GEOMETRIC POTENTIAL OF MOMS-02/D2 DATA FOR POINT POSITIONING, DTM AND ORTHOIMAGE GENERATION

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ABSTRACT

The paper presents investigations on the geometric potential of MOMS-02/D2 data using three images over a testfield in Australia. The sensor model employed is presented and the point positioning accuracy for different control point, model parameters, and image measurement versions is analysed. The achieved accuracy for the fore/aft channel combination was 6 - 7 m in all three coordinates by using only 10 control points and quadratic attitude rates. Automatic DTM and orthoimage generation was performed again based on the fore and aft channels with 13.5 m pixel size. DTM generation is based on matching using geometric constraints and being able to match images with any scale or rotational differences. The evaluation of the DTM and orthoimage accuracy was based on limited reference values. The available qualitative and quantitative accuracy measures indicate a DTM accuracy (without any manual editing) of 0.5 - 1 pixel RMS and a maximum error of ca. 30 m. The planimetric accuracy of the orthoimages is ca. 0.5 pixel.

1. INTRODUCTION

The great majority of past and current satellite-based optical sensors employ linear CCDs scanning in a pushbroom mode. For stereo acquisition either across-track (SPOT) or along-track (J-ERS 1) has been employed. The latter method offers the advantage of near-simultaneous image acquisition, thus making stereo interpretation and mensuration much easier. For this reason, most planned satellite-based optical sensors will employ this stereo mode, some in addition to across-track stereo for more frequent revisiting. The along-track stereo is implemented using two or three linear CCDs, usually each with a separate lens system. Another tendency is the increase of the geometric resolution. Available data from civilian electro-optical sensors have a resolution of up to 4.5 m, while several systems with 1 - 3 m resolution are planned to be launched starting from 1996. These developments offer new possibilities for mapping - in continuously increasing scales - and derivation of important products like DTMs, orthoimages and orthoimage maps, classification maps etc. especially for many countries where this information does not exist, is outdated or not accurate enough.

MOMS-02 is a high resolution, along-track stereo, three-line imaging system. Its sensor description and modelling, a system overview and other information are given in Ackermann et al., 1990, Ebner et al., 1992, and Seige, 1993. Here, only a brief overview will be given. MOMS-02 employs seven channels, four multispectral and three panchromatic. For stereo imaging the 4.5 m resolution nadir panchromatic channel and the 13.5 m resolution fore and aft panchromatic channels are used. The fore and aft channels have a look angle of 21.5° with respect to the vertical, thus leading to a B/H ratio of 0.8. MOMS-02 has different acquisition modes. The images used in this test were acquired with mode 1, and have a dimension of 2976 x 8121 pixels (fore and aft), and 8304 x 8121 pixels (nadir). A nadir image that covers the same area as the fore or aft channel actually consists of three subimages, that slightly overlap (120 pixels) in flight direction. Thus, an image covers an area of 40 x 110 km^2 and 37 x 109 km^2 for the fore/aft and nadir case respectively.

The paper presents investigations on the sensor modelling and geometric point positioning accuracy of the MOMS-02 sensor, and methods, including accuracy evaluation, for generating DTMs and orthoimages.

2. TEST DATA

The three images used (fore/aft/nadir) were taken in April 1993 during the D2 Space Shuttle Mission. They depict a deserted and flat region in the southeast Northern Territory, Australia with very little vegetation and almost no cultural features apart from a few dams, tracks and fences. Figure 1 shows a 3D view of an image part which is typical of the region. These images were selected because they were the only ones where high quality ground truth was available.

The ground truth mainly consisted of about 80 points that were measured with GPS with an accuracy of ca. 10 cm during two campaigns in 1994 and 1995. A big problem was the identification of the points in the images. The definition of many points, due to lack of other more suitable cultural features, was poor (see Figure 4). The sensor resolution was too coarse for some points (e.g. fences), while the temporal difference between image acquisition and survey (e.g. different water levels) caused problems in identifying some good image points. Details on the testfield and the GPS control point survey are given in Fraser et al., 1996. Additional ground truth included a 17 km profile along a fence line with height data every 1 m and an accuracy of 10 - 20 cm. The profile was acquired with a roving GPS antenna with aim the quality evaluation of derived DTMs.

