CALIBRATION OF DIRECTLY MEASURED POSITION AND ATTITUDE BY AEROTRIANGULATION OF THREE–LINE AIRBORNE IMAGERY

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ABSTRACT

The registration and geometric rectification of airborne scanner imagery is a prerequisite for the processing and analysis of this type of images. Within the paper the geometric processing of scanner imagery acquired from the Digital Photogrammetric Assembly (DPA), which is an airborne camera consisting of three pan–chromatic line arrays for stereo imaging and four line arrays for multi–spectral imaging will be described. The sensor system is completed by a module consisting of a differential GPS receiver configuration and an Inertial Navigation System (INS). Within the paper the georeferencing by an integrated GPS/INS component in combination with an aerial triangulation based on the three–line principle of the camera is presented. Additionally, the generation of DTM and ortho images from this type of imagery is demonstrated.

1 INTRODUCTION

Up to now digital full frame cameras with an image format comparable to conventional analog photogrammetric cameras do not exist. Alternatively, linear CCD arrays which are available at affordable prices can be used in order to benefit from a direct digital data acquisition. Since the CCD is oriented perpendicular to the flight direction of the aircraft, image strips are generated due to the aircraft motion by scanning the terrain surface (pushbroom principle). If multiple sensors are combined parallel to each other multispectral and/or so–called three–line imagery can be obtained. Within these three–line systems the central CCD linear array is looking to the nadir whereas the two others look backward and forward, respectively.

In principle this three–line configuration enables the reconstruction of the flight path. The exterior orientation can be computed for each scan–line applying the well known coplanarity or collinearity constraints for tie and control points. The exclusive use of the three–line geometry for georeferencing is sufficient for spaceborne applications, where additional constraints can be formulated due to the smooth flight trajectory. For airborne applications the direct measurement of position and attitude of the imaging sensor is indispensable due to the high motion dynamics of these environments. Even though the required exterior orientation can be provided by a GPS/INS system alone, the combination of GPS and INS with the three–line image geometry in an aerotriangulation represents the most flexible approach. The integration of the GPS/INS component into an automatic aerotriangulation of the airborne three–line scanner imagery is e.g. required to increase the reliability and accuracy of georeferencing. If high precision applications are aspired the whole sensor system has to be calibrated. These calibration terms include corrections for the in–flight alignment of the INS, offsets and drifts for the INS measurement, and the misalignment between the GPS, INS and camera system. For the calibration tie points between the forward, nadir and backward looking channel are determined by automatic image matching. Similar to a standard GPS–based aerotriangulation a small number of ground control points is required to enable datum transformation and to provide control information in order to increase the reliability and precision of the georeferencing process.

Following a short discussion of the different approaches for georeferencing airborne three–line imagery (section 2) an integrated approach using GPS, INS and aerotriangulation will be described (section 3). The importance of the different sensor components for the georeferencing depends on the aspired application, the required accuracy and the costs and availability of the necessary hardware parts. Therefore special interest will be paid to the analysis of the error types which are introduced by the different sensors. The benefits of an integrated georeferencing process taking advantage of the complementary error behavior will be demonstrated.

After georeferencing the image data, the terrain surface i.e. a Digital Terrain Model (DTM) can be obtained by again making use of the along–track stereo capability of the camera. Similar to the DTM acquisition from full frame imagery, where two aerial photographs are mutually oriented to achieve stereoscopy by a relative orientation, the three original image strips acquired by the forward, nadir and backward locking channel have to be transformed geometrically for the same purpose. Each scan–line is projected to a planar surface defined by a horizontal plane at the mean terrain height using the exterior orientation parameters determined in the previous step. Within this so–called rectification step distortions in the original images resulting from the high frequency motion of the aircraft are eliminated. Hence problems of the matching procedure resulting from these distortions are avoided and a dense grid of parallaxes can be measured automatically in order to derive the DTM. In addition to the automatic generation of DTMs from three–line imagery the production of ortho images will be presented in section 4.

2 PRINCIPLES OF GEOREFERENCING THREE–LINE IMAGERY

Similar to full frame images three–line imagery can be georeferenced by applying geometric constraints in the framework of an aerotriangulation, if a sufficient number of tie and control points is available. Alternatively, direct georeferencing can be applied using a GPS/INS module which is integrated by a Kalman filter. Both approaches are discussed in the following in order to motivate a combination of both methods by using a GPS/INS based aerotriangulation of three–line imagery.

2.1 Three–line geometry

Applying the standard method of photogrammetry, the six parameters of camera orientation $(X_0, Y_0, Z_0, \omega, \varphi, \kappa)$ can be determined by geometric constraints between object points and the corresponding image coordinates. Within this method connection between multiple images is formed by measuring corresponding points in different images and by enforcing intersection constraints between them. Additionally image coordinates of known control points are measured and related to the ground assuming a perspective projection.

