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SPOT stereo matching for DTM generation

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ABSTRACT

This paper presents a matching algorithm for automatic DTM generation from SPOT images that provides dense, accurate and reliable results and attacks the problem of radiometric differences between the images. The proposed algorithm is based on a modified version of the Multiphoto Geometrically Constrained Matching (MPGC). It is the first algorithm that explicitly uses the SPOT geometry in matching, restricting thus the search space in one dimension, and simultaneously providing pixel and object coordinates. This leads to an increase in reliability, and to reduction and easier detection of blunders. The sensor modelling is based on Kratky's polynomial mapping functions to transform between the image spaces of stereopairs. With their help epipolar lines that are practically straight can be determined and the search is constrained along these lines. The polynomial functions can also provide approximate values, which are further refined by the use of an image pyramid.

Radiometric differences are strongly reduced by performing matching not in the grey level but in gradient magnitude images. Thus, practically only the information in stripes along the edges is used for matching. Edges that exist in only one image can be detected by subtracting quasi registered images in the upper levels of an image pyramid. The points to be matched are selected by an interest operator. Gross errors can be detected by statistical analysis of criteria that are provided by the algorithm and by a robust analysis of the heights within local neighbourhoods.

The results of an extensive test using a stereo SPOT model over Switzerland will be reported. Matching with different options and the qualitative comparison of the results based on thirty thousand check points will be presented.

1. INTRODUCTION

The motivation behind this research was the aim to improve matching of SPOT images by integration of the sensor geometry and the treatment of radiometric differences. As far as the authors know, none of the published matching methods explicitly exploits the SPOT geometry to restrict the search space. Since SPOT does not have a perspective geometry in flight direction, accurate epipolar images can not be generated without the use of a DTM and thus the existing matching algorithms perform a 2-D search. The authors investigated Kratky's polynomial mapping functions (PMFs) (*Kratky, 1989a*) which transform from image to image, image to object and object to image space. For the computation of the coefficients of the PMFs the results of a rigorous bundle adjustment are used. The PMFs are much faster and almost equally accurate as the rigorous transformations. When the ray of an imaged point is projected by using the PMFs onto the other image of a stereo pair (epipolar line) it is with a very good approximation a straight line. If a straight line is defined by the projection of a small ray segment which is centred at the correct point position in object space, then the deviation of the epipolar line from the straight line would be 0.25 pixel for a height error of more than 7 km. Thus, the aforementioned straight line can be used as a quasi epipolar line. More details on the characteristics of the PMFs can be found in *Baltsavias and Stallmann, 1992a*.

Attempts to circumvent the problem of radiometric differences have concentrated on using images acquired within a short time interval. However, this is difficult to achieve and does not solve the problem. The along-track stereo will strongly reduce these problems but can not eliminate them due to different perspective views, clouds and occlusions. Fusion and matching of multitemporal and multisensor data, as in change detection applications, will retain their importance even in the era of along-track stereo. Thus, the authors decided to attack this problem, which has been up to now treated only to a limited extent. The idea is to use gradient magnitude images, thus eliminating radiometric differences in areas of low texture. Preliminary investigations have shown that the majority of the edges remain stable. However, different edges exist due to clouds, shadows, different perspective views, new edges within fields due to agricultural activities, human intervention, water level, snow coverage, changes in the tree canopies etc. (Figure 1). A method should be developed to try to detect the different edges.

A third aspect of our research was the development of algorithms for the automatic detection of blunders.

Figure 1. Radiometric differences due to agricultural activities (left pair) and due to clouds and shadows (right pair).

2. TEST DATA

A stereo SPOT panchromatic level 1A model over W. Switzerland was acquired. The inclination of the sensor's optical axis was 23.4° R and 19.2° L respectively, leading to a B/H ratio of ca. 0.8. The acquisition dates were 20.7.1988 and 27.8.1988 with significant radiometric differences between the two images, particularly in agricultural areas. Figure 1 shows some typical image parts with large radiometric differences. The elevation range was 350 - 3000 m. The following preprocessing was applied to the original digital images:

- reduction of periodic and chess pattern noise
- Wallis filtering for contrast enhancement

136 control and check points were used with Kratky's rigorous SPOT model (Kratky, 1989b). 10 of the points were used as control points with a linear model of the attitude rates of change. The pixel coordinates were measured in one image manually and transferred to the second one by template matching. The RMS of the check points was 9 - 10 m in planimetry and 6 m in height.