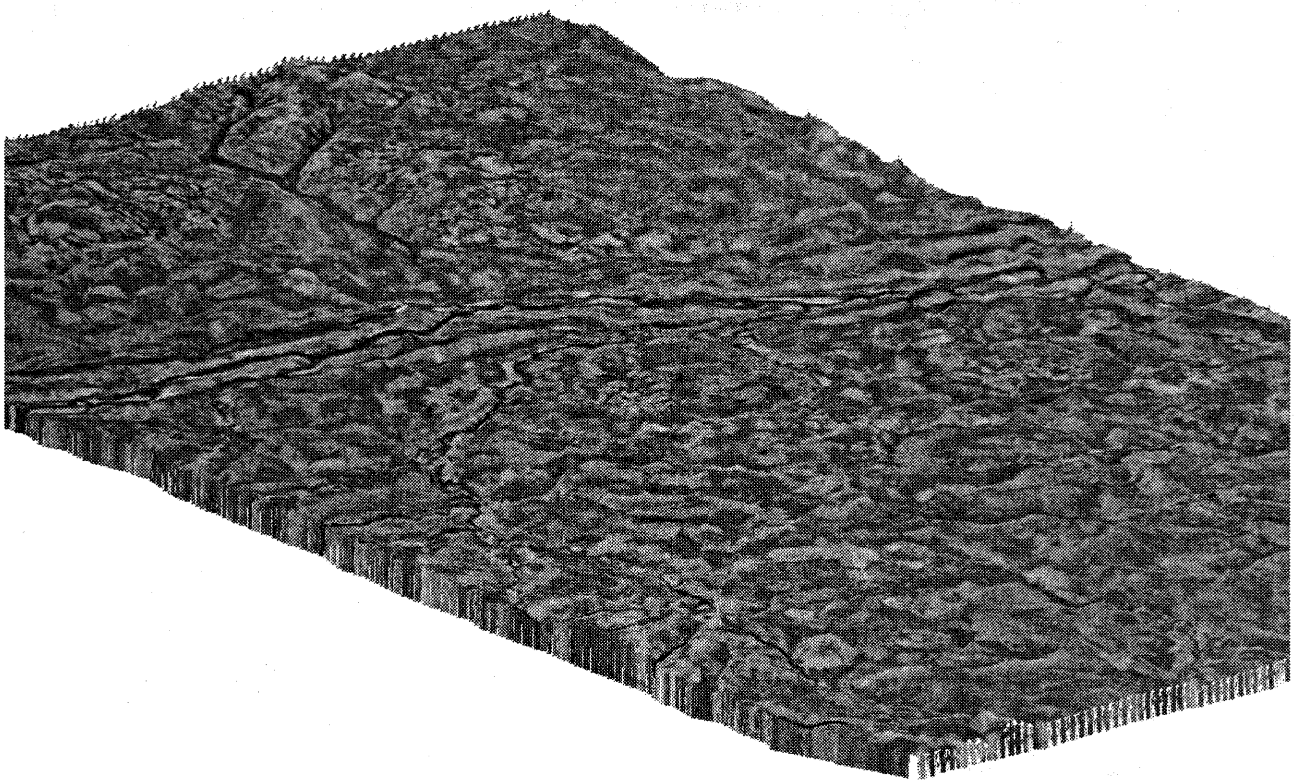

Figure 1. 3D parallel view of the top left part of the fore channel (12 x 20 km). Orthoimage overlayed on automatically derived DTM using a height exaggeration factor of 7.

The images, especially the nadir one, were of very poor radiometric quality. The temperature on the Space Shuttle was too high and this caused among other problems the application of unsuitable sensor calibration parameters. In all images the following problems existed: positive and negative spike noise, pattern noise, and small grey value range (ca. 50 grey values were occupied). The nadir channel had additional problems: blemished lines (single or double, with very light or dark values) in the left part of the image, different grey level mean in the left and right part (the line CCD consists actually of two optically butted CCDs which had different gain and offset due to the aforementioned calibration problems), strong pattern noise at the left of the left image part (different grey level mean every three lines and every two columns), and higher grey level mean (ca. 25 grey values) than the mean of the fore and aft channels.

These radiometric problems are grave especially for DTM and orthoimage generation. The control point measurement, particularly if it is done manually, is not influenced so much. Thus, for the control point measurement we did a strong contrast enhancement and radiometric equalisation of the images using Wallis filtering. For DTM and orthoimage generation the following preprocessing was performed. For the fore/aft channels: median filtering, generation of an image pyramid (required for DTM matching), and Wallis filtering at each pyramid level. For the nadir channel: grey level interpolation of the blemished lines, median filtering, gain and offset transformation of the right image part to fit to the left one, smoothing of a narrow band along the border line of the left and right part, image pyramid generation, and Wallis filtering at each pyramid level. For the 0th pyramid level a Gaussian filtering was applied before the Wallis filter to reduce the pattern noise and the formation of grey level regions caused by the median filter. Some results are shown in Figures 2 and 3 and speak for themselves. A minor problem was due to the 3 x 3 median filtering: grey level regions were formed in homogeneous areas (posterising), and small objects (among them also some control points) were distorted or partially eliminated. This could be reduced by using a smaller support for the median filtering.

