MULTISENSOR MAPPING USING SAR IN CONJUNCTION WITH OPTICAL DATA

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ABSTRACT

In the nineties, operational SAR satellites like ERS-1, JERS-1 or Radarsat will provide microwave image data. Simultaneously, existing and future satellite missions will acquire optical image data. This paper focusses on the feasibility of stereo fusion of SAR and optical image data, which is difficult due to the different radiometry of the images. A first experiment on multi-sensor stereo mapping using the RSG software package to combine a multi-parameter airborne SAR image with a SPOT HRV image of mountainous terrain in the Austrian Alps is presented. Basic steps and results of 3-D data extraction from this image pair and subsequent quality control are illustrated.

KEYWORDS: SAR, Optical, Image-Matching, 3-D, Mapping

1 INTRODUCTION

A multitude of remote sensing images of our planet is acquired in various remote sensing missions. Due to the wide diversity of sensor systems and user applications a need arises to merge and analyse image data from multiple sensors. For instance, major cartographic objectives are the geocoding of remote sensing images *to* or the extraction of 3D topographic information from stereo pairs *in* a defined reference system. An exact relation between image data and ground data is only possible if *parametric mapping models* and *cartographic transformations* are considered and if - in the case of image geocoding - digital elevation models (DEMs) are integrated (Raggam 1990, [7]).

Many studies can be referred to concerning the analysis and treatment of optical scanner images like SPOT, Landsat or others. Concerning stereo mapping, a representative reference is given by Day and Muller (1988, [2]). Also SAR image pairs are exploited for 3D data extraction using photogrammetric approaches (Raggam et al., 1989 [6]), SAR shape-from-shading (Thomas et al., 1991 [11]) or SAR interferometry (Hartl, 1991 [4]). First experiments combining images from different optical sensors for stereo mapping are reported by Welch et al. (1990, [12]) or Raggam and Almer (1991, [9]), both combining a SPOT and a Landsat TM image (more or less having the same imaging geometry) to a stereo model.

In order to further investigate the potential of multisensor stereo pairs, an experiment has been carried out combining a SPOT image with an aircraft SAR image to derive 3D topographic information. A prerequisite for this objective is the availability of software, which is capable to treat different image data sets through the simultaneous consideration of the respective parametric mapping models. It should allow to arbitrarily combine the mapping models of any image pairs to achieve a high degree of geometric accuracy as possible for the location of individual ground features.

The multisensor experiment described in this paper makes basic use of the *R*emote Sensing *S*oftware Package *G*raz *(RSG)*, which has been developed by the Institute for Image Processing and Computer Graphics (DIBAG) and incorporates many years of experience in the geometric treatment of non-photographic data. This software package follows the requirements stated above and can treat the majority of digital images available today through the integration of the mapping models of optical and microwave scanner images, but also of central perspective images getting spread in digital photogrammetry.

2 ALGORITHMIC ASPECTS

The ultimate prerequisite for multisensor stereo image analysis is the algorithmic fusion of such data through the integration of the respective parametric mapping models, which have to be used when relating the ground coordinates of a target point to the corresponding image pixel coordinates. These models are comparably simple and well known from photogrammetry for perspective geometry, whereas more complex algorithms are required for dynamically scanned images from either active or passive sensors. For these, the continuous movement of the sensor along a curved orbit has to be considered. An overview of the mapping models for perspective images as well as for optical and SAR scanner images is given in Raggam and Almer (1990, [8]).

2.1 Stereo Model Set-up

Concerning any mapping applications aiming at high geometric accuracy, a methodology to determine or refine individual parameters of the mapping models based on ground control points (GCPs) is an essential tool. Therefore, an appropriate procedure has been developed at DIBAG, following the philosophy of photogrammetric bundle adjustment techniques and accepting images having any of the imaging geometries mentioned above.

For the respective images to be treated the parameters of the imaging models first have to be initialized with reasonable values. After this initial step the mapping equations of an image on the one hand contain image pixel coordinate measurements of target points and, on the other hand, approximately known mapping parameters. For these the best fitting increments have to be determined. An overdetermined equation system usually is achieved by a sufficient number of GCPs, each contributing 2 equations. Following least squares adjustment techniques, a proper Taylor series expansion of the mapping equations results in a modified linear system to determine the mapping parameter increments.