3. MODIFIED MPGC

MPGC is described in detail in Baltsavias, 1991. It combines least squares matching (involving an affine geometric transformation and two radiometric corrections) and geometric constraints formulated either in image or object space. The constraints lead to a 1-D search space along a line, thus to an increase of success rate, accuracy and reliability, and permit a simultaneous determination of pixel and object coordinates. Any number of images (more than two) can be used simultaneously. The measurement points are selected along edges that are nearly perpendicular to the geometric constraints line. The approximations are derived by means of an image pyramid. The achieved accuracy is in the subpixel range. The algorithm provides criteria for the detection of observation errors and blunders, and adaptation of the matching parameters to the image and scene content.

In the case of matching of SPOT images the geometric constraints were formulated as follows. First, given a measurement point in one of the images (template image) a height approximation is needed. If the existing approximations refer to the pixel coordinates, then the height is computed by using the pixel coordinates in the reference image, the x pixel coordinate in the second image and the image to image PMFs. This height Z is altered by a height error ΔZ . Using the heights $Z + \Delta Z$, $Z - \Delta Z$, the pixel coordinates in the template image are projected by the image to image PMFs in the second image where they define the geometric constraints line. In the sequel, this quasi epipolar line will be referred to as epipolar line. The centre of the patch of the second image which is used for matching is forced to move along this line by means of a weighted observation equation of the form

$$v_c = (x + \Delta x) \cos \beta + (y + \Delta y) \sin \beta - p \quad (1)$$

where (x, y) the approximate pixel coordinates of the corresponding point in the second image and $(\Delta x, \Delta y)$ the unknown x- and y-shift.

Equation 1 is equivalent to the distance of a point $(x + \Delta x, y + \Delta y)$ (the patch centre of the second image) from a straight line. The epipolar line is expressed by the normal equation of a straight line, where p is the distance of the line from the origin and β is the angle between the perpendicular to the line and the x-axis.

If the patch of the second image does not lie on this line, then it jumps onto the line right in the first iteration. With our data, the epipolar lines are approximately horizontal, i.e. any error in the y-direction will be eliminated right in the first iteration. Since the epipolar lines are horizontal, the measurement points must be selected along edges that are nearly vertical in order to ensure determinability and high accuracy. Some advantages of the geometric constraints will now be presented. SPOT images include due their small scale a high degree of texture, i.e. edges. Measurement points lying along edges nearly vertical to the epipolar line can not be safely determined with other matching techniques, but with our approach they can as they lie at the intersection of two nearly perpendicular lines. Figure 2 illustrates such an example. Another usual problematic case is that of multiple solutions. With geometric constraints side minima can only result if they fall along the epipolar line. Figure 3 shows an example with and without geometric constraints.

Figure 2. Matching along edges without (left) and with (right) constraints. The epipolar line is the white line in the right image. The black frame is the initial position and the white frame with the black centre cross the final position.

Figure 3. Multiple solution matching without (left) and with (right) constraints.

4. DATA PREPROCESSING AND SELECTION OF MEASUREMENT POINTS

First, the gradient magnitude images are computed. To reduce weak edges due to noise, which is very noticeable in SPOT images, all gradients with a magnitude less than a threshold T are set equal to T . The threshold is selected as a function of the mean and the standard deviation of the gradient magnitude image (in this case $T = \text{mean} - \text{standard deviation}$). The same function should be used for both images to ensure equal treatment. The threshold should not be too high otherwise (a) useful texture is deleted, and (b) the edges are broken and significant differences between the two images occur due to different edge strength. This approach eliminates noise but also low texture which is however not very likely to lead to accurate matching results. An example is shown in Figure 4.

