# ON THE PREFORMANCE OF DIGITAL AIRBORNE PUSHBROOM CAMERAS FOR PHOTOGRAMMETRIC DATA PROCESSING – A CASE STUDY

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## ABSTRACT

Within the paper the results of several studies will be presented, which have been carried out at ifp in order to evaluate the performance of digital airborne pushbroom cameras for photogrammetric data acquisition. In close cooperation with the respective system developers the DPA (Digital Photogrammetric Assembly) of DASA, the HRSC (High Resolution Stereo Camera) and the WAAC (Wide Angle Aircraft Camera), both of DLR have been tested. The aim of the paper is twofold. First the accuracy potential of the investigated systems is demonstrated. For that purpose the results of a photogrammetric point determination using imagery of the different systems collected over a well defined test field are presented. In the second part the photogrammetric processing chain covering the reconstruction of exterior orientation and point determination, but also tasks like DTM and ortho image generation will be compared for pushbroom and for full frame imagery. The discussion of theses differences will help to demonstrate the impact of applying pushbroom imagery during the standard photogrammetric evaluation process.

## 1 INTRODUCTION

Within the past decade the transition from analogue towards digital photogrammetric systems has almost been completed. Up to now the only missing link to close the chain of a completely digital workflow results from standard photogrammetric image recording, which is still based on analogue film material to be scanned for digitisation. For these reasons great effort has been made on the development of digital airborne camera systems, which currently are starting to appear. One of the main problems aggravating this development was the limited size of available CCD frames. In order to allow a simple substitution of the analogue film by a digital sensor, the extent of a CCD frame should coincide with the size of the conventional full film format at a pixel resolution of 9 – 14 µm. Due to the very small market and extremely low chip yield to be expected during the production of such devices, this type of sensor will not be available in a predictable future. The maximum extent of currently available CCD's covers only one forth of the imaging size of a standard aerial camera. Nevertheless, this limited size is not too crucial while aiming on image collection for small and medium-sized projects. Furthermore, problems resulting from the weaker block geometry during aerial triangulation can be avoided if direct georeferencing based on GPS/inertial measurement is applied. For these reasons a number of systems based on available full frame CCD technology are already operational (Thom and Souchon 1999), (Toth 1999). Image size and geometry comparable to conventional cameras can also be achieved based on available image frames if several synchronously operating digital camera heads are combined (Hinz 1999).

As an alternative, full frame images can be substituted based on linear CCD arrays applying the so-called pushbroom principle. Within this approach image strips are generated using a CCD perpendicularly oriented to the direction of flight. Since defect free linear arrays can be produced relatively simple, they are available at affordable prices. Electronic exposure control can be easily realized and multispectral and/or stereo imagery can be collected by combining multiple sensors parallel to each other. Cameras based on linear CCD sensors like the DPA (Müller et.al. 1994), WAAC (Sandau and Eckert 1996) or HRSC (Wewel et. al. 1999) were the first digital systems being used for airborne mapping applications. An overview on the parameters of these systems is given in Table 1. In Figure 1 to Figure 3 image samples of the different airborne pushbroom systems are depicted, which were collected for the studies to be discussed in this paper over the ifp test field close to Stuttgart, Germany. For comparison Figure 4 presents a scanned RMK image of the same area, additionally

Since aerial triangulation and photogrammetric point determination is rather different for pushbroom systems compared to standard approaches, which are usually applied for full frame imagery, the accuracy of this process has been a crucial issue during the evaluation of pushbroom systems. This topic will be discussed in the following section. Additionally, the use of linear imaging sensors is more difficult with respect to photogrammetric data processing and requires an increased computational effort during the subsequent processing chain including DTM and ortho image generation. This topic will be discussed in the second part of the paper.

| | WAAC | DPA | HRSC | RMK[a] (wide angle) |
|---|---|---|---|---|
| Focal length [mm][b] | 21.7/ | 80/40 | 175/175 | 153/153 |
| Field of view [deg] | 80 | 74 | 12 | 74 |
| Number of stereo lines | 3 | 3 | 5 | (1)[c] |
| Number of MS-lines | - | 4 | 4 | (3)[c] |
| CCD-line [pixel][d] | 5184 | 12000 | 5184 | 15300[e] |
| Pixelsize [µm] | 7 | 10 | 7 | 15[e] |
| Swath width [m][f] | 3360 | 3000 | 415 | 3000 |
| GSD [g] [m][f] | 0.65 | 0.25 | 0.08 | 0.20 |

Table 1: Parameters of tested camera systems

a: for comparison
b: stereo/multispectral module
c: B/W (1) or colour (3) or colour – infrared (3) films
d: stereo module only
e: scan resolution : 15 µm
f: flying height above ground: 2000 m
g: ground sampling distance