Within the adjustment procedure arbitrary parameter subsets of line scanner geometry, SAR geometry or perspective geometry may be selected for an image to be optimized. This procedure may be applied to both stereo-partners seperately, but also in a simultaneous adjustment combining the mapping equations for both stereo partners. In the latter case, homologue points measured in both images can be used beside control points to contribute additional conditions to the equation system.

2.2 Stereo Mapping Procedure

A scheme for automated (multisensor) stereo mapping as it is realized in the *RSG* software package is shown in Figure 1. As illustrated, stereo mapping purposes need the image data to have the same geometric properties. In case that the input images are different in orientation and pixel resolution, which in particular is the usual case for multisensor image data, a preparatory relative registration of one stereo partner using a linear pixel transformation *(epipolar resampling)* has to be done.

In a next step, points have to be matched and measured in the stereo pair. In contrast to the algorithmic fusion of multisensor image pairs, which is possi-

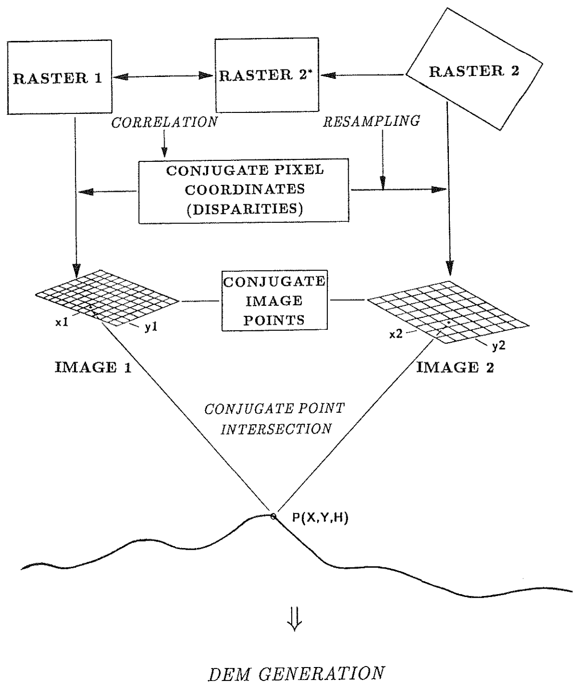

Figure 1: Scheme of automated stereo mapping

ble provided the respective imaging models are implemented (Raggam and Almer, Refs. [8], [9]), the human and especially machine stereo fusion of multisensor stereo data may cause severe problems. Concerning the automatic matching of multisensor image data, the great variety of sensors with their different characteristics needs to allow *digital image correlation* in both the spatial and the fourier domain. Beside product-moment correlation or phase correlation, also a hybrid approach combining grey-level based matching methods with feature based methods as suggested by Paar and Pölzleitner (1991, [5]) should be considered. The a-priori definition of candidate points where correlation shall be performed or the determination and neglection of badly correlated points are further essential tools.

To convert the output of the correlation step, i.e. the pixel coordinates of a point in both images of the stereo-pair, to three-dimensional information, a spatial stereo intersection of geometry-specific projection lines/curves has to be performed *(conjugate point intersection)*. Cartographic coordinates of the respective points in planimetry and height are determined in a least-squares intersection procedure based on sensor-specific imaging equations and imaging parameters (cf. Raggam and Almer, 1990 [8]).

Having three-dimensional point data available in a defined map projection, they may be used to *generate a digital elevation model*. This procedure is based on the triangulation of irregularly distributed points on ground, where the incorporation of break lines enables realistic shapes of the terrain to be achieved. A regular digital elevation model raster is obtained by a triangle-to-raster conversion, and minor raster roughness may be eliminated by raster smoothing based on various criteria.

3 SOFTWARE ASPECTS

The software package *RSG* (GEOSPACE and JOANNEUM RESEARCH, 1992, [3]) follows the requirements for multisensor image analysis and is based on algorithms as described in the previous section. It offers the possibility for geometric processing and output quality assessment of digital remote sensing data acquired from air- and spaceborne optical and radar sensor systems. Basic features of this software are:

- capability to treat different image data sets in multiple combinations with a high degree of geometric accuracy;
- use of parametric descriptions of the imaging geometry;
- integration of existing relief information represented by digital elevation models (DEMs);
- stereoscopic extraction of three-dimensional relief information and generation of DEMs therefrom;
- application of central perspective, line scanning, and circular projection data (SAR) in any combination, including stereo and multisensor data.