As already mentioned, the measurement points are selected along edges nearly perpendicular to the epipolar lines. In order not to reduce the number of the selected points too much (and thus their density, which influences the DTM accuracy), points along edges with an angle of $\pm 45^\circ$ with the perpendicular to the epipolar line should also be selected. To avoid clustering of good points a thin-out window for non-maxima suppression is defined. To reduce the selection of points lying at small and faint noisy edges the points are extracted in the first level of the image pyramid. Our approach is to match the same number of points in all pyramid levels. Thus, a selected point must have the aforementioned properties in all pyramid levels. Generally, the approach to be followed is to detect good points in all levels of the image pyramid of the template image and keep the points that appear in all pyramid levels. However, these SPOT images had a lot of texture and this was expressed in all pyramid levels. By going up in the image pyramid, the relative number of selected points was actually increasing.

Figure 4. Grey level image (left), gradient magnitude image (middle), thresholded gradient magnitude image (right)

To avoid selecting points at regions of radiometric differences, especially ones with a large area extent (like clouds), the following approach is used. Using the PMFs and an average height of the scene (derived either from a priori knowledge or from the average height of the control points used in the rigorous SPOT model), or a polynomial transformation derived from the pixel coordinates of the control points, the search image is registered with the template image. If the registration were perfect, a simple subtraction of the two images would give us the different edges. Since the registration is not perfect, an image pyramid is created so that at the highest level the misregistration error is within pixel range. Then through subtraction, the different edges are detected by binarising the difference image with an absolute threshold. This binary image can eventually be dilated in order to avoid selecting points whose patch would partially fall inside areas with radiometric differences. These disturbance areas are projected in all pyramid levels and convolved with the selected points in order to clean the selected points. An example is shown in Figure 5. With this method small radiometric differences cannot be detected.

Figure 5. Top row: left (left) and right (middle) SPOT image at 4th pyramid level and normalized difference image (right). Bottom row: binarized difference image (left), image with selected points (middle), image with cleaned selected points (right)

5. DERIVATION OF APPROXIMATIONS

After the PMFs are computed an average height is used in order to determine the position of the selected points in the search image. To check the quality of these approximations the 136 points were projected onto the search image by using an average height of 1000 m, and these pixel coordinates were compared to the known ones. The RMS differences were 32 pixels in x and 2 pixels in y, with the maximum error being 72 and 5 pixels respectively. Thus, a refinement of these approximations by an image pyramid approach is necessary. An alternative approach would be to actually transform and resample the search image by using the PMFs and the average height. In this case, the disadvantages are (i) the computational costs for the transformation and the resampling, and (ii) the degradation of the data. The advantages include: (i) matching can be performed using only shifts, thus resulting in computational gains which in case of many points exceed the losses, (ii) detection of radiometric differences can be applied as proposed above, and (iii) since the y-parallax of the co-registered images is very small, the images can be viewed stereoscopically (which is anyway required in digital photogrammetric workstations).

6. ACCURACY TESTS

The accuracy of the matching algorithm was tested by using the 25 m DTM of Switzerland which is generated by the Federal Office of Topography. The DTMs of the 1:25000 map sheets 1224 and 1225 were acquired. Each DTM has 701 x 481 nodes in E-W and N-S direction respectively. The DTMs are produced by bicubic interpolation in x and y direction, whereby the known heights are supplied by digitised contours, lake contours and spot heights. The accuracy of these DTMs was checked by bicubic interpolation of ca. 1000 spot heights and comparison to their known values which have an accuracy of ca. 1 m. The 1224 DTM was derived from ca. 107000 height values and has an accuracy (RMS) of 1.9 m. The height range is 900 m but the terrain is

generally smoothly changing (average slope 7°). The 1225 DTM was derived from 252000 height values, has an accuracy of 4.1 m and a height range of 1500 m. Although it is not the most extreme case that can be encountered in Switzerland, the terrain is in most parts steep (average slope 18°). Forests cover ca. 20% of map sheet 1224 and 35 - 40% of map sheet 1225. In the latter there are also lakes covering ca. 4% of the area. Some clouds were present. The radiometric differences were larger in map sheet 1224 which included agricultural areas.