In case of pushbroom imagery, parameters of the exterior orientation are required for each three–line image, consisting of a triple of scan lines looking in the forward, nadir and backward direction. In principle for that purpose tie points have to be determined for each scan line. Since this is impossible for practical applications, the parameters of the exterior orientation are only determined for certain positions, so–called orientation points. Between these orientation points, the parameters of the exterior orientation are interpolated to calculate position and orientation for the remaining scan lines. Physical models of the trajectory can be additionally utilized for that purpose. The main advantage of this approach is that – excepting the required control points – no auxiliary data acquisition is necessary since all required information is contained in the images. Especially for spaceborne applications sufficient accuracies can be reached due to the smooth trajectory of satellites and due to the applicability of orbital constraints, which additionally supports the solution and the interpolation between orientation points. For the spaceborne three–line pushbroom camera MOMS sub–pixel accuracy has been reported by (Ohlhof, 1995) or (Baltsavias and Stallmann, 1996).

For airborne applications due to the the high motion dynamics an interpolation between orientation points without auxiliary measurement is no longer feasible. For that purpose position and orientation have to be determined by additional sensors like INS. Still the three–line geometry is primarily utilized for georeferencing by the reconstruction the exterior orientation for a number of orientation points using coplanarity and collinearity condition provided by tie and control points (Müller et al., 1994). Within this approach an INS provides auxiliary data for interpolation between the orientation points. Since a large number of tie points is required, automatic image matching is applied. This results in a large computational effort compared to the automatic aerotriangulation of full frame imagery or compared to direct georeferencing. Problems might occur for low–contrast areas or forest areas, since automatic image matching can be insufficient in these regions to provide the required amount of tie points.

2.2 Direct georeferencing

Direct georeferencing, i.e. the direct measurement of the exterior orientation of an imaging sensor by an integrated system consisting of receivers of the Global Positioning System (GPS) and a strapdown Inertial Navigation System (INS) has been used for a number of applications. Within these approaches the INS data are integrated with GPS double differential measurements in a Kalman filter configuration. Accuracies for camera position of 15 cm and 0.015° for camera orientation have been verified in several tests. In these test aerotriangulation with standard photogrammetric cameras was used to provide reference values for the exterior orientation. By a spatial intersection of image rays using the directly measured positions and orientations of the camera a standard deviation of 20 to 30 cm was reached for the ground coordinates of the reference points from flying heights of 1000 m above ground (Scherzinger, 1997), (Skaloud et al., 1996).

The INS error model, which is estimated by the Kalman filter usually includes navigation errors (attitude, position, velocity) and correlated sensor noise terms (gyro drift, accelerometer biases). Additional calibration terms have to be determined due to the physical displacement of the GPS antenna and the INS system from the perspective center of the imaging sensor. Hence, a constant displacement vector has to be added to the GPS/INS integrated position to obtain the position of the camera perspective center in the GPS reference frame. The components of the translation vector are measured by conventional surveying techniques before the flight mission. Additionally, a constant misalignment exists between the INS and the imaging sensor and has to be taken into account to obtain correct orientation parameters of the camera perspective center. Since the sensor axis in both devices can not be observed, this misalignment has to be determined by an in–flight calibration using a small number of tie and control points.

One problem while integrating GPS/INS is the determination of heading, which will usually be less accurate than the determination of roll and pitch. Actually, the better the constant velocity condition is maintained during the flight, the better roll and pitch will be determined and the poorer the estimation of heading will be. Only when the aircraft manoeuvres in such a way that major horizontal accelerations are introduced, the heading accuracy will be improved. GPS updates are sufficient to eliminate pitch and roll oscillations to the level of INS attitude noise, but similar results cannot be achieved in heading without a regular pattern of large horizontal aircraft accelerations (Schwarz, 1995).

Within the decentralized Kalman filter approach, the GPS observations are used as external updates to correct systematic errors of the INS position and orientation. The INS positions can be used to bridge GPS outages during flight turns since GPS carrier phase cycle slips or losses of lock can be detected and corrected. Still a GPS trajectory without systematic errors is required. Even though GPS positioning methods have been established for several years, this might not be possible for all applications. Constant systematic errors are still likely to happen, especially if the ground receiver station is placed at a great distance from the mission area (Ackermann, 1996). Large distances up to 500 km or more, can be highly essential for some applications. For standard applications using full frame imagery, these systematic errors can be compensated in GPS supported aerial triangulation, where GPS positioning is connected with the stable geometry of aerial block triangulation.

3 AEROTRIANGULATION BY COMBINING GPS/INS AND THREE–LINE GEOMETRY

Similar to GPS supported aerial triangulation an integrated approach should be applied for the georeferencing of three–line imagery by combining GPS, INS and three–line geometry in an aerial triangulation. This approach should

- enable a control of the georeferencing process by increasing the reliability of the whole system.
- allow an operational processing in terms of
  - the number of required tie and control points, which should be less or equal compared to standard aerial triangulation with full frame imagery.
  - the potential of an automated processing.
- enable a self–calibration of the camera.
- provide a higher accuracy compared to direct georeferencing by GPS/INS integration, particularly if only data for the single image strips are available.

