Robustness of Wavelet-Based Stereo Matching for Variable Acquisition Geometries Using Simulated SAR Images

A. Schubert, D. Small, E. Meier, D. Nüesch

Remote Sensing Laboratories, University of Zürich; Winterthurerstrasse 190; CH-8057 Zürich; Switzerland

Tel: +41 1 635 6523 FAX: +41 1 635 6842, Email: {schubert,daves,meier,nuesch}@geo.unizh.ch

Abstract - **It has been shown that Digital Surface Models (DSMs) generated using stereo SAR can be used to ease the phase-unwrapping process during interferometric height model generation. In addition, wider availability of combined stereoscopic and interferometric coverage generated by air- and spaceborne sensors makes the combined use of the two techniques more feasible.**

This paper describes a series of experiments whereby different stereo acquisition geometries were simulated for an airborne X-band SAR sensor. The product of such a simulation, taking the topography, flight geometry, and local illuminated area into account, is a pair of amplitude images in slant range geometry. The use of such simulations allows rigorous control of error sources. A phase-based, multi-resolution image-matching technique built on the discrete wavelet transform is used to measure the parallax field between simulated image pairs, and a geocoded height map is generated in each case. The robustness of the matching algorithm across variable sensor configurations is thereby determined.

Same-side stereo geometry is assumed, as is a typical airborne flight height of 2.8km. Matching accuracy and the subsequent height accuracy of the DSMs are evaluated by varying the sensor incidence angles and stereo intersection angle. The optimal flight geometry for a test area in Switzerland is determined.

I. INTRODUCTION

The motivation for pursuing the integration of stereo within an InSAR framework is to overcome the weaknesses of the latter method, namely:

- Ground control points (GCPs) are required for interferometric **phase calibration**.
- InSAR topography estimation requires a delicate **phase-unwrapping** step, which can be greatly aided by an existing low-frequency DSM.
- Areas of **low coherence** in interferograms, especially due to temporal decorrelation during multi-pass InSAR or vegetation presence, are topographically unresolvable or provide unsatisfactory height estimates.

Although a stereo DSM will not provide nearly the height resolution of an InSAR DSM, InSAR processing can benefit from the availability of a low-resolution DSM.

II. STEREO PROCESSING CHAIN

A series of experiments were performed, each involving the following steps:

- Simulation of a SAR image stereo pair
- Coarse mapping of slave into master geometry
- Disparity field (parallax) estimation
- Generation of a geocoded height map, or Digital Surface Model (DSM)

The goal of this study was to produce a DSM for various acquisition geometries, and to evaluate the results. During all experiments, the sensor parameters such as central frequency and pulse repetition frequency (PRF) were held constant. Also, the sensor flight height was fixed at 2.8km, and the same test site was used for all image pairs. In this way, the results are not only comparable directly with one another, but also with those obtained using an existing SAR image pair that was acquired in 1999 over the same area by an airborne sensor with similar properties, also flown at an altitude of 2.8km.

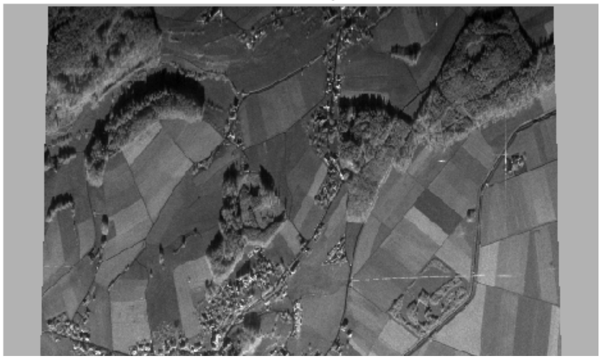
The stereogrammetric processing consists of the disparity estimation, or matching, and its subsequent conversion to heights in a map geometry by simultaneously solving the range-Doppler equations for the stereo pair.