3. SENSOR MODEL

We used the model developed by Kratky, 1989. Kratky's model processes single and stereo images of various sensors including SPOT, Landsat, J-ERS 1 and MOMS-02 and is easily expandable to include new sensors with similar geometries, as they become available. It is an extended bundle formulation considering in a rigorous way all physical aspects of satellite orbiting and of earth imaging, together with geometric conditions of the time-dependent intersection of corresponding imaging rays in the model space. The ephemeris data (position and attitude) are not necessary but for some sensors they may be used optionally. Orbital perturbations are taken into account by allowing the orbital segment to be shifted with respect to its expected nominal position. The total number of unknowns per image is 14 - 6 elements of exterior orientation, linear and quadratic rates of change for the rotation angles, a change Δf for the camera constant, and a quadratic distortion in x (corresponding to a shift of the principal point along the CCD sensor). The quadratic rates may be dropped (linear model). Six weighted constraints keep the orbital positions of the two sensors within statistical limits

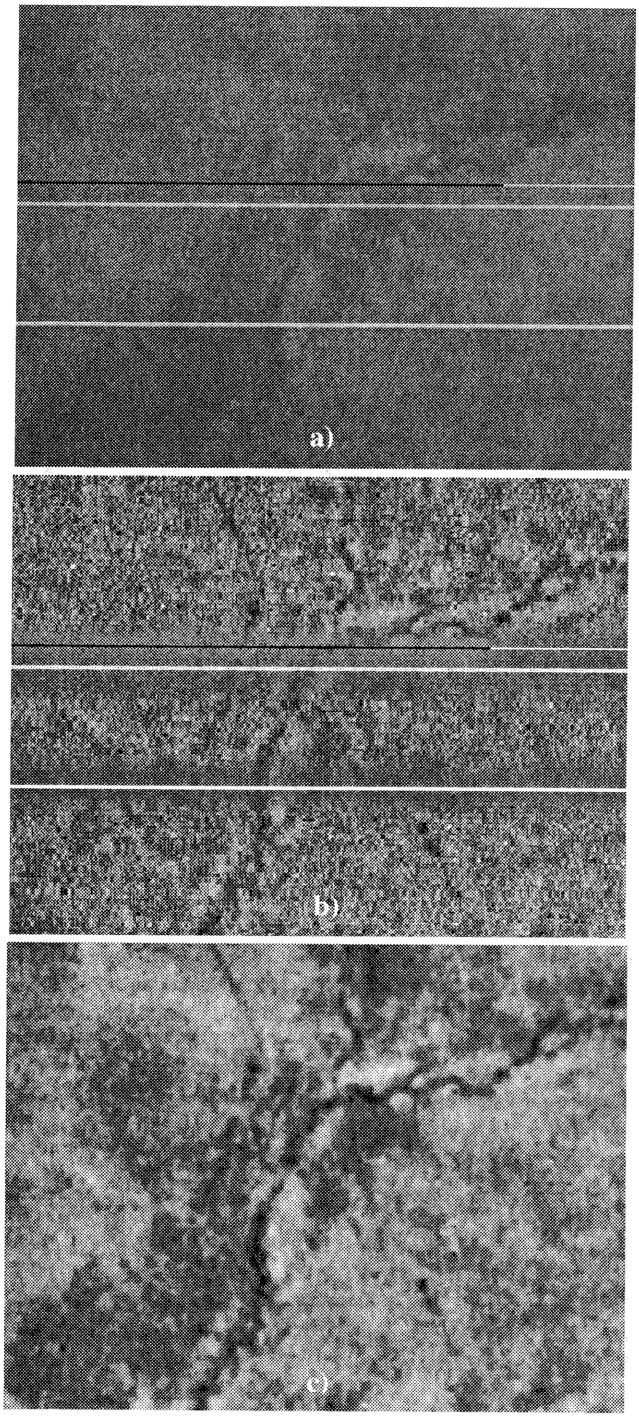

Figure 2. Top left part of the nadir channel: a) original, b) as a) after contrast enhancement to show the noise, c) after preprocessing.