The general idea is to perform an aerotriangulation of the three–line imagery in order to calibrate the position and attitude, which are provided from the GPS/INS module. Similar to the approach proposed by (Gibson, 1994), these terms contain INS error terms,

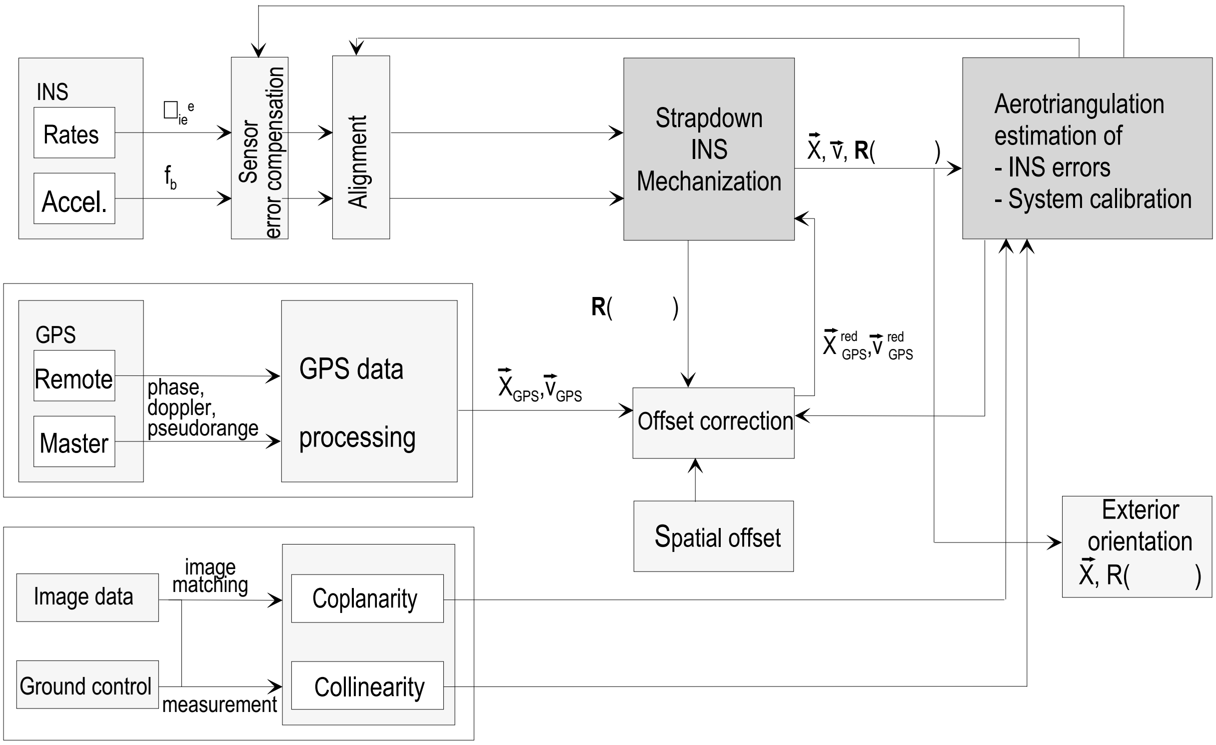

Figure 1: Workflow of georeferencing.

as well as parameters for system calibration resulting from the physical offsets of the different sensors.

The basic concept of our algorithm, which is presented in figure 1 is as follows. First a strapdown INS mechanization is performed, which is supported by the GPS measurement. Similar to the Kalman filter concept, an INS error model including navigation errors, sensor noise terms and additional calibration terms has to be provided for INS mechanization. After mechanization the error terms are updated using the values estimated in the aerotriangulation step. This procedure – strapdown INS mechanization and aerotriangulation – is iteratively repeated until the final solution is reached.

3.1 INS error terms

The mechanization of the INS angular rates and linear accelerations is done in a geocentric earth fixed coordinate frame. The use of this coordinate system is straightforward, because the GPS measurements are obtained in the same frame and therefore no additional transformations are necessary. More details about the algorithm can be found in (Wei and Schwarz, 1990).

For the initial mechanization, the INS measurements are reduced by the sensor offsets including the gyro drift $\omega_1, \varphi_1, \kappa_1$ and the acceleration offsets, which are estimated by assuming a straight flight line resulting in zero values for the mean accelerations. Additionally, at the beginning of the integration, the initial relation between the INS body frame and the local level frame is necessary. The initial position for each flight line is obtained by GPS. A first estimation of the initial yaw angle κ_0 is calculated from the GPS positions rotated to the local level frame. The initial roll angle ω_0 and pitch angle φ_0 are assumed to be zero. Using the estimated initial alignment and sensor offsets the mechanization is done, whereas the INS derived positions are updated via GPS at every GPS measurement epoch.