A. Image Simulation

The height model used to simulate (and validate) the results was obtained using the single-pass airborne DoSAR InSAR system from Dornier [1]. Fig. 1 shows the DoSAR height model for the test site, an area in the Swiss midlands north of Berne. The three raised forms are forest stands. The radiometric SAR image simulator [2] was used to create stereo pairs with the desired geometric properties. As can be seen in Fig. 2, the largest

Fig. 1. The DoSAR reference digital surface model [m]

Real image



Simulated image

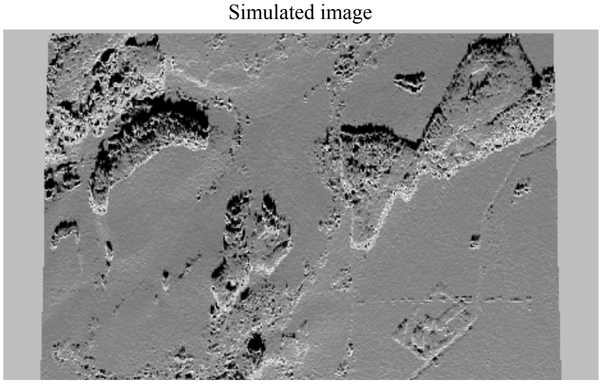


Fig. 2. Real image and simulation of the same scene

difference between the real and simulated images is the lack of information in areas where the backscatter depends on the surface characteristics. This is to be expected, since the DoSAR DSM contains no information about the landcover types. In spite of this, the matching algorithm was observed to work well even in image areas with few prominent features or textural variations.

B. Disparity Field Estimation

The matching approach used during this work was first outlined by H-P. Pan in 1996 [3], known as *uniform full-information image matching.* At its core is a wavelet multiresolution decomposition of the image. A complex discrete wavelet transform using Magarey-Kingsbury wavelets [4] is calculated for the pair, which produces lossless representations of the images at multiple resolution levels. Initial tests using this matching algorithm were promising [5]. For a given homologous pixel pair, the 3-D position in Swiss map coordinates is calculated as described in [5]. The resulting geocoded DSM is then compared to the DoSAR height model used to generate the simulated images, allowing direct evaluation of its quality.

III. RESULTS AND DISCUSSION

The choice of incidence angle θ and difference between θ_1 and θ_2, called the stereo intersection angle, has long been a matter of debate. It has been shown, for example in [6], that the decision should also take the type of terrain relief into account. For a given terrain-height variability, the choice of the geometric parameters is critical in determining the quality of the resulting DSM. Six same-side geometries were simulated for the Küttigkofen test site, using sensor parameters similar to the AeS sensor described earlier. Three simulations involved varying the incidence angle for both sensors together (parallel beams with overlapping footprints). For the other three, the incidence angle of one sensor was held fixed while that of the second sensor was varied. The absolute sensor positions were chosen such that the desired combination of incidence angles was met for constant and equal sensor heights, while centering the overlap between the sensor footprints (the stereo window) on the test area. In particular, the three forest stands are visible in all of the output DSMs. The simulations assumed idealized flight conditions, that is, the flight tracks were perfectly parallel, and the squint angle was zero (zero-Doppler simulations).

As a control, a real pair for the same test area, obtained using the X-band AeS airborne sensor [5] being simulated, was also used to extract a stereo DSM. This was compared to the result obtained by simulating the same scene, this time without the zero-squint and parallel-track simplifications.

The typical output DSM size of approximately 1.3km $\times$ 2.6km contained 845000 pixels, each 2.0m on a side. Each DSM obtained was compared to the DoSAR model and error statistics were calculated for the entire image. Table 1 summarizes these statistics for the geometric configurations simulated, as well as for the DSM obtained using the real AeS amplitude pair. The results indicate a clear preference for intersection angles at mid-scene not exceeding about 17°, while sensitivity to the incidence angle alone is lower. The best result was obtained for the case of two 42° incidence angles, resulting in a mid-scene intersection angle of 10.5°. Bringing the incidence angles down to 27° or up to 57° produced results with similar accuracies, although the 27° case was slightly better, probably due to the lower mid-scene intersection angle naturally resulting from lower overall incidence angles. For the best case of 42° each, the difference between the obtained DSM and the DoSAR DSM is shown in Fig. 3. The major source of error is clearly due to regions of radar shadow behind the forest stands; the heights assigned to the shadows are nearly equal to the forest stand height at the upper edge. This is to be expected, since shadow regions are matched to each other radiometrically. There are also two smaller areas of height underestimation caused by a mismatch due to strong local shadow and foreshortening effects in these parts of the treetops.