In a previous test published in *Baltsavias and Stallmann, 1992b* the accuracy potential of the algorithm was tested by using good approximations that were derived from the reference DTMs.

For matching, the following 5 different versions were compared:

Version 1: patch size 17 x 17, no geometric constraints, conformal transformation

Version 2: patch size 17 x 17, constraints, conformal transformation

Version 3: patch size 17 x 17, constraints, shifts only

Version 4: patch size 17 x 17, constraints, conformal transformation, grey level images

Version 5: patch size 9 x 9, constraints, shifts only

All versions used gradient magnitude images with the exemption of version 4 that used grey level images. The aim was to compare constraints vs. no constraints, grey level vs. gradient magnitude images, conformal vs. shift transformation, and shifts with different patch sizes. The case of affine transformation was excluded a priori because in many cases it is not stable since the selected points lie at edges and thus two scales and one shear are often not determinable.

Table 1 shows the difference between the 34000 - 38000 matched points and the reference DTM, whereby the cleaned data refer to the matching results after automatic blunder detection.

Table 1 Differences of estimated heights (cleaned data) to heights bilinearly interpolated in the reference DTM (in meters)

Version	1224				1225			
	max. absolute	RMSE	mean	% ≥ 40 m	max. absolute	RMSE	mean	% ≥ 40 m
1	31.0	7.2	+1.8	0.0	42.9	8.9	+1.1	0.0
2	33.8	8.5	+2.7	0.0	44.8	9.4	+1.5	0.1
3	38.7	9.5	+2.9	0.0	47.6	11.2	+1.1	0.2
4	40.9	9.6	+3.3	0.0	48.0	10.0	+2.3	0.1
5	41.7	10.2	+2.7	0.0	52.7	10.7	+1.5	0.2

In the here presented test, the same points were matched but their approximations were derived by a hierarchical approach using image pyramids. 6 pyramid levels, including the original image were used. They were created with a decimation factor of 2 and a 3x3 Gaussian low-pass filter. Due to the non-filtering of the borders of the pyramid levels and a border for half the patch size to be used in matching, some border points could not be matched and were excluded a priori. The same points were matched in all pyramid levels.

From the five versions of the old test, version 5 was dropped and a new version 6 was used. It is similar to version 2 but instead of a conformal transformation, only two shifts and one rotation were used, since the scale was not expected to be always well-determinable as the points were lying along edges. Table 2 shows these results for the 0th pyramid level. Unsuccessfully matched points are those that needed more than 20 iterations.

Table 2 Matching versions

Version	1224		1225	
	Successfully matched points	Iterations per point	Successfully matched points	Iterations per point
1	85.0%	5.8	89.1%	5.2
2	92.8%	4.1	94.4%	4.1
3	97.6%	3.3	97.4%	3.6
4	86.1%	4.7	89.7%	4.3
6	96.0%	3.7	96.8%	3.9

These results were analysed for automatic detection of blunders. The criteria that have been used for quality analysis are: standard deviation of unit weight from the least square matching, correlation coefficient between the template and the patch, number of iterations, x-shift (i.e. change from the approximate values), standard deviation of x-shift, y-shift, standard deviation of y-shift, and the size of the used shaping parameters.

After matching, the median (M) and the standard deviation of the mean absolute difference from the median ($s(MAD)$) were computed for each criterion. The median and the $s(MAD)$ were used instead of the average and the standard deviation because they are robust against blunders. For each criterion, the threshold for the rejection of a point was defined as $M + N \cdot s(MAD)$. N was selected to be 3 for all criteria with the exemption of the number of iterations, the two shifts and the scale which should be left to vary more ($N = 4$). A point was rejected (i) when one of its criterion did not fulfil the aforementioned threshold (relative threshold derived from the image statistics), or (ii) one of its criteria did not fulfil a very loosely set threshold, e.g. for the correlation coefficient 0.2 (absolute threshold, valid for all images). The same N and absolute thresholds were used for all versions.