After integration for each scan line k of the image strips the parameters of exterior orientation (position X_k, Y_k, Z_k, attitude $\omega_k, \varphi_k, \kappa_k$) are available. The positioning accuracy is mainly dependent on the accuracy of the GPS positioning. The attitudes are corrupted by a constant offset $\omega_0, \varphi_0, \kappa_0$ due to the incorrect initial alignment and the unknown misalignment between the INS body frame and the image frame. Additionally, there are some remaining drift effects $\omega_1, \varphi_1, \kappa_1$ caused by uncorected sensor offsets.

These remaining errors are corrected in the following aerial triangulation step. In order to determine the unknown offset parameters and time dependent drift parameters standard photogrammetric techniques for relative (coplanarity condition) and absolute orientation (collinearity condition) can be used. For reasons of simplicity and flexibility the standard formula of the collinearity condition will be utilized:

$$\vec{X}_P = \vec{X}_0 + \lambda \mathbf{R} \cdot \vec{x}_P \tag{1}$$

where

$\vec{X}_0 = \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix}$	coordinates of perspective center
$\vec{X}_P = \begin{bmatrix} X_P \\ Y_P \\ Z_P \end{bmatrix}$	coordinates of object point
$\mathbf{R}(\omega, \varphi, \kappa)$	rotation matrix
$\vec{x}_P = \begin{bmatrix} x_P \\ y_P \\ -c \end{bmatrix}$	coordinates of image point
λ	scaling factor

The coordinates of perspective center $\vec{X}_0$ and the orientation $\mathbf{R}(\omega, \varphi, \kappa)$ are in principle provided by the GPS/INS system. As discussed earlier the INS orientations have to be corrected by an offset and drift parameter. Hence, the equation (1) is a function of the unknown INS error parameters $\hat{\omega}_0, \hat{\varphi}_0, \hat{\kappa}_0, \hat{\omega}_1, \hat{\varphi}_1, \hat{\kappa}_1$. These parameters are estimated in a least squares adjustment approach for each image strip. The corrected attitudes $\bar{\omega}_k, \bar{\varphi}_k, \bar{\kappa}_k$ are calculated using equation (2) for each scan line:

$$\begin{aligned} \bar{\omega}_k &= \omega_k + \hat{\omega}_0 + \hat{\omega}_1 \cdot t \\ \bar{\varphi}_k &= \varphi_k + \hat{\varphi}_0 + \hat{\varphi}_1 \cdot t \\ \bar{\kappa}_k &= \kappa_k + \hat{\kappa}_0 + \hat{\kappa}_1 \cdot t \end{aligned} \tag{2}$$

Optionally, offset and drift parameters for the sensor position can be estimated in order to correct possible systematic errors of the GPS trajectory.

3.2 System calibration

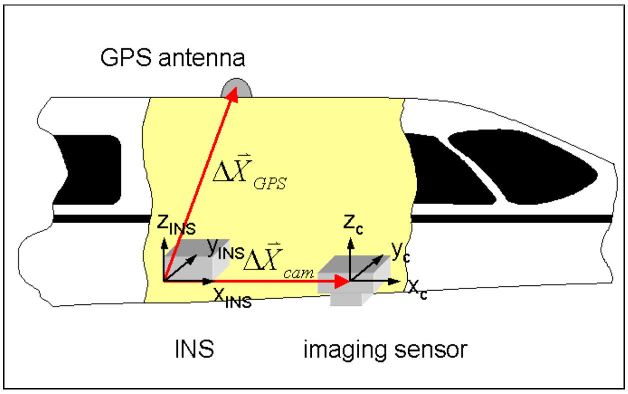

Figure 2: Sensor configuration

The physical displacement of the GPS antenna and the INS system from the perspective center of the imaging sensor as well as the constant misalignment between the INS and the imaging sensor have to be additionally taken into account. These parameters required for system calibration are also presented in figure 2. For this reason the collinearity equation (1) has to be modified to:

$$\vec{X}_P^m = \vec{X}_0^m + \mathbf{R}_b^m \left[\lambda \cdot \mathbf{R}_i^b \cdot \vec{x}_P^i + \Delta\vec{X}_{cam}^b - \Delta\vec{X}_{GPS}^b\right] \tag{3}$$

where

$\vec{X}_P^m = \begin{bmatrix} X_P \\ Y_P \\ Z_P \end{bmatrix}^m$ object point vector in the mapping frame (m).

$\mathbf{R}_b^m(\bar{\omega}_k, \bar{\varphi}_k, \bar{\kappa}_k)$ rotation from the INS (body) system (b) to the mapping frame.

$\vec{X}_0^m = \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix}^m$ GPS position of the antenna phase center in the mapping frame.

$\mathbf{R}_i^b(\Delta\hat{\omega}, \Delta\hat{\varphi}, \Delta\hat{\kappa})$ rotation from the image coordinate system to the body frame.

$\vec{x}_P^i = \begin{bmatrix} x_P \\ y_P \\ -c \end{bmatrix}^i$ image vector in image frame (i).

$\Delta\vec{X}_{cam}^b = \begin{bmatrix} \Delta X_{cam} \\ \Delta Y_{cam} \\ \Delta Z_{cam} \end{bmatrix}^b$ offset from the INS to the imaging sensor given in the body frame.