RSG is modular and hardware-independent in design and can, therefore, easily be adjusted to the individual user's requirements. Its modular structure allows the user to start with a minimum configuration and add additional modules, as required. The hardware-independent design permits the installation on PCs, workstations and mainframe computers. It has to be regarded complementary to a conventional image processing system (IPS) or geographic information system (GIS), but it comprises well-defined interfaces, which facilitate its integration into or communication with such systems. The basic modules of the software can be summarized as follows:

General Software: *Data management* software modules are available for the handling of images and points within individual tasks/projects or to serve as data import/export software interfaces with most of the common image processing systems. Furthermore, *general point transformation* software takes care of the cartographic transformation of points. Modules for the *set-up of an initial mapping model* as well as for the *optimisation of the imaging model* by means of an adjustment procedure cover major functionalities of the package. The definition of a *polynomial transformation* (registration) is also possible.

Geocoding: Beside the conventional *polynomial rectification*, which may be applied to any type of input and output coordinates, the software for the DEM-based *geocoding* is implemented for the three major remote sensing imaging geometries. Modules for *quality control* allow the calculation of statistical parameters of the rectified image product and various graphic presentations such as residual vector plots.

Stereo Mapping: This software subpackage covers modules for *control point and tie point administration* and for *parameter adjustment/optimisation* for a stereo-model. This provides the basis for a subsequent *stereo correlation* to find homologue image points and for the *stereo intersection* to calculate their corresponding ground coordinates. *Quality control* programs enable to check the performance of the stereo mapping model as well as the correlation output.

DEM Generation: A *triangulation* procedure is applied to irregularly distributed points. After the optional integration of break lines a digital raster elevation model can be generated by *triangle-to-raster conversion*, and finally *raster smoothing* can be pursued.

Bundle Adjustment: Modules related to this subpackage handle the imaging models and points for a block of images. A combined optimisation of the imaging models by means of an adjustment procedure as well as *quality assessment routines* equivalent to the single image or stereo-model set-up procedure are included.

4 DEMONSTRATION EXPERIMENT

4.1 Multisensor Stereo Data

For the first time, an experiment was carried out to generate a DEM from a multi-sensor stereo model combining a microwave SAR image and an optical SPOT line scanner image, which have quite different radiometry. The high-mountaineous glacier region Oetztal in the Austrian Alps with terrain heights ranging from 1745 up to 3768 meters, which has been subject to various previous studies, was also the test area for this experiment. For such high relief terrain the potential of (multi-sensor) stereo mapping is of particular interest. For this area,

- a **multispectral SPOT 1 HRV-2 image**, having a nominal pixel size of 20 meters and a sensor off-nadir look angle of about 22.7 degrees and

- a **NASA multifrequency polarimetric airborne SAR image**, having a pixel resolution of 12.1 m in azimuth and 6.66 m in range direction (slant range geometry), a flying height of about 8200 meters and a SAR look angle of some 37 degrees in near range

were linked to a multisensor stereo pair. The stereo configuration of this image pair, combining crossing flight paths of optical line scanner geometry and microwave circular imaging geometry, is schematically shown in Figure 2. This complex arrangement yields images which - beside radiometry - are very different in their geometric properties. This in particular applies to mountain foreslopes being very compressed or even overlaid in the SAR image for this high-mountain test area.