IV. CONCLUSIONS AND OUTLOOK

The quality of a DSM generated by stereo matching is heavily dependent on the quality of the match, i.e. the measured parallax between the images. For any given matching algorithm, a compromise between two criteria must be met: (a) increased image similarity improves the match quality, and (b)

TABLE 1: GEOMETRIC CONFIGURATIONS AND RESULTING STEREO-DSM ERROR STATISTICS

Experiment	Incidence angle 1 [°]	Incidence angle 2 [°]	Intersection angle at mid-scene [°]	Mean height error (Stereo DSM - DoSAR DSM) [m]	Standard deviation [m]	Pixels with < 5m error [%]	Pixels with < 10m error [%]	Pixels with < 20m error [%]
Variable incidence angle (2-image simulations)	57	57	17.0	4.3	10.2	75.5	84.5	92.2
	42	42	10.5	**0.1**	**4.0**	**90.9**	**96.3**	**99.2**
	27	27	8.5	-0.6	6.6	77.6	87.3	97.9
Variable intersection angle at mid-scene (2-image simulations)	37	27	12.9	-2.0	8.1	78.6	86.6	94.9
	47	27	25.7	-4.0	10.5	63.5	75.2	88.6
	57	27	38.1	-6.3	13.1	48.2	66.8	83.5
Real pair	42	42	10.5	3.6	8.1	57.3	82.1	94.9
Simulation of real pair (same geometry and squint)	42	42	10.5	1.0	4.4	88.0	95.2	99.1

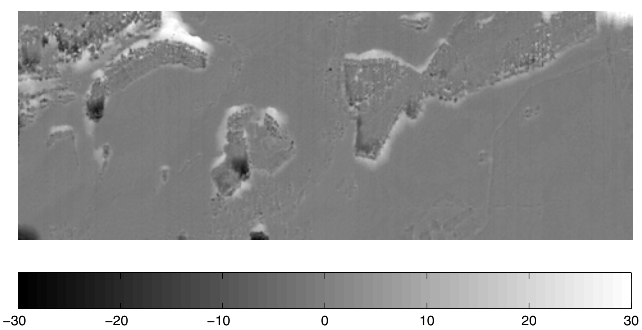


Fig. 3. Difference between obtained DSM and DoSAR DSM for best-case result of two 42° incidence angles [m]

increased dissimilarity increases the relief information inherent in the pair. Clearly, the wavelet-based matching approach used during these experiments produces the best matches - and hence the best DSMs - when this compromise tends more towards image similarity as opposed to dissimilarity. This implies rather small intersection angles, which maximizes the similarity, and incidence angles of approximately 45°, providing sufficient parallax without extreme range-dependent object distortions.

The measured accuracy of the real-pair DSM was somewhat lower in comparison to the equivalent simulated case. The source of this difference may be partly the quality of the match, which was less "clean" than that obtained for the simulated pair. A further reason is the fact that the DoSAR DSM, used to generate the simulations, was also used for the real pair as a reference. The error statistics generated for the real-pair DSM are the only ones that also measure the errors in the DoSAR DSM with respect to the true topography imaged, which can be as large as approximately 1m or more over forested areas [5]. The simulations do not include this error source; their mean differences, as measured against the DoSAR DSM, are therefore smaller.

Further experiments are planned, whereby non-zero track-crossing angles and possibly opposite-side stereo cases will be simulated, for the test site described here, as well as another site with more mountainous terrain. In addition, the matching algorithm will be applied to simulated spaceborne image pairs, perhaps similar to those obtainable by the newly-launched ENVISAT ASAR instrument. The stereo processor will be integrated within a larger InSAR processing chain, where the stereo DSM will be used as input to the phase-flattening process.

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