AUTOMATIC PHOTOGRAMMETRIC PROCESSING OF SPOT IMAGERY FOR POINT DETERMINATION, DTM GENERATION AND ORTHOPROJECTION

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ABSTRACT:

For the photogrammetric processing of SPOT imagery a completely automatic procedure is described. It includes a sophisticated region growing image matching algorithm, point determination using a polynomial approach for orbit modelling, the generation of digital terrain models (DTM) and the computation of orthophotos. Only the image coordinates of a number of ground control points must be measured interactively.
The procedure is evaluated by means of two practical projects. In contrast to many other investigations of SPOT the whole images were processed and ample independent control information for a sound statistical accuracy check was available. The achieved empirical height accuracy of better than 10 m is a very good result considering the small base-to-height ratios of 0.4 and 0.6 respectively.

Key words: SPOT, automatic evaluation, image matching, point determination, DTM, orthoimage

1. INTRODUCTION

Since 1986 the French SPOT satellites (SPOT = satéllite pour l'observation de la terre) provide digital topographic imagery on a regular commercial base. The images are taken from a near-polar orbit at an altitude of approximately 830 km and an image scale of roughly 1:800.000. Due to the oblique viewing capabilities, stereo images - one from each orbit - can be acquired with an acceptable base-to-height ratio. It is this feature, which makes SPOT images interesting to the photogrammetric community.

SPOT 1 has already reached the end of its anticipated life time, but continues its service. SPOT 2, a version identical to SPOT 1, is presently the main source for image data. With SPOT 3 ready for launch in early 1993 and SPOT 4 and 5 having been announced and financially secured, the longtime availability of SPOT imagery seems to be guaranteed.

It is behind this background, that the Chair for Photogrammetry and Remote Sensing, Technical University Munich and the Industrieanlagen-Betriebsgesellschaft mbH, Ottobrunn (IABG) have decided to develop digital photogrammetric processing tools for SPOT imagery. This paper describes the current status of development. Earlier reports have been given in /Heipke 1990; Heipke, Kornus 1991/.

The aim of the development is the automatic derivation of digital terrain models (DTM) and orthoimages. This involves a number of different steps. The main ones are:

- identification and measurement of ground control points (GCP) in the stereo images,

- determination of conjugate points in the images (image matching),
- calculation of the elements of exterior orientation (generalized bundle adjustment),
- forward intersection of the conjugate points,
- generation of a DTM (and follow-up products),
- computation of an orthoimage.

The data flow for the processing of SPOT imagery is depicted in figure 1. At present, human interaction is only necessary for the identification and measurement of the GCP.