This blunder detection scheme was successfully applied in the old test. In the current test some problems occurred. The number of the remaining points in the 0th level was significant decreased when the blunder detection test was applied after each pyramid level. Thus, we decided to apply the test only to the results of the 0th level. However, wrong points in the upper pyramid levels were diverging from their correct position as matching sequentially proceeded down the image pyramid. These points were typically fitted to a side-minimum and thus were not detected by the blunder detection test. Since they were far away from their correct position, their height was gross erroneous, sometimes by several hundred meters. In this case the problem to be solved is to exclude blunders, from arbitrarily, and partly not densely, distributed points.

To achieve this we developed an algorithm that uses robust statistics of the heights (based again on median and $s(MAD)$) within 3 neighbourhoods centred at each point to be examined, whereby a minimum number of points within each neighbourhood is required to ensure a safe estimation of the statistics. The size of the neighbourhood and the minimum number of neighbours, which is proportional to the former, are decreased when the height gradient magnitude increases, i.e. the terrain becomes steeper. Points that do not fit to their neighbourhood are either replaced by their neighbourhood median or rejected. The aim of this adaptive local nonlinear filtering was to reject the blunders, without smoothing the terrain, and propagating the blunders as is the case with low-pass filtering. Points with very few neighbours are rejected, although they may be critical for a complete surface description and correct DTM interpolation. Although the algorithm needs further development and testing, it performs well, particularly when the point density is sufficient. Table 3 gives information on the amount of rejected points.

Table 3 Points rejected by the two automatic blunder detection methods

Version	1224			1225		
	Percentage over all points		Remaining good points	Percentage over all points		Remaining good points
	Method I	Method II		Method I	Method II	
1	21.2%	7.1%	9835	19.9%	3.7%	13410
2	16.7%	5.9%	12171	16.9%	3.2%	15183
3	13.4%	4.3%	13876	14.1%	3.4%	16359
4	19.4%	6.8%	10394	18.0%	2.6%	14103
6	15.8%	4.9%	13077	16.8%	3.4%	15645

As it can be seen from Table 2 and Table 3, the amount of successfully matched points decreases and the percentage of detected blunders increases when (i) no geometric constraints are used (version 1), and (ii) grey level images are used (version 4). From the remaining versions, the one using shifts results in more successful points because it is more stable (robust) than versions 2 and 6 which use a scale/rotation and a rotation respectively and because less criteria are used for the first blunder detection method. Constrained matching needs less iterations per point than the unconstrained version, especially when only shifts are used (see Table 2). The above results are valid for both map sheets in spite of the different terrain form and land usage.

For the accuracy analysis two comparisons were made:

- The matched points are bilinearly interpolated in the reference DTM grid and the differences between the interpolated heights and the heights as estimated by matching are computed (Table 6 - Table 6).
- A new DTM was derived from the matched points and compared to the reference DTM (Table 6).

Table 6 gives an accuracy estimate of the raw results of the 0th pyramid level. Table 6 is like Table 6 but includes only the points that exist in all five versions (12330 points for map sheet 1224 and 15766 for 1225 respectively). These tables, and particularly Table 6, permit a comparison of the matching accuracy of the five versions. Version 2 and 6 perform similarly with the latter being slightly more accurate. Version 3 is worse, and version 1 and 4 are clearly the less accurate.