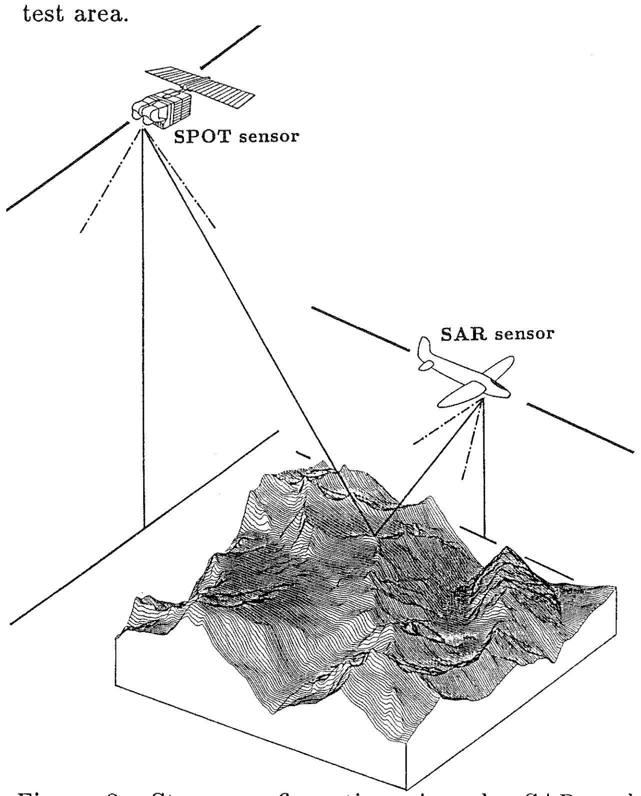

Figure 2: Stereo configuration given by SAR and SPOT image acquisition geometry.

4.2 A-priori Stereo-Mapping Accuracy Assessment

High-precision geometric treatment of multisensor data requires a number of precise GCPs, which have been measured in the input images and in a topographic 1 : 25 000 map. They were used to determine sensor-specific mapping parameters and, moreover, to optimize these parameters in a least-squares parameter adjustment as described in section 2.1.

To evaluate an a-priori stereo mapping accuracy for the SAR - SPOT stereo model the epipolar lines defined by common GCP pixel coordinates may be intersected to determine coordinates on ground, which subsequently can be compared to the measured coordinates of the GCPs. The respective statistical values of the resulting coordinate differences, like minimum-, maximum- or RMS-residuals, are given for that model in Table 1. A graphic presentation of the residuals is given in Figure 3, showing a composite vector plot of planimetric and height residuals.

TABLE 1
Statistics of residual errors on ground for the SAR - SPOT stereo model.

	East	North	Height
$\vec{r}_{min}$	-21.1	-21.9	-34.9
$\vec{r}_{\|min\|}$	1.4	0.3	0.5
$\vec{r}_{max}$	23.0	20.7	43.9
$\vec{r}_{avg}$	0.0	0.1	0.4
$\vec{r}_{sd}$	11.0	12.9	21.1
$\vec{r}_{rms}$	10.7	12.5	20.5

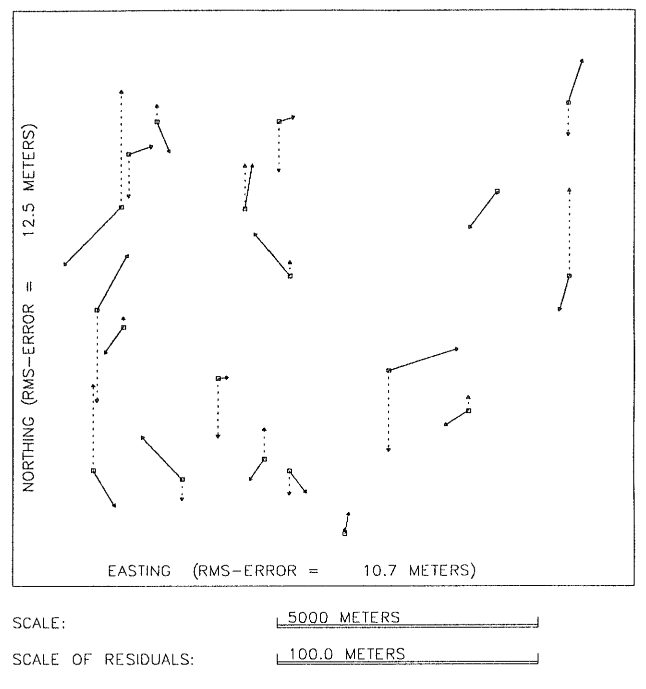

Figure 3: Composite residual vector plot showing planimetric errors (solid lines) and height errors (dotted lines) for the SAR - SPOT stereo model.