Figure 1: WAAC image (flying height 3000 m, GSD 1m)

Figure 2: DPA image (flying height 2000 m, GSD 25 cm)

Figure 3: HRSC image (flying height 3000 m, GSD 12 cm

Figure 4: RMK image (scanned at 15 µm resolution, flying height 2000 m, GSD 20 cm)

## 2 IMAGE REGISTRATION

In order to reconstruct the exterior orientation of the camera system, which is a major task during the evaluation of photogrammetric image data, different orientation methods can be applied. These approaches can be separated into direct and indirect methods. In classical photogrammetry based on full frame imagery the georeferencing problem is usually solved indirectly based on the application of geometric constraints between corresponding image and object points. For single image data this procedure is realised by spatial resection and is generalised to an aerial triangulation (AT) for multiple images. In that case the exterior orientation parameters for the perspective centre of each image are estimated as one group of the estimation process within a bundle block adjustment.

In principle this approach can be transferred from full frame to line imagery. Nevertheless, image geometry is much weaker in case of pushbroom imagery, since each image consists of one or - in case of multi-line scanners - multiple lines, which are recorded simultaneously. In case of three-line systems, like they were tested in this study, an image consists of a triple of scan lines looking in the forward, nadir and backward direction. In order to georeference these images, the orientation parameters have to be reconstructed for each image, i.e. each triple of scan lines. Assuming a data rate of 200Hz during image collection, resulting in a GSD of 40cm for the image strips at an aircraft velocity of 80m/s, 1200 unknowns have to be determined within one second for the reconstruction of camera positions $(X_0, Y_0, Z_0)$ and attitudes $(\omega, \varphi, \kappa)$. Obviously, the number of observations, i.e. available tie and control points is far from being sufficient to determine this large amount of unknowns. Therefore, additional information is required in order to model the changes in position and orientation between the points of exposure. For spaceborne applications this can be realized by applying an appropriate kinematic model. Polynomials and/or Kepler elements can be used in this context due to the smooth trajectory.

### 2.1 Direct georeferencing

For airborne applications, the high motion dynamics results in the need for a direct georeferencing. Thus, the direct measurement of the exterior orientation of the imaging sensor for example by an integrated GPS/inertial system is mandatory. Usually, these GPS/inertial measurements are integrated based on a decentralized Kalman filtering approach. Within this process, an optimal integration of GPS observations and data provided by an Inertial Measurement Unit (IMU) is performed, where the information from GPS (position, velocity) serves as update information for the master filter of inertial data processing. This master filter estimates the nine navigation error states (position, velocity, attitude) and additional error terms, which represent any other systematic error effects of the inertial measurement that cannot be separated (Scherzinger 1997).

For direct georeferencing, additional calibration terms have to be determined due to the physical displacement of the GPS antenna and the inertial system from the perspective centre of the imaging sensor. Hence, a constant displacement vector has to be added to the integrated position in order to obtain the camera perspective centre in the GPS reference frame. The components of the translation vector can be measured by conventional surveying techniques before the flight mission. Additionally, a constant misalignment exists between the inertial system and the imaging sensor. This so-called bore sight alignment has to be taken into account to obtain correct orientation parameters of the camera perspective centre. Since the sensor axis in both devices can not be observed directly, this misalignment has to be determined by an in-flight calibration using a small number of tie and control points.

Another problem during GPS/inertial integration 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 IMU attitude noise, but similar results cannot be achieved in heading without a regular pattern of large horizontal aircraft accelerations.

Several tests have shown the high potential of these integrated GPS/inertial systems for georeferencing of image data. One problem while generalising these results is the fact that the overall performance of the integrated GPS/inertial positions and attitudes is highly correlated with the quality of the used sensor components and the accuracy of the updating information from GPS. Even though the inertial measurement can be used to bridge short GPS outages or to detect small cycle slips of the carrier phase measurements, the overall performance will degrade, if the GPS position and velocity update information are of minor quality for a longer time interval. The correction of long term systematic errors is not possible. Especially in case of photogrammetric applications, where the distance between remote and master receiver can be very large due to operational reasons, at least constant offsets for GPS positions have to be expected resulting from insufficient modelling of the atmospheric errors. These long term errors cannot be modelled in the dynamic model of the filter and will introduce errors in the georeferencing process. For all these reasons, an integrated approach has to be applied for the georeferencing of pushbroom image data by combining and utilizing as many information from different sensors as possible, like GPS and inertial data, but also tie and control point observations in object and image space.