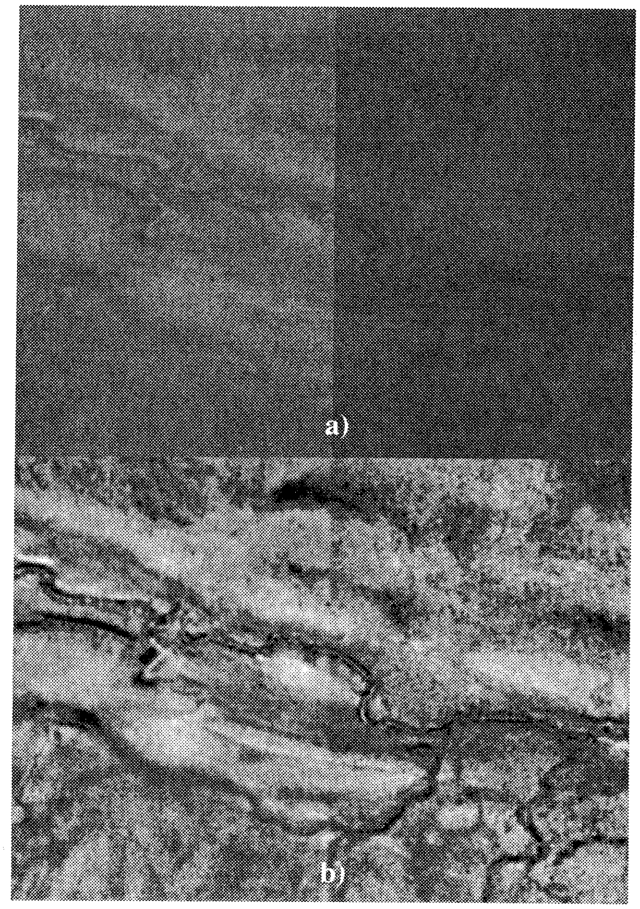

Figure 3. In a) part of the original nadir image. In b) after preprocessing.

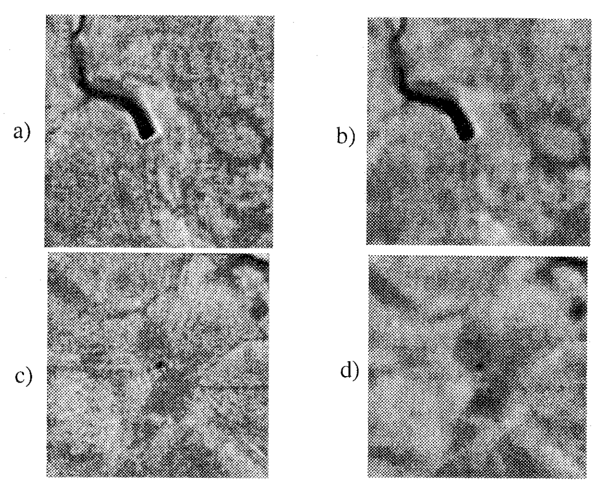

Figure 4. Good [a), b)] and poor [c), d)] definition control point in nadir and fore preprocessed images respectively.

from the expected nominal orbits or the ephemeris data. Twelve absolute constraints are enforced in order to keep projection centres moving strictly along appropriate elliptical orbital segments. Thus, linear and quadratic rates of change in X, Y, Z, which are eventually used as given values, are calculated. The minimum number of full control points is 4 for the linear model of attitude changes and 6 for the quadratic.

Kratky also provides direct projection equations from one space to another (two image spaces, object space) by means of polynomial mapping functions (PMFs). The PMFs consist of 3rd - 4th degree polynomials with 11 - 16 terms, whereby the object space is reduced to two dimensions by extracting the elevation, i.e. the elevation Z is an independent parameter connecting all three 2D spaces. The polynomial coefficients are estimated by least squares adjustment after the sensor orientation is estimated by the strict model. The PMFs are much faster and almost equally accurate as rigorous transformations using the strict model (difference < 0.1 pixel). We have used the PMFs with SPOT images in matching for DTM generation, and orthoimage generation with great success (Baltsavias and Stallmann, 1993). More details on the characteristics of the PMFs and how they can be employed for the above mentioned tasks can be found in Baltsavias and Stallmann, 1992.