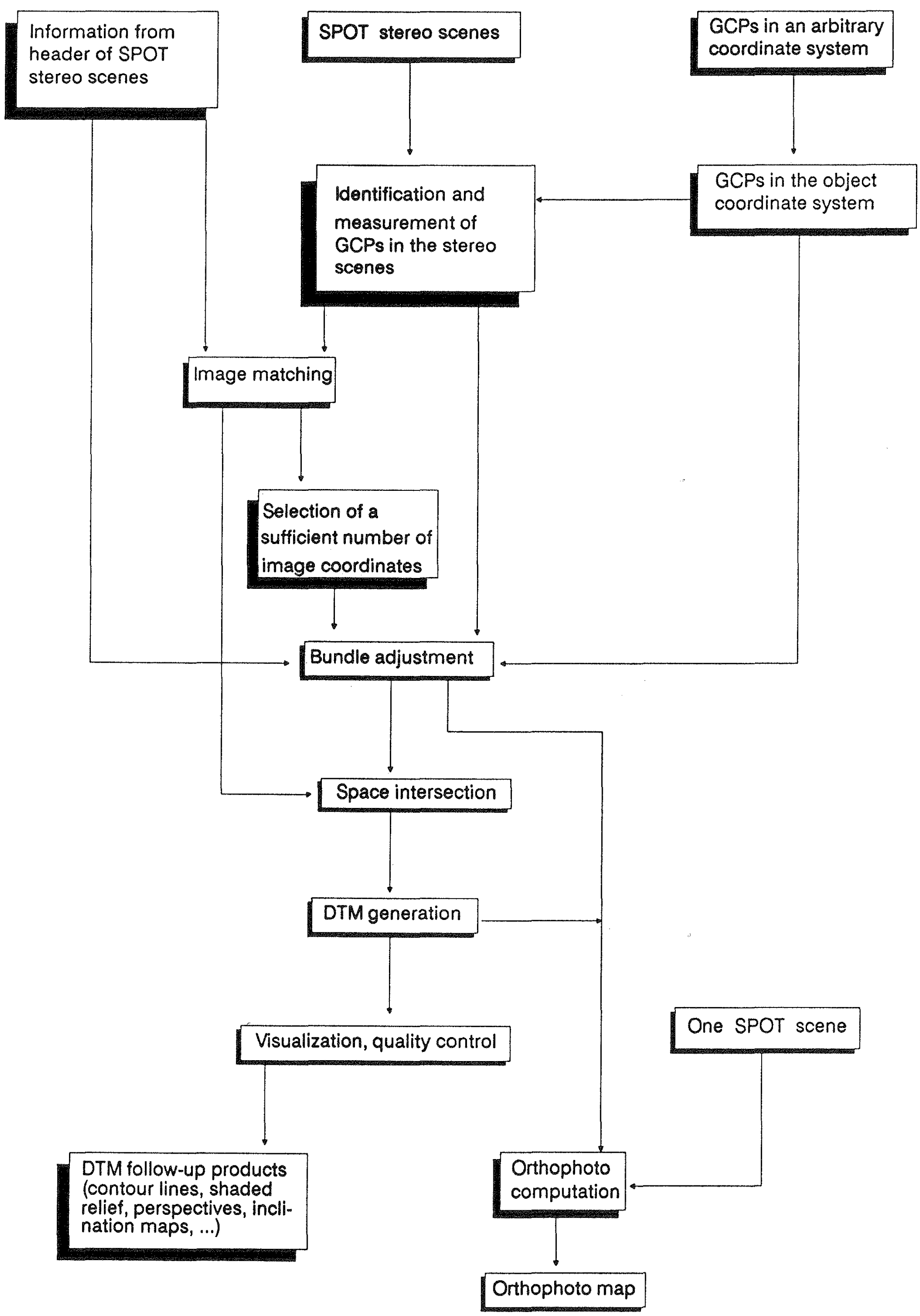

Fig. 1: Photogrammetric processing of SPOT images, data flow

The most difficult tasks are image matching and the generalized bundle adjustment using a proper model for the satellite's movement during the data acquisition. Therefore, these are dealt with in more detail in the next two chapters. Two projects are described in order to demonstrate the capabilities of the method. In contrast to many other investigations of SPOT the whole images were processed and ample independent control information for a sound statistical accuracy check was available.

2. IMAGE MATCHING

Least squares image matching /Förstner 1982/ is known to yield the most accurate results. This method has also been applied to SPOT imagery /Otto, Chau 1989/. Their region growing algorithm has been selected for this project, but has been refined with respect to robustness of the results.

In the following a short explanation of the used algorithm is given. One pair of conjugate points is assumed to be approximately known. It is called the starting point. By matching the template and search matrices surrounding the starting point, the exact coordinates of the conjugate points and the corresponding geometric and radiometric transformation parameters are computed. Also the correlation coefficient ρ between the two matrices, the semi-major axis of the error ellipse of the points, and the differences to the initial values are determined.

Next, the template and search matrix are shifted by a constant amount to the left (this amount is called STEP in the following). The matching is then repeated in the new position using the results from the starting point as initial values. The same is done for the positions to the right, on top, and under the starting point. The results for all four neighbours of the starting point (coordinates of conjugate points, geometric and radiometric transformation parameters, correlation coefficient) are entered in a list in the order of decreasing value of ρ.