$\Delta\vec{X}_{GPS}^b = \begin{bmatrix} \Delta X_{GPS} \\ \Delta Y_{GPS} \\ \Delta Z_{GPS} \end{bmatrix}^b$ offset from INS to GPS denoted in the body frame.

In contrast to a standard aerial triangulation the sensor orientation and position is provided by the GPS/INS system, i.e. the parameters of the exterior orientation $\vec{X}_0^m$ and ω_k, φ_k, κ_k are directly measured. Within the aerial triangulation the INS errors $\hat{\omega}_0$, $\hat{\varphi}_0$, $\hat{\kappa}_0$, $\hat{\omega}_1$, $\hat{\varphi}_1$, $\hat{\kappa}_1$ (see equation 2) and the misalignmnent $\Delta\hat{\omega}$, $\Delta\hat{\varphi}$, $\Delta\hat{\kappa}$ between the INS and the camera have to be determined. The displacement $\Delta\vec{X}_{GPS}^b$ between GPS antenna and the imaging sensor, as well as the offset $\Delta\vec{X}_{cam}^b$ between INS and camera can be measured by conventional terrestrial surveying. Optionally, it is also possible to estimate systematic errors of the GPS trajectory in the adjustment. For each unknown object point (i.e. tie, new and check points) the coordinates $\vec{X}_P$ have to be determined in the adjustment. As observations for the adjustment coordinates of corresponding image points in the image strips have to be provided. In our approach signaled points are measured manually, additional tie points are provided by automatic intensity based image matching (Förstner, 1993).

The INS error terms, the parameters for system calibration, and the object point coordinates are determined by iteratively applying the INS mechanization followed by the bundle adjustment. After this process the corrected exterior orientation for each scan line k as well as the object point coordinates are available.

3.3 Practical results – the DPA experiment

The procedure discussed above was applied using data provided by the DPA sensor system. The development of this system started in the late eighties and was done by the Daimler–Benz Aerospace (DASA), formerly the Messerschmitt–Bölkow–Blohm (MBB) company.

The basic parameters of the optical part of the DPA system are given in table 1. The stereo module consists of a double lens, composed of three CCD lines (forward, nadir and backward view) with 6000 pixel. Two linear arrays are optically buttoned, respcetively, providing wide–angle geometry with a total width of 12000 pixel. The convergence angle is $\pm 25^\circ$ between the nadir, backward and forward looking channel, respectively. At a flying height of 2000 m above ground the ground pixel size is 25 cm. The camera is completed by a spectral module for the acquisition of multispectral images in the red, green, blue and near infrared spectral range.

Stereo module	
Focal length	80 mm
Line array	2×6000 pix/line
Pixelsize	10 μm
Data resolution	8 bit
Convergence angle	±25°
Spectral range	515 – 780 nm
Spectral module	
Focal length	40 mm
Line array	6000 pix/line
Pixelsize	10 μm
Data resolution	8 bit
Spectral range	440 – 525 nm
	520 – 600 nm
	610 – 685 nm
	770 – 890 nm

Table 1: Basic DPA camera parameters

For the geometric accuracy evaluation of the integrated sensor system a testflight over the well surveyed test site Vaihingen/Enz (size 4.5×10 km^2) near Stuttgart, Germany, was carried out. For ground control 200 points using white PVC plates or paintings with the size of 1×1 m^2 were signaled. A subset of 38 points was measured using a network of static differential GPS baselines. The remaining ground control points were determined using traditional photogrammetric aerial triangulation. The obtained accuracy was 2 cm for the horizontal and 3 cm for the vertical components. The image coordinates were measured manually in the original three images of the DPA. All ground control points were signaled and could be easily measured in that data.

To evaluate the point positioning accuracy several runs of the orientation program using different control point distributions, number of tie points, strip length and number of correction parameters were performed. For a typical run an image strip of 10 km length and 3000 m width 6 control point were used, all other signaled points were included as unknowns in the bundle adjustment and used as check points to control the georeferencing. The accuracy derived from the check point differences in image space was 30 to 40 μm rms equivalent to 3 to 4 pixel. The corresponding accuracy in the object space was 0.7 to 1.0 m in planimetry and 1.5 to 2.0 m in height. The results were quite disappointing since the aspired subpixel accuracy in image and object space could not be achieved. The use of more control points and tie points as well as higher order error terms for the orientation parameters provided by the INS did not result in a significant improvement of accuracy.

An analysis of the acquired INS data showed, that the utilized hardware did not work properly. The utilized strap–down six degree of freedom INS is manufactured by Sagem and consists of two Sagem GSL82 two axes dry tuned gyroscopes and three Sundstrad QA2000 accelerometers. Nominally the noise (rms max) of the gyro is $5 \cdot 10^{-2}$ °/s. This is a usual value for a navigation grade INS, which is adequate for our application. Caused by an hardware error in the A/D conversion during data acquisition the resolution of the gyroscopes and of the accelerometers was reduced significantly. This resulted in a sensor noise approximately three times higher than the nominal value. Simulations showed that most of the error budget of the georeferencing process can be explained by this fact. Since the hardware error has been eliminated in the meantime, further tests will follow in the near future.