Table 4 Differences of estimated heights (raw data) to reference DTM (in meters)

Version	1224				1225			
	max. absolute	RMSE	mean	% ≥ 40 m	max. absolute	RMSE	mean	% ≥ 40 m
1	1260	75.5	+2.7	10.9	1944	94.4	-3.3	9.0
2	1917	62.9	+1.5	9.1	1973	88.5	-0.2	7.3
3	1931	68.3	+2.7	8.4	2074	97.9	0.0	8.8
4	1854	63.9	+6.3	11.7	2845	132.9	+16.2	8.4
6	1566	65.8	+2.8	8.2	1339	78.1	-1.1	8.1

Table 5 Differences of estimated heights of identical points of all versions (raw data) to reference DTM (in meters)

Version	1224				1225			
	max. absolute	RMSE	mean	% ≥ 40 m	max. absolute	RMSE	mean	% ≥ 40 m
1	1154	62.3	+3.3	8.0	1911	74.0	-3.8	6.8
2	695	37.5	+2.9	4.7	1933	56.4	+0.1	4.2
3	735	40.6	+3.4	4.3	1924	54.2	-0.4	5.1
4	1854	55.0	+5.3	9.0	2845	131.4	+15.6	6.9
6	731	37.0	+2.9	4.2	1141	48.2	-0.7	4.7

Table 6 shows the final results after blunder removal. The results of map sheet 1225 were initially similar to those of map sheet 1224. However, many mountainous areas remained with very few points and the errors after interpolating a DTM were large. Thus, the criteria of the second blunder detection method were relaxed, less points were rejected but this resulted in worse accuracy values for map sheet 1225 in Table 6.

Table 6 Differences of estimated heights to reference DTM after 2st blunder detection method (in meters)

Version	1224				1225			
	max. absolute	RMSE	mean	% ≥ 40 m	max. absolute	RMSE	mean	% ≥ 40 m
1	76	7.9	+1.6	0.3	225	11.2	-1.0	1.1
2	78	9.3	+2.5	0.3	218	13.6	-0.4	1.5
3	428	14.7	+3.0	0.7	401	17.3	-1.0	2.8
4	131	10.5	+3.0	0.6	294	12.7	+0.9	1.4
6	82	9.6	+2.5	0.5	198	14.9	-0.9	2.0

From a comparison of Table 5 and Table 6 it is clearly visible that the two methods for blunder detection lead to an immense improvement of all accuracy indicators. Automatic quality control is indispensable and can take over the job of tedious and time-consuming manual editing. The maximum absolute error, the RMSE, and the percentage of errors over 40 m of Table 5 have been improved on the average by a factor 1.4, 2.1 and 3.2 respectively after using the first blunder detection method. The latter results have been further improved by a factor 6.2, 3.2 and 2.5 after using the second blunder detection method. The second blunder detection is particularly attractive, since it rejects 3 - 7 times less points than method I. The points rejected by method I as well as the unsuccessful points of Table 2 include many wrongly rejected good points. This deficiency can be easily removed and a cooperation between the different blunder detection procedures is planned. The percentage of errors greater than 40 m is generally less than 2%.

Large errors occur especially in three types of areas:

- At the mountain-ridges and cliffs. At these regions there are surface discontinuities and forests. Additionally interpolation errors occur because the density of the selected points was low at these regions and thus the terrain surface could not be modelled correctly (see Figure 6 and Figure 6 with the large triangular meshes for DTM interpolation).
- At forest areas, because the matched points are on the tree tops and the reference DTM refers to the earth surface.

(c) On the lake surface (see top centre of Figures 6 and 7). The selected points lied on either sides of the lake, and at certain places much higher than the lake surface. Thus, the large triangles that were used for the DTM interpolation were lying much higher than the lake surface.

The RMSE is in the 10 m level and compares very favourably with the 6 m RMS in Z of the 126 manually selected and matched check points. The accuracy difference includes errors due to the polynomial mapping functions (max. 1 m), the matching, the interpolation within the reference DTM and errors of the reference DTMs. A comparison of Table 6 with Table 1 (with very good approximations) shows a slight accuracy decrease of the former results while the maximum absolute errors increase. The mean difference is small, indicating absence of large systematic errors. It is generally always positive because (i) area-based matching tends to measure higher than the actual surface when the terrain is rugged, and (ii) the tops of the trees were measured in forested areas. The small negative mean difference in map sheet 1225 is due to the existence of blunders which were primarily negative.