Table 1 shows a good accuracy in particular in planimetry, but also in height. However, this a-priori accuracy is estimated using well defined control points, and a comparable accuracy presumably will not be achieved in operational stereo mapping based on these multisensor image data, because there homologue image points have to be measured all across a scene also in more critical areas.

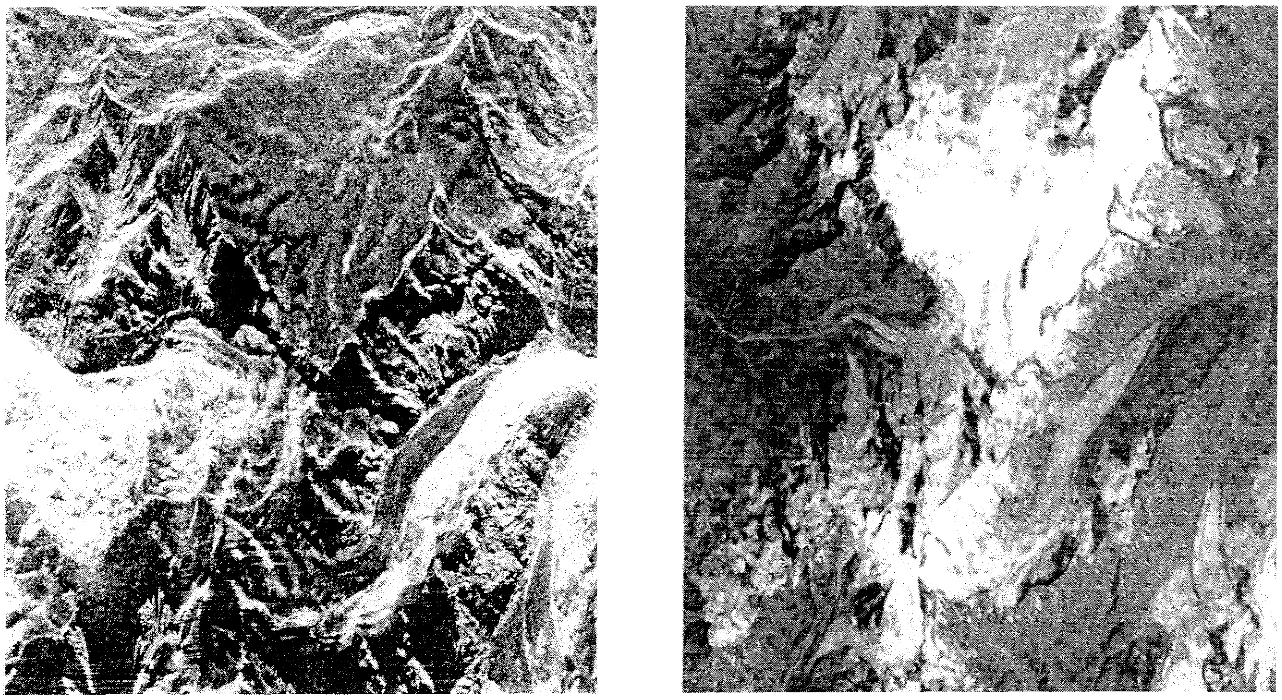

Figure 4: Aircraft SAR (left) and resampled SPOT XS (right) input images.

4.3 DEM Generation

Following the procedure described in section 2, a preparatory *epipolar resampling* of the SPOT XS image to the geometry of the SAR image was carried out in order to achieve an image pair which corresponds in its geometric properties except effects depending on terrain topography. As can be suspected from Figure 4 showing the resulting image pair, this specific stereo model still can be considered to represent a kind of worst case in the context of multisensor stereo mapping.

For this experiment the measurement of corresponding image points was done interactively using a proper display tool for a parallel measurement of coordinates in the images shown above. A stereoscopic measuring mode might have provided a better performance for individual parts of the stereo model, although real human stereo fusion more or less is prohibited by the radiometric image differences in most areas. In order to derive a global shape of the terrain, some 500 points could be measured interactively, mainly being located along drains and terrain ridges.