4 DTM GENERATION

For georeferencing, the exterior and interior orientation of the imaging sensor as well the geometry of the sensed surface has to be known. Therefore, the georeferencing is completed by the acquisition of a Digital Terrain Model (DTM).

Due to the flight movement scanner images show distortions mainly caused by attitude variations of the camera. These distortions not only affect the visual impression, they also prevent the stereo viewing and result in problems for automatic image matching procedures. At least a number of points can be determined also in the original images by image matching but a dense parallax measurement, which is required for DTM acquisition is not feasible. In order to eliminate these distortions a rectification process is applied.

4.1 Rectification

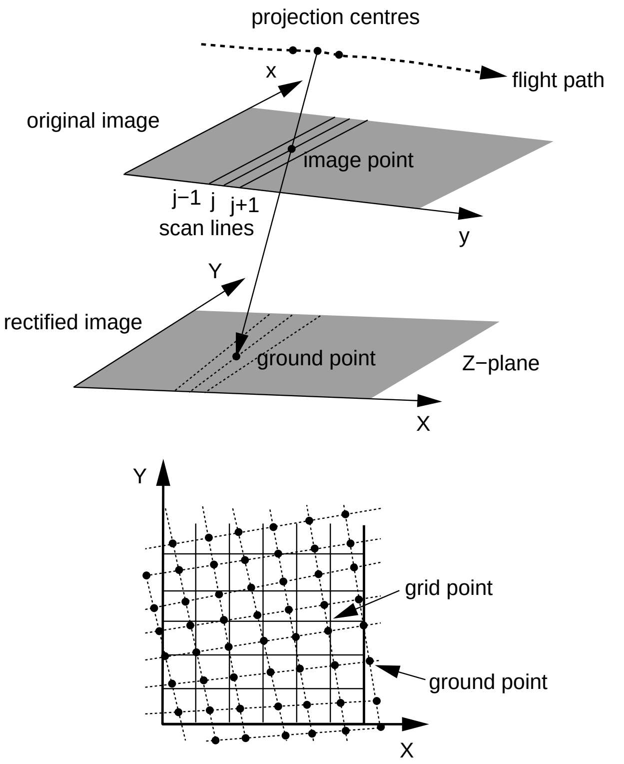

Figure 7: Image rectification

For the rectification a horizontal plane located at a mean terrain height is defined (Z–plane). As indicated in figure 7 the direct method of image rectification is applied. Each pixel in the image space is projected on the Z–plane utilizing orientation and position of the respective scan line. The resulting ground points are irregularly distributed in this plane and carry the grey value of the corresponding image points. The transfer to the regular grid is solved by interpolation using weighted averaging of grey values of all neighboring points within a certain radius. The weight is chosen reciprocal to the distance between the grid points and its neighbors.

The rectification of the stereo channels results in nearly epipolar images. Depending on the terrain height corresponding image points are shifted parallel to the flight direction. Due to a horizontal aircraft motion perpendicular to the ideal straight line of flight, a small base perpendicular to the flight direction can occur. Since this base (e.g. 10 to 20 m) is rather small compared to the base in the direction of flight, the effect for stereo viewing and image matchig is negligible. Nevertheless, for airborne scanner images only quasi–epipolar images can be generated, remaining small vertical parallaxes must be expected during stereo processing.

An example for the generation of epipolar imagery from three–line pushbroom imagery is given in figures 3 to 6. Figures 3 and 4 show image strips acquired by the DPA stereo module at a flying height above ground of 2000 m. The figures present data from the forward and the nadir channel, respectively. Stereo viewing is