### 2.2 Combined aerial triangulation

Similar to the standard approach of GPS supported aerial triangulation, the combined aerial triangulation allows the modelling of remaining systematic errors like systematic long term errors in the orientation parameters from GPS/inertial integration. At least for the determination of the bore sight angles some observations from image space have to be taken into account. Additionally, using a combined approach additional parameters for system calibration (lever arms between the different sensor components) and self-calibration of the imaging sensor (e.g. focal length) can be introduced to increase the accuracy of direct georeferencing. Within this aerial triangulation the photogrammetric coplanarity (relative orientation) and collinearity (absolute orientation) constraints are used for the estimation of the error terms. Without going into details here, the standard collinearity equation

$$\mathbf{X}^m = \mathbf{X}_0^m + \lambda \mathbf{R}_P^m \cdot \mathbf{x}^P \quad (1)$$

has to be modified to

$$\mathbf{X}^m = \mathbf{X}_0^m + \mathbf{R}_b^m \cdot \left[ \lambda \mathbf{R}_P^b \cdot \mathbf{x}^P + \Delta\mathbf{X}_{Cam}^b - \Delta\mathbf{X}_{GPS}^b \right] \quad (2)$$

in order to consider the translation offsets $\Delta\mathbf{X}_{Cam}^b, \Delta\mathbf{X}_{GPS}^b$ between GPS, inertial system and imaging sensor as well as the rotational offset $\mathbf{R}_P^b$ between IMU and imaging sensor (bore sight alignment). The rotation matrix $\mathbf{R}_b^m$ from the body system $b$ of the inertial system to the mapping fame $m$, as well as the coordinates of the phase centre of the GPS antenna denoted in mapping frame $m$ are provided by the GPS/inertial system. Within a combined aerial triangulation applying GPS, inertial data and photogrammetric observations, these parameters can be expanded by correction terms to refine the GPS/inertial system exterior orientation parameters (Haala et al. 1998). In addition, terms for self-calibration of the imaging sensor can be determined.

## 3 PRACTICAL RESULTS

In order to check the geometrical accuracy of the different systems a number of testflight were conducted over the ifp photogrammetric testfield about 25km north-west of Stuttgart, Germany. The testfield consisted of approximately 130 signalised points covering an area of about 7km x 5km. Usually, a subset of 30 points was determined using static GPS baseline observations, the remaining points were calculated using standard aerial triangulation of analogue aerial images. Therefore, the ground control points were available with an accuracy of 2-3cm and could serve as reference points for the required accuracy investigations. In the following sections the results for object point determination by combined aerial triangulation for DPA, RMK and HRSC will be presented. Since these investigations presume a high geometric resolution of the imagery, the results for WAAC imagery will not be discussed, since for this system only image data with 1m pixel size was available.

### 3.1 Object point determination from DPA data

For DPA data originally the so-called three-line principle was employed as main source of information. In the original approach the exterior orientation of the camera is reconstructed for distinct points of time, so-called orientation points (Müller et al. 1994). Positions and attitudes between these orientation points are interpolated using the inertial data. The orientation determination is almost completely based on the photogrammetric constraints in this approach, even though the IMU provides direct measurements of the sensor orientations and these data are introduced in the adjustment. Due to this concept, hardware restrictions were accepted, which enable the collection of inertial data only for single image strips. The lack of a continuous inertial data collection prevents the application of a standard Kalman approach, which enables the determination of the initial attitude by a static or in-flight alignment. In-flight alignment is obtained from gyrocompassing and the combination of GPS derived velocities to the inertial measurements during aircraft maneuvers, which are usually performed before image data collection to provoke accelerations in all directions.

Instead, the initial orientation has to be added as additional unknown to the combined aerial triangulation process in case of DPA data. After integration of GPS and inertial measurements the parameters of exterior orientation (position $X_i, Y_i, Z_i$, attitude $\omega_i, \varphi_i, \kappa_i$) are available for every measurement epoch $i$. The positioning accuracy is basically dependent on the accuracy of the GPS positioning. The attitudes are mainly corrupted by a constant offset $\boldsymbol{\omega}_0 = \omega_0, \varphi_0, \kappa_0$ due to the incorrect initial alignment, which is assumed to be close to zero for the roll $\omega$ and pitch angle $\varphi$, whereas a rough initial heading $\kappa$ is obtained from the GPS trajectory. Usually, also drift errors $\boldsymbol{\omega}_1 = \omega_1, \varphi_1, \kappa_1$

caused by remaining sensor offsets are also present. In order to get highest accuracies for the georeferencing process, these errors have to be additionally determined by the combined aerial triangulation, resulting in the improved attitudes.

$$\overline{\boldsymbol{\omega}}_i = \boldsymbol{\omega}_i + \boldsymbol{\omega}_0 + \boldsymbol{\omega}_1 \cdot t \tag{3}$$

These terms, which represent the errors of the orientation parameters from the IMU have to be added to the calibration terms already described in equation (2). Even though this is a simplification of the true error behaviour, since additional errors introduced due to the correlations between the attitudes are not considered here, the best solution is obtained after a few iteration steps. The basic concept of our algorithm is as follows. First a strapdown inertial mechanization is performed, which is supported by the GPS measurement. Similar to the Kalman filter concept, an error model including navigation errors, sensor noise terms and additional calibration terms has to be provided for inertial mechanization. After mechanization the error terms are updated using the values estimated in the aerotriangulation step. This procedure - strapdown inertial mechanization and aerotriangulation - is iteratively repeated until the final solution is reached (Haala et al 1998).