The first point of the list is chosen as new starting point. All its remaining neighbours in the distance of STEP are attempted to be matched in the same way, and the results are entered in the list if certain criteria are fulfilled (see below). After matching the neighbours, the new starting point is deleted from the list, and the next point is processed. The algorithm stops, if the list is empty. In this case either all points of the scene have been matched, or no point in the neighbourhood fulfils the mentioned criteria.

The selection of these criteria and the corresponding thresholds is essential for the robustness of the algorithm. In this investigation the following conditions were set up for entering a pair of conjugate points into the list:

- the correlation coefficient must be larger than a threshold ρ_{min},
- the semi-major axis of the error ellipse must be smaller than a threshold,
- the difference to the initial values must be smaller than a threshold (this means that the height difference between neighbouring points in object space must lie below a certain threshold),
- the number of adjustment iterations must be smaller than a threshold.

If more than one GCP is available, all of them (including their neighbours) are matched independently. The resulting lists are then merged to form a single one. Matching is continued using the combined list.

3. GENERALIZED BUNDLE ADJUSTMENT

In the generalized bundle adjustment the ground coordinates of the object points and the exterior orientation parameters are simultaneously determined from image coordinates of the object points, ground control information and optionally a variety of non-photogrammetric data (e.g. GPS or INS measurements of camera positions or attitude). Due to the dynamic acquisition mode of a line scanner like SPOT each image line basically has its own set of six exterior orientation parameters. In practice the determination of the exterior orientation parameters for each line is not possible. For piecewise smooth flight paths, their temporal variation can be expressed in terms of a mathematical function (e.g. polynomial, circular or elliptical arc). The number of unknowns then reduces to the number of coefficients of this function.

A variety of different parameter models for the reconstruction of the exterior orientation has been applied in the past /e.g. Wu 1986/. The functional model used here is based on extended collinearity equations /Hofmann et al. 1982; Müller 1991/. The exterior orientation parameters are determined only for so-called orientation images, which are introduced at certain time intervals. In between, the parameters of an arbitrary image line are computed from the values of the neighbouring orientation images, using a Lagrange polynomial (LP). One advantage of the LP approach is that the coefficients are the (unknown) exterior orientation parameters of the orientation images themselves /Ebner et al. 1992/.

In both practical examples four orientation images at a distance of about 2000 image lines were introduced for each orbit. The temporal variation was modeled by a 3rd order LP. XYZ object coordinates for the projection centres of these orientation images were derived from the SPOT header information. It was assumed that these coordinates have high relative and moderate absolute accuracy, i.e. that the shape of the orbit is well represented in these data, but not its absolute position in space. In order to model these accuracy properties, observation equations for the coordinates of the projection centres were formulated including additional offset parameters. The relative accuracy is expressed by the standard deviations assigned to the observation equations; the absolute accuracy is represented by the standard deviations of the offset parameters.

In the adjustment the ground coordinates of the object points, the exterior orientation parameters of the orientation images, and the offset parameters were considered as unknowns. They were estimated from the image coordinates, position observations derived from the SPOT header data, and coordinates of the GCP. Attitude observations of the exterior orientation parameters were not considered in the adjustment.

4. PRACTICAL PROJECTS

In this chapter, the results of two projects termed "Heidelberg" and "Priorat" respectively are reported in order to demonstrate the capability of the described approach.

4.1. Heidelberg

4.1.1. Project description. The images depict an area near Heidelberg, Germany (see figure 2). They were recorded on November 8 and 17, 1988 respectively. The base-to-height ratio amounts to 0.4. In the image from November 17 a few clouds in the north west and south west are visible, the other image is entirely free of clouds. The Rhine valley can be seen in the west of the scene, the upper north shows the Odenwald, a mountainous region with heights of up to 600 m.

834 GCP derived from high altitude aerotriangulation and well distributed over the images were given. These GCP have an accuracy of about 3 m in planimetry and 5 m in height. Since for the measurement of image coordinates no adequate digital device was available, these were measured stereoscopically on an analytical plotter using film hardcopies provided by SPOT IMAGE. The large number of GCP provides an excellent means for independent control.