In the next step, epipolar lines, defined by the coordinates of the correlation points, were intersected in order to calculate cartographic coordinates of the points in planimetry (easting, northing) and height. Using again the RSG software package a triangulation procedure was applied to the input data. Thereby, interpolation lines were defined along terrain ridges to optimize the triangulation result. Triangle-to-raster conversion and subsequent raster smoothing were applied to achieve a raster DEM for a sub-area of 10.5 by 8 kilometers, which is shown in Figure 5 in an oblique view from south. For comparison, a reference digital elevation model is available for the Oetztal test area, which has been derived from topographic 1 : 25000 maps with an initial pixel spacing of 12.5 meters. Figure 6 shows the equivalent frame of the map-derived DEM. Contour line plots of these DEMs are shown in Figures 8 and 9, respectively.

For a quality assessment of the achieved DEM the software package RSG offers a direct comparison of DEM raster files. Hence, the individual heights of the stereo-derived DEM were directly compared to the reference DEM data. The resulting difference DEM is shown in Figure 7. Statistical parameters of the height difference have been calculated, which are summarized in Table 2. In comparison to Table 1 these values are rather large, showing a standard deviation of 60 meters, and minimum and maximum differences of - 223 and + 269 meters, respectively. Besides, a systematic shift of the stereo-derived DEM is expressed by a mean value of 42 meters.

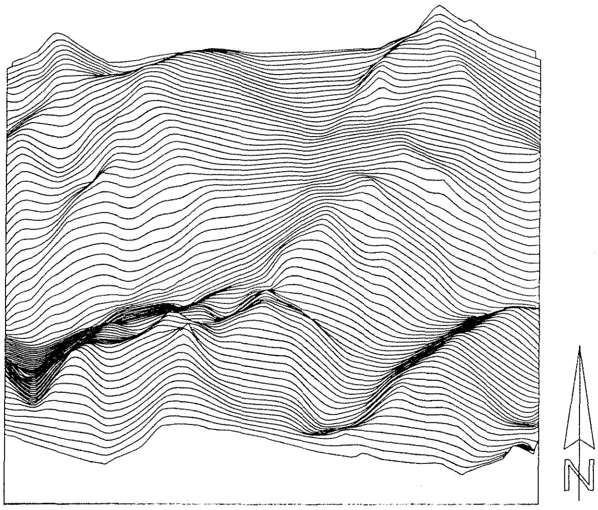

Figure 5: Axonometric oblique view of the stereo-derived DEM.

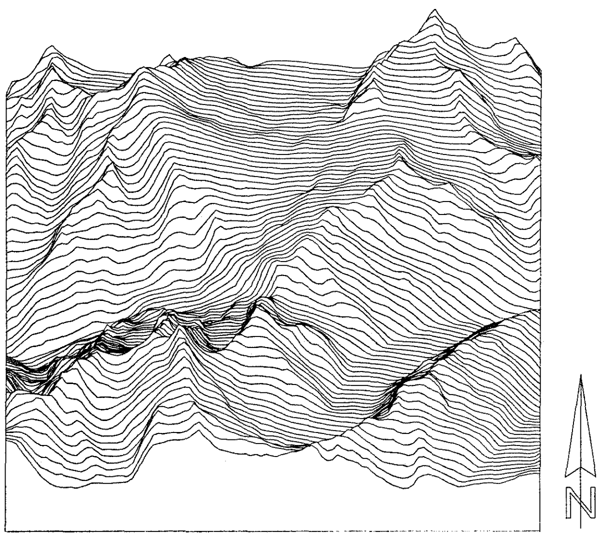

Figure 6: Axonometric oblique view of the map-derived DEM.

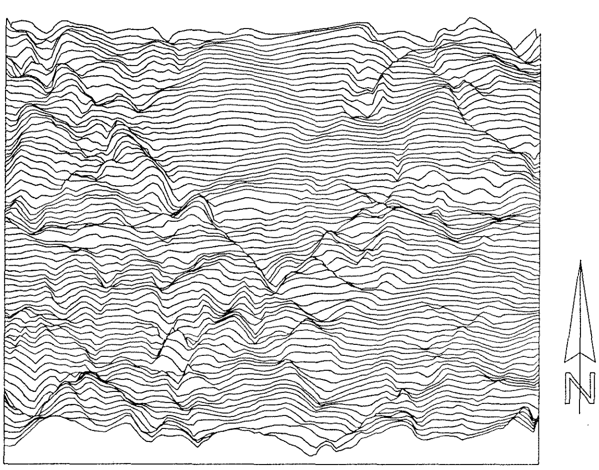

Figure 7: Axonometric oblique view of the difference DEM.