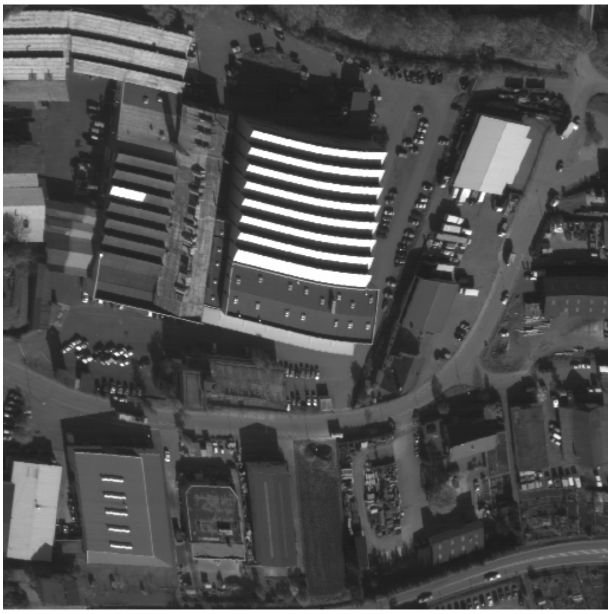

Figure 3: Original image of the forward channel

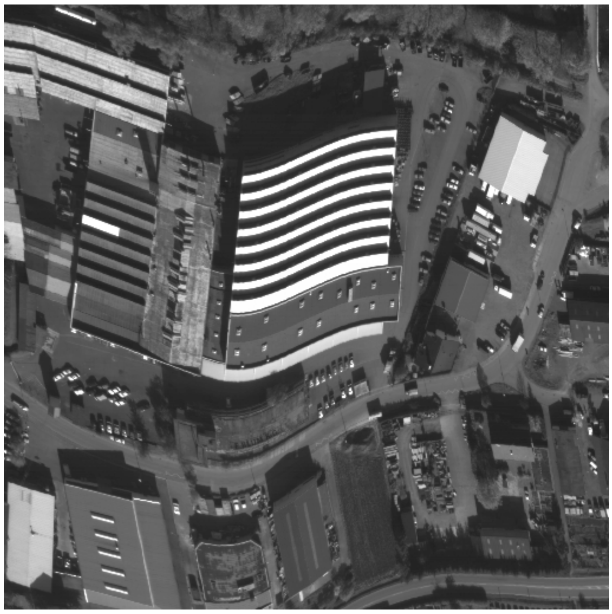

Figure 4: Original image of the nadir channel

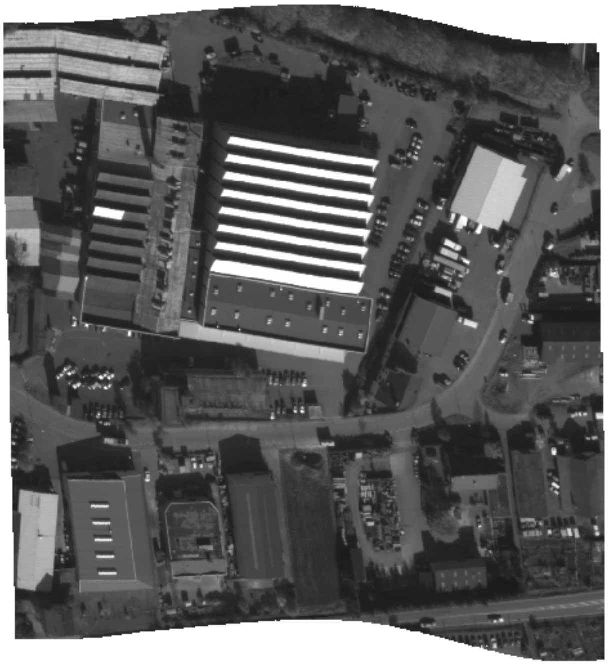

Figure 5: Rectified image of the forward channel

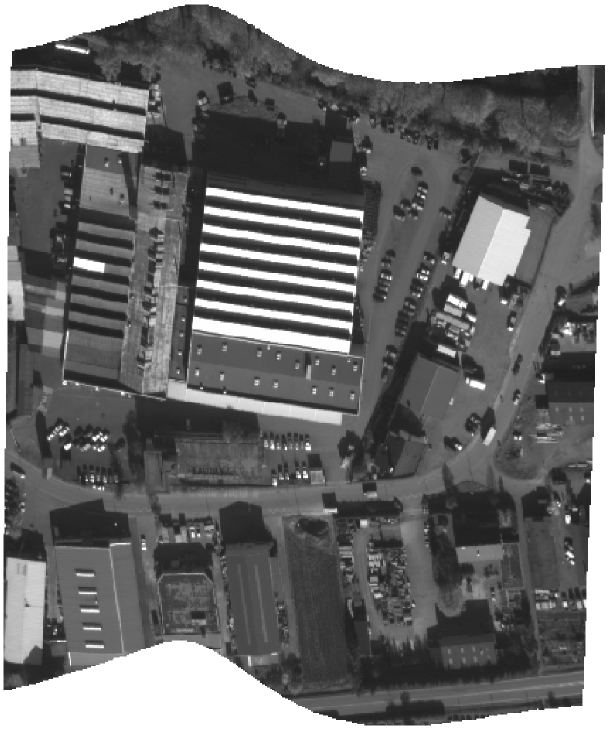

Figure 6: Rectified image of the nadir channel

prevented by the distortion resulting from the motion of the camera during the flight. Figure 5 and 6 show the quasi–epipolar images generated by the rectification process. These images are used for parallax measurement in the DTM generation process.

4.2 Point determination in rectified images

Within rectified imagery, the application of automatic image matching as well as interactive measurement is possible with the same performance and quality than for full frame imagery. Nevertheless, in contrast to the processing of full frame imagery, the rectified images can not be directly used for point determination by spatial intersection. Within the original scanner imagery the y–coordinate of an image point coincides with the index of the scan line, i.e. the corresponding parameters of the exterior orientation can be directly accessed. After the rectification step this simple relation between pixel coordinates and corresponding exterior orientation is lost. Due to the flight movement, scan lines projected to the Z–plane are not parallel any more. Therefore the direct correspondence between the coordinate in the direction of flight and the time of pixel acquisition is not valid any more.

