{2} \cos \alpha_M,
\end{aligned}
$$

with $\alpha_M = \frac{1}{2}\left(\arctan\frac{y_4}{h_F} + \arctan\frac{y_3}{h_F}\right)$. The radii $r_{1\ldots4}$ can be easily obtained from the values $y_{1\ldots4}$.

Since the lengths of the sets of object and shadow pixels do not always fulfill the ideal conditions, further tree models for high trees and groups of trees have been developed [6].

In order to get realistic heights some plausibility criterions have been derived. Unexpectable object heights and relations can be avoided with these criterions. After passing these criterions, the estimated parameters are entered in the height map.

Finally, smooth surfaces of the woods are achieved by lowpass filtering of the concerned areas in the height map. The assumption of a plane roof of buildings is realized by evaluating average heights for each building. If only a part of a shadow has been segmented, the height of the corresponding elevated object will be estimated for this part and will then be taken for the whole elevated object.

4 Generation and visualization of the 3D model

From the obtained height map a 3D model is generated and visualized using a graphic computer. The 3D model is obtained by subsampling the height map and creating a 3D mesh consisting of connected triangles. The nodes of the 3D mesh represent the samples of the height map.

The texture of the original SAR image cannot be used directly for the 3D model because the elevated objects appear at wrong positions. Therefore the elevated objects are shifted in range direction according to their estimated heights and the distance between antenna and object. The arising gaps are filled by mirroring parts of the texture in front of the object. By this means the errors in the SAR image are compensated for and it can now be projected onto the 3D mesh.

The resulting 3D model is visualized by rendering it simultaneously according to two virtual cameras, representing the eyes of the observer. The two images are displayed on a screen via a stereoscopic projector with orthogonal polarization. The observer gets a spatial impression of the 3D model by looking at the screen with polarized glasses.

5 Results

The proposed method has been applied to multilook SAR images from an airborne SAR sensor. Fig. 3 shows an original image of Oberpfaffenhofen. Especially the shadows at the edges of the woods are visible very well. Fig. 4 shows the resulting height map. The estimated heights show a high correlation with the expected ones.

Figure 3: *Original SAR image of Oberpfaffenhofen, Germany. The azimuth (flight) direction goes from left to the right and the range direction downwards.*

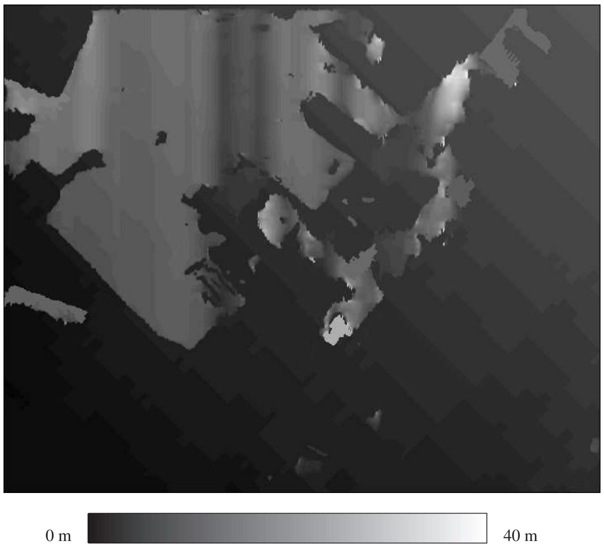

Figure 4: *Resulting height map*

Fig. 5 shows a sample view of the generated 3D model. The wood in the foreground is the same as at the left margin of Fig. 3. A good match between texture and 3D mesh can be observed. Some buildings have not been reconstructed correctly due to the fact that the shadows couldn't been separated from the streets behind the buildings. The woods and most of the single trees have been segmented correctly and thus they are reconstructed very well.

In Fig. 6 a closer view of the building in the upper right corner of Fig. 3 can be seen. Fig. 7 shows the 3D mesh of the same region. Due to the coarse grid of the 3D mesh the 3D shape of the building is not approximated as good as in Fig.4.

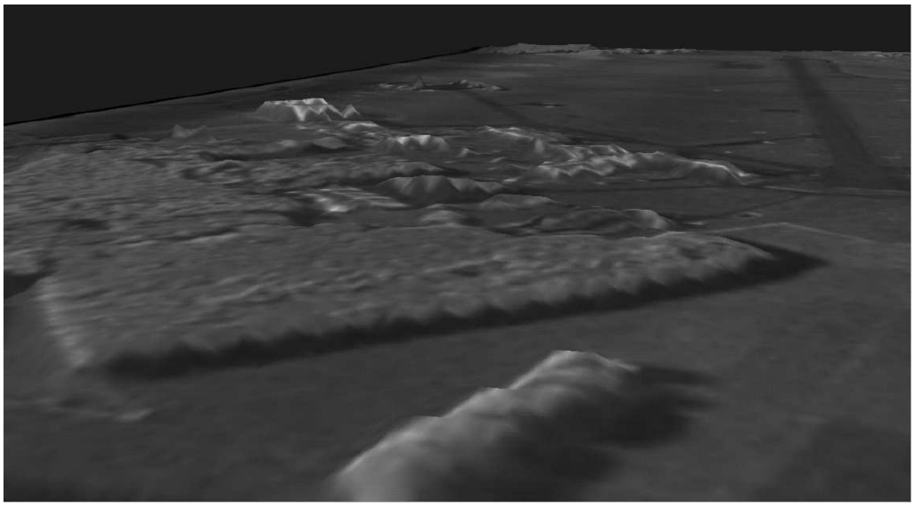

Figure 5: *Visualization of the generated 3D model*

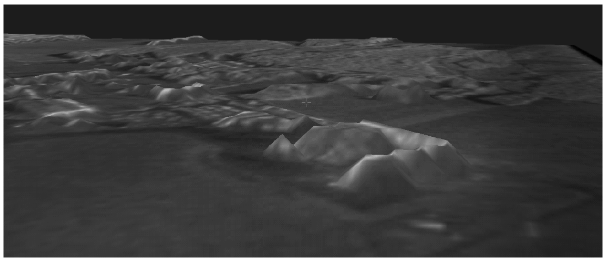

Figure 6: *Reconstructed buildings*

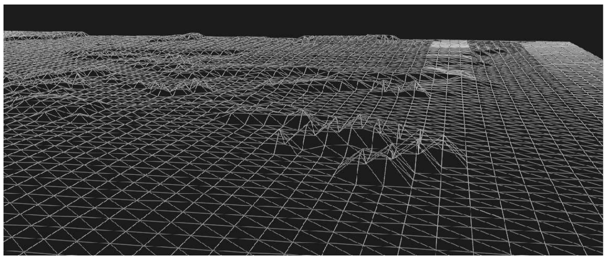

Figure 7: *3D mesh of the same region as in Fig. 6*

6 Conclusions

An algorithm for 3D reconstruction of buildings and vegetation from SAR images has been presented. It evaluates the shadows behind such elevated objects which have been segmented in the image. After assigning the shadows to suitable elevated objects, it is possible to calculate the heights of the elevated objects from the radial shadow lengths, the height of the ground and the system parameters. The wrong positions of elevated objects in SAR images are corrected. The corrected image serves as texture for a 3D model of the landscape which is generated using the estimated heights.

The estimated heights show a high correlation with the expected ones. The resulting 3D model gives a realistic view of the landscape including buildings and vegetation. An even more realistic view can be achieved by inserting separate detailed trees and buildings from a computer graphics library at the places of these objects in the 3D model.

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