For image matching ten points out of the available GCP were selected as starting points. The size of the template matrix was set to 19 * 19 pixels. From experience the following thresholds were introduced:

- 0.6 for the minimum correlation coefficient ρ_{min},
- 0.1 pixel for the maximum semi-major axis of the error ellipse,

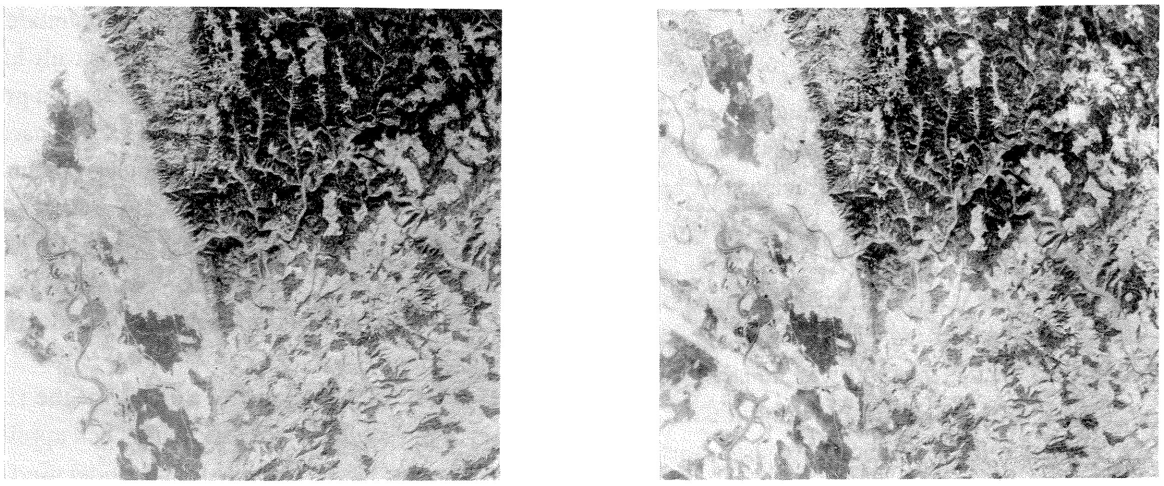

Fig. 2: The images for the project "Heidelberg"

- 2.5 pixels for the maximum difference to the initial values (corresponding to a maximum height difference between adjacent points of about 30 m),
- a maximum of 10 adjustment iterations.

For STEP different values were investigated. Since the computing time increases roughly by $STEP^2$, STEP should be chosen as large as possible. On the other hand it was found that neighbouring template matrices must overlap in order to achieve acceptable results. This means that STEP must be smaller than the size of the template matrix. Best results were obtained for values between 10 and 15. For STEP = 10 the algorithm provided more than 230.000 conjugate points. From the criteria mentioned above ρ_{min} = 0.6 proved to be the most important one. More than 70 % of those points, which were found to be incorrect, had a correlation coefficient below 0.6. The coverage of the images was fairly equal.

For the bundle adjustment the following information was introduced:

- interactively measured image coordinates of the 834 check points. The observations were treated as uncorrelated with an equal standard deviation of $\sigma_o = 5\ \mu m$.
- automatically derived image coordinates of about 6600 equally distributed conjugate points such that correlation coefficient of each point is a local maximum with the same σ_o,
- a varying number of equally distributed GCP with a standard deviation of $\sigma_{X,GCP} = \sigma_{Y,GCP} = 3$ m and $\sigma_{Z,GCP} = 5$ m.
- the XYZ object coordinates for the projection centres of the 2 * 4 orientation images with a relative accuracy of 1 m and with an absolute accuracy of 1000 m.