3.1. Point Measurement

The measurement of the GCPs proved to be a very difficult task. Although their ground coordinates were accurate to 10 cm, their actual accuracy is rather in the 1 - 5 m range due to problems in their identification. For the image measurement we used existing image coordinates, sketches on printed image chips, and all three preprocessed images. The image coordinates were refined by the following procedure. After some runs of Kratky's bundle all blunders, like measurement of wrong fencelines etc., were identified and corrected or removed, if their identification was not possible. The use of the Wallis filter and the nadir image helped a lot in this procedure. Then, 30 points with good image and ground measurements and distributed over the whole image format were selected and used as control points. Their image coordinates were further refined by runs of the bundle and analysis of the image residuals. Since the confidence in the ground coordinates was much higher than the one in the image coordinates, it is expected that when ground and image coordinates do not fit, this is due to image measurement errors. After having a strong and accurate geometry, the rest of the GCPs were sequentially introduced as control and their image coordinates were corrected by the same procedure. Even if a point had an error (note that gross error were removed beforehand), it could not have a large effect on the sensor orientation due to the strong and accurate network. This procedure was performed for the fore and aft channels. In addition, the manual measurements in the fore image were used as reference and transferred to the aft image by Least Squares Matching (LSM). In the nadir channel the measurements were much more difficult due to the higher noise, which was further enhanced by the Wallis filter. Thus, the results of the bundle were suboptimal. We plan to use the images, as preprocessed for the DTM generation, to repeat this task. The whole procedure took two whole days. The image coordinates were distributed to and used by other colleagues with good results (Fraser and Shao, 1996).

3.2. Evaluation of the Point Positioning Accuracy

To evaluate the point positioning accuracy we made several runs of the bundle for the fore/aft images using 3 control point distributions (6, 10 and 20 points), linear and quadratic attitude rates, and image measurements in the aft image done manually and by LSM. The selection of the control points was based on their image quality and distribution over the whole image. The manual and matching measurements led to similar results. Previous tests with SPOT images have always shown that matching measurements lead to better accuracy in height, because the points in left and right images correspond better. This was not the case here, because (a) the manually measured image coordinates were refined by the use of bundle and the correspondence between left and right images was already very good, and (b) due to poor point definition and high noise the accuracy of matching was decreased. The results for the matching image measurements are shown in Table 1.

Table 1. Geometric positioning accuracy. RMS errors of check points (in m).

Model	GCPs	Check points	σ_0	X	Y	Z
L	20	45	6.0	9.9	7.4	9.4
L	10	55	7.7	9.0	8.7	10.1
L	6	59	10.1	10.9	8.1	12.2
Q	20	45	3.6	6.2	6.4	6.7
Q	10	55	2.9	6.7	5.9	7.4
Q	6	59	2.3	7.4	10.7	7.9

The quadratic version is clearly better than the linear one. With SPOT the difference between the two versions was small. An explanation for the clearly better performance of the quadratic version with MOMS-02/D2 can be either a less stable orbit of the space shuttle, or the larger image dimensions in flight direction (110 versus 60 km for SPOT). We also tried additional control point selections, keeping their number as above. While the 10 and 20 point versions were not sensitive to the selection of the GCPs as long as their distribution was reasonable, the 6 point version, due to its very weak redundancy, depends a lot on the point quality. As Table 1 shows the difference between the 10 and 20 point version is minimal. As a conclusion we can state that for the given sensor model, 10 control points with quadratic attitude rates and image measurements by matching lead to good results. For the fore and aft images of MOMS-02 an accuracy of 6 - 7 m, i.e. ca. 0.5 pixel, for all three coordinates was achieved.

4. DTM GENERATION

DTM generation was performed automatically using a modification of the MPGC algorithm (Baltsavias, 1991). MPGC is based on LSM and extends it by use of geometric constraints to reduce the search space and simultaneous use of any number of images. The constraints lead to a 1D search space along a line, thus to an increase of success rate, accuracy and especially reliability, and permit a simultaneous determination of pixel and object coordinates. The measurement points are selected along edges that do not have a direction similar to the direction of 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 (i.e. erroneous grey levels) and blunders, and adaptation of the matching parameters to the image and scene content. The modified MPGC makes use of the PMFs to constrain the search along pseudo epipolar lines (Baltsavias and Stallmann, 1992) and has been previously used for SPOT images (Baltsavias and Stallmann, 1993). In its current implementation it can be used only for two images.