Corresponding points P_1 and P_2 measured in the rectified (quasi–epipolar) images refer to one point P in 3D object space (Figure 8). Due to the assumption of an average terrain height these points have incorrect coordinates in object space: different planimetric coordinates $P_1(X_1, Y_1)$ and $P_2(X_2, Y_2)$ and the height of the rectification plane $Z = Z_1 = Z_2$. The correct position in 3D object space can be derived by a two step procedure.

1. Back projection of the corresponding points P_1 and P_2 into the

original image space P’ and P” by collinearity condition.

2. Spatial intersection of the corresponding rays using of the exterior orientation results in correct object coordinates X_P, Y_P, Z_P.

Compared to the processing of full frame imagery the back projection is more expendable since the scan line in which a object point is imaged has to be determined. The location of the corresponding scan line can be found with an iterative search algorithm. After starting with an initially guessed line in the image strip, the corresponding scan line is found by minimizing the perpendicular distance to the corresponding CCD line in the camera frame.

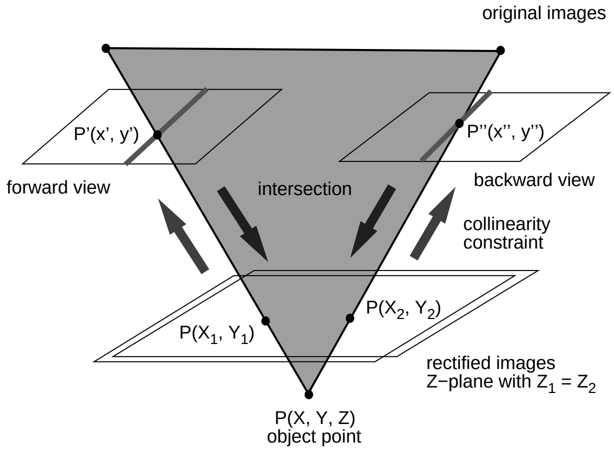

Figure 8: Point determination in rectified imagery.

4.3 Generation of ortho images

Even for large photogrammetric blocks consisting of conventional full frame imagery the corresponding image for each terrain point can be easily determined after aerial triangulation. Afterwards the terrain point can be projected into the image in order to define the corresponding grey value by applying the well known collinearity equation. This procedure is also known as indirect method of ortho image generation. In principle, the same method can be applied for scanner imagery. In contrast to full frame images a pushbroom image strip consists of a large number of single image lines, which have a width of one pixel. For this reason, the number of image lines, i.e. single images is considerably larger compared to a block consisting of full frame images. Therefore the effort for the determination of correspondences between grey values, i.e. image coordinates and terrain points during ortho image computation is much larger for pushbroom imagery. In principle, the problem of ortho image generation from pushbroom imagery by the indirect method is very similar to the problem of back–projecting points from rectified imagery to the original image strips during point determination as described in section 4.2. For computational reasons it can be better, to apply a ortho image generation by the direct method, similar to the the rectification step described earlier. For that purpose the image ray is no longer intersected with a horizontal Z–plane, but with the DTM surface.

A result of the DTM and ortho image generation from DPA imagery is presented in figure 9. The figure shows a 3D visualization of a DTM acquired by automatic intensity based image matching between the rectified forward and backward looking channel. The overlaid ortho image was generated using the nadir looking channel. The DTM represents a region of 2×3 km^2 and was not height exaggerated for visualization.

5 CONCLUSION

Within this article an approach for the automatic georeferencing of three–line pushbroom imagery has been presented. The direct georeferencing by an integrated GPS/INS component is combined with an aerial triangulation based on the three–line principle of the camera. Within this aerial triangulation step correction parameters for the exterior orientation provided by the GPS/INS measurements as well as parameters for the calibration of the whole sensor system can be determined. The georeferencing is completed by a DTM and ortho image generation.

Compared to the photographic image acquisition the direct recording of digital imagery has a lot of benefits like the direct availability of the data and the higher dynamic range and spectral resolution of the digital images. Since up to now digital full frame cameras with an image format comparable to conventional analog photogrammetric cameras are not available, the digital image acquisition by linear CCD arrays is a very promising alternative. In contrast to full frame imagery, the direct measurement of position and attitude of the imaging sensor is vital for airborne scanner applications like three–line pushbroom cameras. In our opinion this has not to be considered as a disadvantage. The direct measurement of camera positions by differential GPS and the integration of this information into GPS–aided aerotriangulation has already become standard within the past decade. Applying the different components GPS, INS and aerial triangulation enable a reliable, accurate and very operational georeferencing of image data. Hence by the integration of INS a further change of photogrammetric techniques similar to the appearance of GPS can be expected also for the processing of full frame imagery.

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Figure 9: 3D perspective view of the ortho image draped over the DSM generated from DPA imagery

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