4.1.2. Results. The results can be seen in table 1. Besides the introduced number of GCP the root mean square errors of all three object coordinates derived from the check points are given. The following conclusions can be drawn:

- according to the accuracy requirements five to six GCP are sufficient in order to obtain accurate results,
- the accuracy in Z lies between 5 and 7 m,

Number of GCP	RMS errors of object coordinates		
	X	Y	Z
5	13.1 m	21.5 m	7.0 m
6	13.6 m	17.4 m	5.5m
10	12.9 m	16.2 m	6.2 m
15	12.8 m	15.5 m	4.3 m

Table 1: Results of point determination

- the planimetric accuracy is worse by a factor of 2 to 3. This phenomena has also been observed by other authors /Dowman 1992/. A possible explanation for this result is the following: most of the check points are road crossing centres, and thus lie in relatively flat areas. If a point at the border of the road rather than in the middle is measured by accident, the resulting height is still correct, but the derived XY coordinates are not. These identification errors can not be detected in the adjustment.
- the accuracy in X is better than in Y. This is a consequence of the use of line imagery: the parallel projection in flight direction (similar to the Y axis) is less stable than the central perspective in the direction perpendicular to the flight path.

With the determined elements of exterior orientation from six GCP a forward intersection was performed for each pair of conjugate points obtained from image matching. Subsequently a DTM was generated using the HIFI programme package /Ebner et el. 1988/. In order to determine the DTM quality, and thus to check the matching results, heights for the 834 check points were interpolated from the derived DTM and compared to the known values. An empirical standard deviation of 10.8 m was obtained. This value represents an independent check of the whole procedure (matching, point determination, DTM generation) over the entire image. It must be regarded as a very good result considering the small base-to-height ratio of 0.4.

The generation of an orthophoto is a standard task given the results computed so far. In this project each orthophoto pixel was projected into one of the images (the cloudfree image from November 8) using the pixel-by-pixel method /Mayr, Heipke 1988/. Since the necessary orientation elements are given for each image line and thus for each point in image space after the bundle adjustment, but not explicitly for an arbitrary point in object space, the transformation was carried out iteratively.

4.2. Priorat

4.2.1. Project description. The second set of test data was provided by the Institut Cartografic de Catalunya, where SPOT panchromatic scenes are being used since 1988 for the production of orthophoto maps at 1 : 50 000 scale. For that purpose a stereopair around Priorat, South Catalonia was available. The images were recorded on September 3 and 9, 1988 with 13.5 and 17.3 degrees sensor inclination respectively and a base-to-height ratio of 0.6. The image coordinates of nine conjugate points were measured interactively in both digital images. Additionally about 30 GCP are given, which were identified and measured in the images; however, the measurements were performed in either the left or the right image, i.e. no conjugate GCP are available.

Image matching was performed in the same way as described for the project "Heidelberg". Using the nine conjugate points as starting points and a value of 10 for STEP more than 250.000 conjugate points were obtained.

For the bundle adjustment about 1300 equally distributed points were selected such that the correlation coefficient of each point is a local maximum. These points were processed together with seven GCP in each of the two images and the XYZ coordinates of the projection centres. The following standard deviations were assumed:

- 5 μm for the image coordinates of the points,
- 1 m for the XYZ coordinates of the GCP,
- 1 m and 1000 m for the coordinates of the projection centres (for the relative and absolute accuracy respectively).

4.2.2. Results. In this project no independent check points were available. However, the derived heights of the 1300 points were checked against the countrywide DTM data base of Catalonia, which is available for the complete territory with an accuracy of approximately 1 - 2 m. The RMS error of the empirical standard deviations of the object points results in μ_Z = 8.8 m.

5. CONCLUSIONS

It has been demonstrated that automatic photogrammetric processing of SPOT imagery for point determination and DTM generation using very few control points is feasible. Independent checks revealed an accuracy of about 15 m in planimetry and 7 m in height.
An important issue, which has not been discussed in this paper, is the low reliability of point determination using SPOT imagery. Due to the local redundancy of 1 for each object point (4 observations, 3 unknowns), the ability to detect observation errors in the adjustment is restricted. A significant improvement in terms of reliability can be achieved , if e.g. 3-line scanner systems are used.
In future an interactive procedure for quality control on all levels of processing will be incorporated into the system. In this way also image areas showing low texture can be reliably matched. For a comfortable measurement of the image coordinates of the GCP and for further processing (e.g. visualization of the results, generation of follow-up products) the software should be integrated into a digital photogrammetric workstation.

6. ACKNOWLEDGEMENT

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