Version 1 (without constraints) is surprisingly good. This is mainly due to the fact that these results are based on fewer points due to many detected blunders (Table 3) through the blunder detection scheme. However, less points lead to a less accurate interpolated DTM especially in mountainous terrain (see Table 6). Another reason is due to the choice of points along nearly vertical edges. Thus, the precision in x-direction is good and errors in y (gliding along the edge) influence minimally the estimated heights due to the horizontal base. Version 4 has similar accuracy as the version with gradient magnitude images (version 2). The difference is not so big again due to many detected blunders for version 4. The shift version (version 3) performed, as expected, worse than versions 2 and 6. Version 6 was expected to perform slightly better than version 2, because with the latter the scale is not always well-determinable. However, the viewing angles and the steep terrain, particularly in map sheet 1225, makes the use of a scale necessary for a better geometric fit of the patch to the template.

In general the results of all versions (with exception of version 3 that had some undetected blunders) are quite similar. This is an indication that our blunder detection scheme worked equally well with all versions although their initial accuracies (see Table 4) differed significant. Our interpretation of Table 6 is that although versions 1 and 4 seem to perform very well, they lead to a less accurate DTM interpolation in rugged terrain because they have less points.

The results of Table 6 are worse than those of Table 6 due to interpolation errors (ca. 270000 points were interpolated from 10000 - 16000 points). Still the results for map sheet 1224 are close to 10 m. The results for map sheet 1225 are worse due to mountainous terrain, many forests and the lake. With denser measurement points they should be close to the results of map sheet 1224. The results of versions 1 and 4 are not worse than those of the other versions for map sheet 1224 because the terrain slope is not large. For map sheet 1225, version 1 is clearly worse but version 4 is surprisingly the best. There are many accidental reasons for that behaviour. The main reason is that version 4 has more points in critical mountainous regions with low point density than all the other versions that used gradient magnitude images (compare the lower right part of Figures 6 and 7). In the latter versions these points were rejected by the first blunder detection method because of the relatively low texture and low correlation coefficient. The parameters for the rejection thresholds were common for all versions, although some of them should differ due to the different nature of grey level and gradient magnitude images, i.e. for the latter they should be relaxed.

Table 7 Differences between new and reference DTM (in meters)

Version	1224				1225			
	max. absolute	RMSE	mean	% ≥ 40 m	max. absolute	RMSE	mean	% ≥ 40 m
1	135	14.4	-0.1	2.6	591	48.7	-9.6	12.6
2	129	14.0	+0.5	2.2	427	36.2	-3.9	10.8
3	414	19.8	+2.3	2.6	442	40.2	-4.3	11.3
4	127	13.9	+1.7	1.9	304	29.0	+0.9	9.1
6	118	13.3	+0.8	1.8	406	36.7	-4.1	11.2

Figure 6. Triangulation mesh for DTM interpolation of map sheet 1225, version 2

Figure 7. Triangulation mesh for DTM interpolation of map sheet 1225, version 4

7. CONCLUSIONS

A matching algorithm for SPOT images was presented that uses a photogrammetric sensor model to impose constraints that reduce the search space from 2-D to 1-D. The algorithm severely reduces the problems caused by radiometric differences, and determines in one step pixel and object coordinates. The use of gradient magnitude images instead of grey level images improves the results. A conformal, a rotation/shift or a shift transformation, the latter however with smaller patch size, may lead to similar results.

Problematic cases like multiple solutions, radiometric differences and occlusions are reduced and the computation time decreases due to the 1-D search. A blunder detection scheme is proposed that uses criteria derived mainly from the statistics of the results. It leads to an impressive improvement of all accuracy indicators. In particular, it reduces the percentage of errors larger than 40 m to 0.5 - 2%. A deficiency of our test was the rejection of too many points, out of which many were correct, with obvious negative influence on the DTM interpolation.

The accuracy of the matching is in the 10 m range. For the interpolated DTM it clearly depends on the density of measurement points and for sufficient density it can be in the 10 - 20 m range. Regions with low point density due to radiometric differences, low texture or shadows can be filled-in with manually measured points before the DTM interpolation.

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