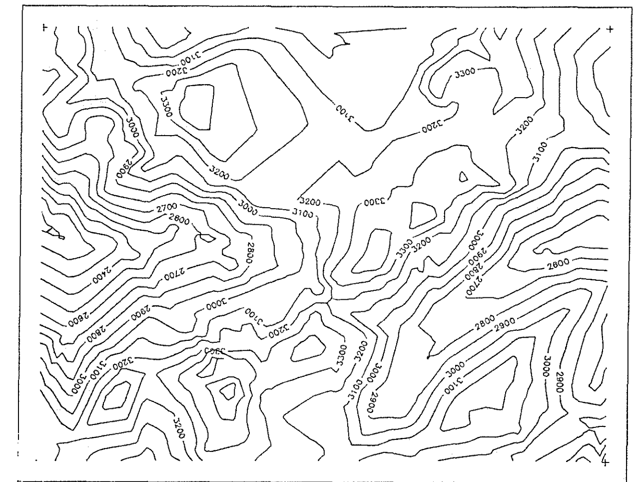

Figure 8: Contour line plot of the stereo-derived DEM (contour interval 100 m).

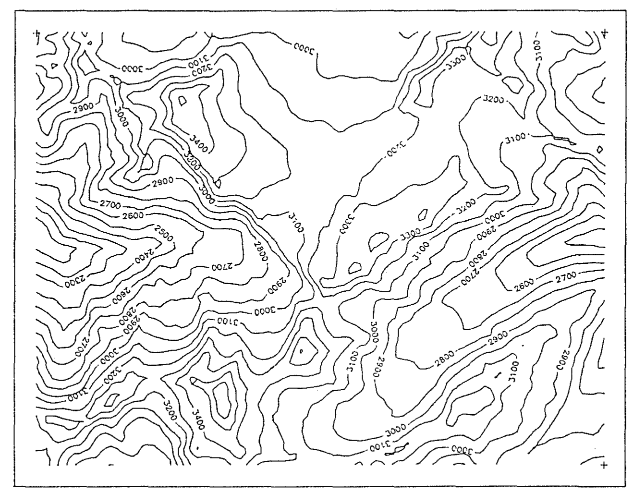

Figure 9: Contour line plot of the map-derived DEM (contour interval 100 m).

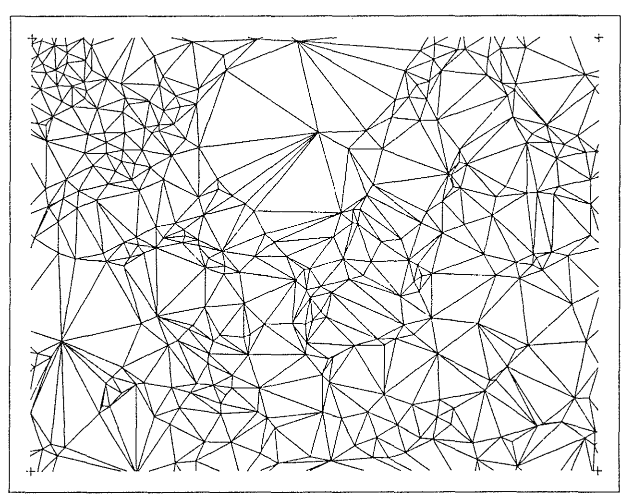

Figure 10: Triangulation intermediate product.

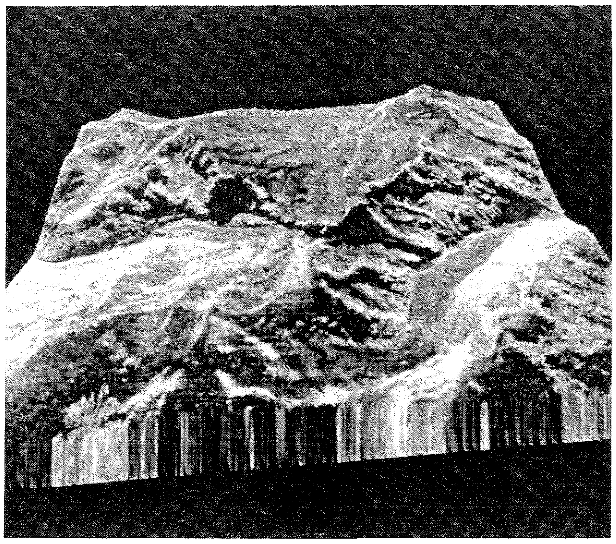

Figure 11: Superposition of stereo-derived DEM and SAR image data.