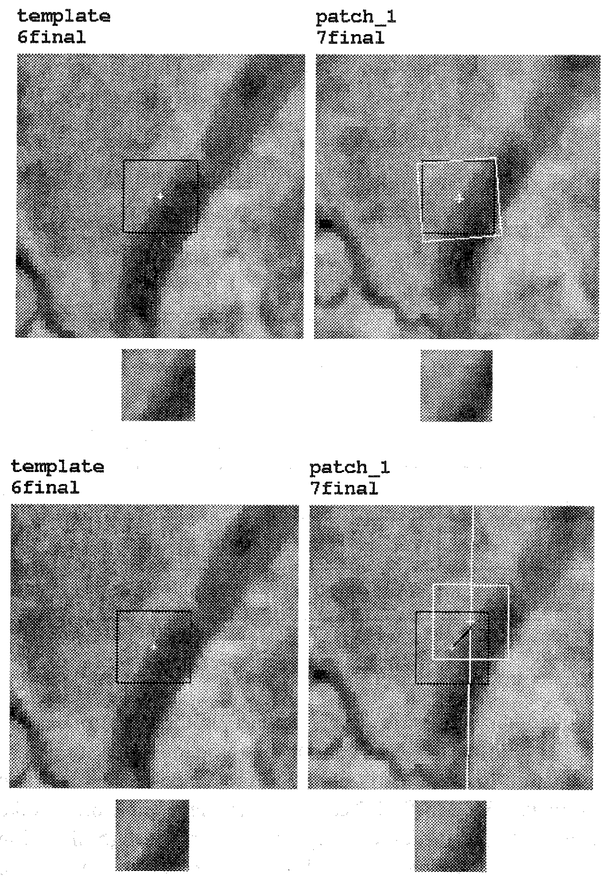

Figure 5. Matching along edges without (top) and with (bottom) constraints. The epipolar line is the white line in the bottom right image. The black frame is the initial position and the white frame with the centre cross the final position.

With along-track stereo, the epipolar lines are vertical, i.e. any error in the x-direction (x is in the sensor direction) will be eliminated right in the first iteration of the matching (see bottom of Figure 5). Since the epipolar lines are vertical, the measurement points must be selected along edges that are not nearly vertical in order to ensure determinability and high accuracy. Some advantages of the geometric constraints will now be presented. Satellite images include due to 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 5 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. Another advantage of our approach is the possibility to give arbitrary approximations for the scales and the shear parameters, that are estimated in matching. This is important for matching the nadir with the other two channels, since their scale difference is 3. The combination of geometric constraints and an approximation for the scales leads to very positive results as Figure 6 illustrates.

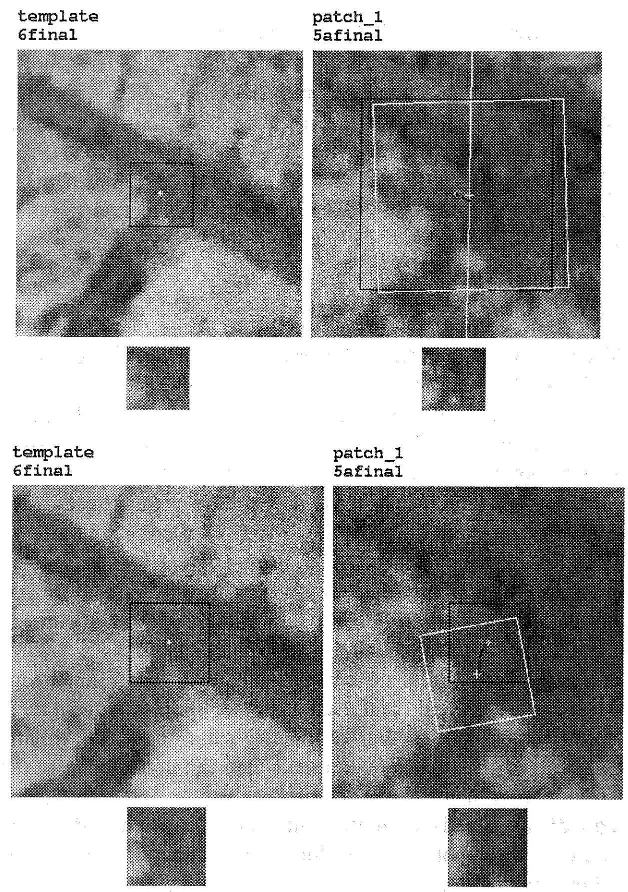

Figure 6. Matching the fore image (left) with the nadir image (right). Top: using constraints and a scale approximation of 3. Bottom: without constraints and no scale approximation (default scale value = 1).

For the DTM test a region (12 x 20 km) covering the top left part of the images was chosen. In this region lied the profile height data that were measured with the roving GPS. Ca. 10,000 points were selected with an interest operator in the fore and were matched in the aft image. Four pyramid levels (incl. the original images) were used for derivation of the approximations. In the last level a conformal transformation with 17 x 17 pixel patch size was used. In comparison to previous DTM generation from SPOT images, the matching was easier. This is partly due to the lack of radiometric differences because of the simultaneous image acquisition, and partly due to the type of terrain (flat and open). The major problems that were encountered were: the lack of sufficient texture in large areas covering up to 1 x 1 km ; the smoothing of discontinuities, especially at creeks, due to the large patch size of 230 x 230 m ; some, very few, regions of radiometric differences (see Figure 7) mainly due to different reflection of water surfaces. To reduce the amount of blunders a test using statistical values that are provided by the algorithm (see Baltsavias and Stallmann, 1993) was performed. Only ca. 2.5% of the points were rejected and they included most of the blunders. The height range of the remaining data was only 84 m, showing that big blunders in the order of hundred or more meters as they have occurred with previous SPOT DTM tests did not occur. Using the ca. 10,000 points a DTM grid with 40 m grid spacing was interpolated and contours were plotted. Visual control of the contours and the representation of DTM as a grey

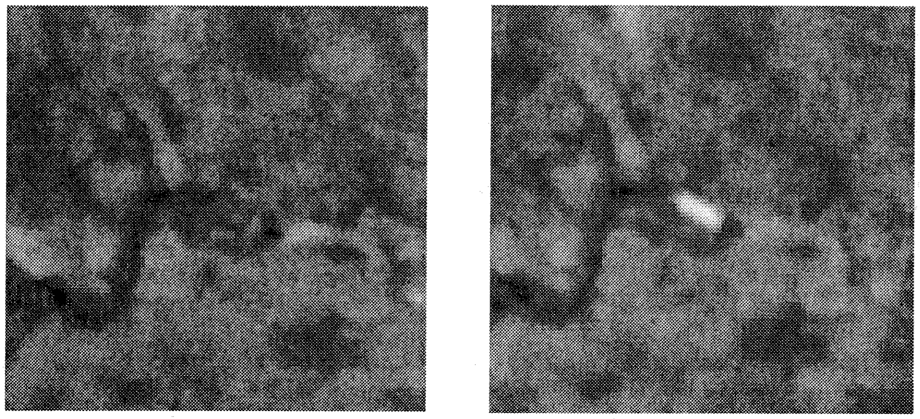

Figure 6. Radiometric differences between fore and aft channels.

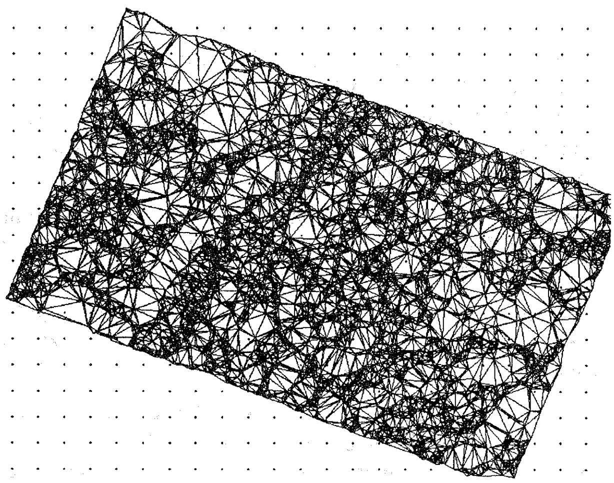

Figure 8. The triangular meshes of the 10,000 matched points used in the 40 m DTM grid interpolation.

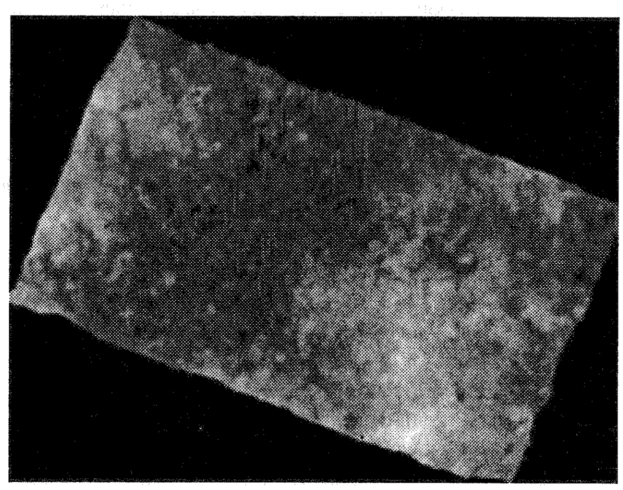

Figure 9. The second 40 m DTM grid displayed as a grey level image.