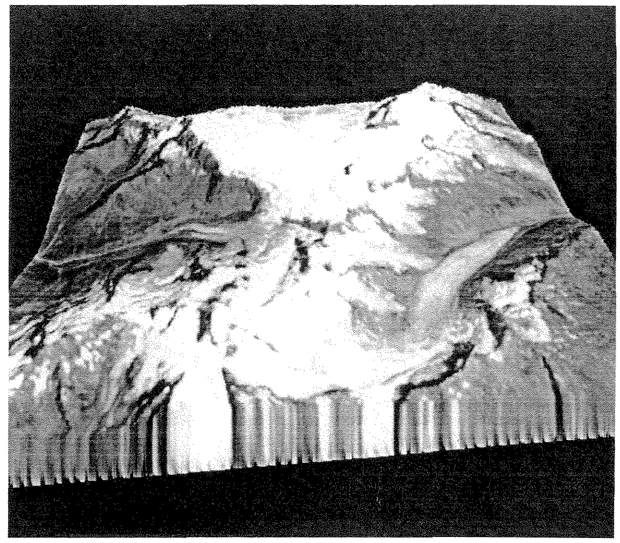

Figure 12: Superposition of stereo-derived DEM and SPOT image data.

This can be explained by the fact, that for certain areas of the terrain no stereoscopic measurements could be made due to shadows or layover in the SAR image or general radiometric homogeneity (cf. Figure 4). There, the triangulation procedure may bridge over whole valleys and drain areas (the more frequent case) or cut terrain ridges. This can be verified by a comparison of contour line plots and the triangle net plot shown in Figure 10. For a quality assessment of the pure multisensor mapping performance such areas should not be considered. Then, the statistics given in Table 2 might be significantly improved.

TABLE 2
Statistical parameters for elevation model differences.

Minimum difference	.....	- 223 m
Maximum difference	.....	+ 269 m
Mean difference	.....	42 m
Standard deviation	.....	60 m

Finally, the stereo-derived DEM has been used to generate geocoded image frames of this area using state-of-the art image rectification techniques (Almer et al., 1991 [1]). An illustration of these image products is given in Figures 11 and 12, showing a superposition of the terrain shape with the image information of the input images.

5 CONCLUSION AND OUTLOOK

For the high alpine testsite Oetztal a multi-sensor stereo mapping experiment has been carried out using an optically scanned multispectral SPOT image and an airborne SAR image. The high geometric performance of this stereo model, determined by the imaging arrangement, by far is decreased by the enormous radiometric differences between the optical and the microwave image. These, moreover, are increased by imaging peculiarities of the SAR image like shadow or layover effects.

Using well defined control points a (theoretical) stereo mapping accuracy was evaluated for this stereo pair, resulting in RMS accuracies of some 15 meters in planimetry and about 20 meters in height. An experiment was carried out to derive a DEM from this multisensor stereo pair, where stereoscopic image point measurements were made interactively. Due to the difficulties mentioned above, this is rather tedious and even impossible in particular in homogeneous areas like shadows, snow fields or glaciers. Although very dense measurements could not be made, it was possible to derive a DEM which globally corresponds quite good to the real shape of the terrain.

For further comprehensive studies concerning multisensor stereo mapping a larger selection of image data, in particular regarding SAR images, is required. Investigations into automated image correlation using such image data will be a major scientific objective. Sasse (1989, [10]) has shown that stereo fusion of such data is feasible provided that appropriate correlation algorithms, filter algorithms and stereo partners, i.e. spectral bands, are selected. However, as shown in this experiment, it is difficult if not impossible even for the human eye to match multisensor images covering *high-mountain* terrain. Presently, for such data interactive work is still superior to automation, which seems to be rather distant from operational realization.

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