level image showed that some small bumps might have remained in the data. The roving GPS data were not available to us, so for a quantitative evaluation of the results we did the following. Using the DTM an orthoimage with a 13.3 m pixel size from the fore channel was generated and the GCPs that were included in it were manually measured. Their pixel coordinates were transformed to ground coordinates, their height was bilinearly interpolated from the underlying DTM, and these values were compared to the adjusted ground coordinates of the bundle. The RMS difference in X, Y, and Z was 6, 5.7, and 5.1 m, while the maximum absolute error was 11.5, 10.5 and 8.1 m respectively. Due to the small number of these points (4), the results are not conclusive. The second approach was based on orthorectified stereo pairs (Baltsavias, 1996). A second orthoimage from the aft channel was generated. If the DTM were correct, the orthoimages of the fore and aft channels should not have any parallax. We measured the parallax with LSM at different well-defined points over a regular grid covering the whole image format. In addition we subtracted the two orthoimages and matched at places where the radiometric differences were high, possibly due to remaining parallaxes. All in all, ca. 50 points were matched and the maximum parallax was 0.6 pixels, i.e. 8 m. A visual control of the difference image showed that most of the differences were due to radiometric differences in the original images and not due to parallax. Only along creeks some parallaxes existed, partly also due to terrain smoothing because of the large patch size.

Some of DTM errors are due to interpolation. The original measurements were ca. 10,000 while the DTM had ca. 152,000 nodes. These errors occur especially in the areas with little or no texture (see the triangular meshes for the DTM interpolation in Figure 8 and compare to image texture in Figure 1, e.g. at the top right part). To reduce this problem we made a second selection of points with the interest operator and relaxed criteria. Thus, 80% more points were matched and a second 40 m grid DTM was interpolated (see Figure 9). A comparison of the two DTMs showed an average difference of 0 m, an RMS of 4.2 m, and a maximum absolute difference of 26 m. 96.2% of the points had a difference of less than 10 m, and 99.9% a difference of less than 20 m. These measures are an indication of the internal precision and repeatability of the algorithm. The maximum difference in particular is a good indicator of the maximum error in any of the two DTMs. The second DTM, as expected, was modelling better the areas that previously had few or no measurements. On the other hand, the choice of points with not very good texture led to more blunders. Our blunder detection method rejected 4% of the points, and another 1.8% of the points were rejected by a second method for detection of DTM spikes based on robust statistics. The remaining points showed slightly more remaining errors than the first DTM.

5. ORTHOIMAGE GENERATION

Using the first DTM and the ground to image PMFs an orthoimage was derived from the fore channel. Its planimetric accuracy was checked as explained in the previous section by the use of the GCPs and the parallaxes between the orthoimages of the fore and aft channels. Another possibility, that was not used here, is to derive new GCPs by finding corresponding points in the two orthoimages, projecting back in the original images and finding ground coordinates through a forward intersection. This procedure works even if the DTM used for the orthoimage generation is erroneous (see Baltsavias, 1996).

The time required for the orthoimage generation (2.4 Mbytes) on a Sun Sparcstation 20 was 39 sec. For an orthoimage of the whole fore or aft channel ca. 3.5 min are required. An overlay of the orthoimage on the DTM is shown in Figure 1.

6. CONCLUSIONS

The data set used for this test is limited. In addition, problems with the GCP identification and the high image noise make this test a bit more difficult than what should be expected with normal quality imagery. However, the great precautions that we took in the measurement of the image coordinates of the GCPs and the image preprocessing lead to the conclusion that the accuracy can not be much better with "normal" imagery. Even under these conditions, we proved that by using the fore and aft channels with a simple, fast but strict sensor model needing only ca. 10 GCPs, an accuracy of 6 - 7 m in planimetry and height can be achieved. When using the nadir and one of the fore or aft channels, the planimetric accuracy should be higher, but the height accuracy should stay, due to the worse B/H ratio, at more or less the same level.

Automatic DTM generation with a novel matching algorithm that makes use of geometric constraints and has no problem in matching of images with any scale or rotational differences was performed. Due to lack of extensive reference values no definitive conclusions on the DTM accuracy can be drawn. Based on the available qualitative and quantitative measures the RMS error of the DTM raw data is 0.5 - 1 pixel, with maximum error close to 30 m. These values will of course vary depending on the form and coverage of the terrain. A dense regular DTM grid will however be less accurate in areas with few or no measurements due to poor texture. To fill-in these gaps and to correct for the few, relatively smal,l remaining errors a postediting is required.

Orthoimage generation poses no problem and can be fast. The only important requirement is a good quality DTM. The planimetric accuracy that was achieved was in the order of half a pixel.

Future investigations will make use of the nadir channel for evaluation of the point positioning accuracy, and DTM and orthoimage generation. In cooperation with the University of Melbourne we will use the roving GPS data for DTM evaluation. Furthermore, new tests using the planned MOMS-Priroda images over areas with good reference DTMs will be performed.

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