For our tests image data was collected at a flying height of 2000m above ground, resulting in a GSD of 25cm. The accuracy derived from the check point differences in image space was 30 to 40µm RMS, which is equivalent to 3 to 4 pixels. The corresponding accuracy in the object space was 0.7 to 1.0m in planimetry and 1.5 to 2.0m 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. The large errors might be caused by uncorrected errors of the DPA inertial system, due to the fact that the IMU was never recalibrated and the spectral analysis of the inertial measurements from the described test showed significant differences compared to data from earlier flights.

### 3.2 Object point determination from RMK data

In order to evaluate the performance of state-of-the-art GPS/inertial systems for the direct measurement of the exterior orientation, a test on the direct georeferencing of a standard full frame analogue camera was carried out. For this purpose a commercial system (POS/DG310 from Applanix, Canada) was used in combination with a Zeiss RMK Top15 aerial camera. Within this test an accuracy in height of about 12 cm (RMS) and a horizontal accuracy of 6.0 cm could be confirmed for 1:13000 imagery collected at a flying height of 2000 m (Cramer 1999).

Since or this study strong block geometry and optimal system geometry was assured, the major importance of camera calibration for direct georeferencing could also be demonstrated. If standard AT is applied, a small error in the focal length of the camera can be compensated by an offset of the calculated $Z_0$ coordinates of the camera air stations. Point coordinates determined at the ground are not affected. In contrast to that, point determination by direct georeferencing is directly influenced by erroneous camera calibration. The accuracy mentioned above could only be obtained by correction of the focal length by 20µm. Otherwise systematic errors in the order of 24cm occurred for the Z-components. Since the ratio of systematic errors for the 1:13000 block and a second block of scale 1:6000 was more or less the same than the ratio between the image scales, it seemed most likely, that these error were not caused by the GPS/inertial orientation parameters, but resulted from the originally incorrect camera calibration and additional non-corrected, scale-depended errors like refraction.

### 3.3 Object point determination from HRSC stereo data

For the geometrical accuracy investigations of the HRSC camera stereo image data of three flight lines in east-west direction of about 10km length were processed. Due to the small swath width of about 600m for the HRSC camera and due to time constraints during the flight, only the middle part of the testfield was covered, and therefore only a subset of 63 ground control points was available for the accuracy tests. The flying height was 3000m above ground resulting in an image scale of 1:17000. The image data were recorded with a data rate of about 440Hz. Due to the mistuned aircraft velocity this resulted in a rectangular GSD of about 17cm in flight and 12cm across flight direction. For georeferencing the scanner system was completed with the integrated GPS/inertial system POS/DG, which was also used during the RMK-test described in the previous section, thus comparable accuracy could be expected.

Within these tests, the exterior orientations of the line imagery were obtained by two different methods. First, the orientations were calculated using the standard Applanix PosProc software for GPS/inertial integration. Using the combined AT software (see section 1.2) only the misalignment between IMU and image frame was estimated. For this test an offset in the height component had to be introduced as an additional unknown resulting from an inconsistency in the vertical coordinate of the GPS master station. Therefore, using the PosProc orientation parameters four parameters for calibrating the exterior orientations plus the unknown object coordinates of the check points were estimated in the combined AT. Alternatively, the GPS positions and the raw inertial measurements from the LR86 system were processed using the approach originally developed at *ifp* for the processing of the DPA data (see section 3.1). Within this software only the GPS/inertial data during the image strips were considered. Due to the missing in air alignment manoeuver, the GPS/inertial attitudes were falsified by constant offsets and linear drift effects. Therefore, these errors were introduced as additional unknowns in the combined AT to refine the preliminary orientations in an iterative adjustment.

For both methods object points on the ground were recalculated using the determined exterior orientations and compared to their reference coordinate values. First the direct georeferencing was done for each flight strip separately and second for the block formed by the three strips. Both orientation parameter sets from the Applanix Kalman filtering and smoothing procedure (PosProc) and the ifp processing were used. As mentioned before, the misalignment angles between IMU and image coordinate frame, the vertical offset and - for the ifp orientation parameters - the additional GPS/inertial error terms were estimated using 3-5 ground control points located in the corners of each image strip. For the processing of the complete block, 4 control points in the corners of the block were introduced.

| strip | Pts. ChP | $\sigma_0$ [μm] | East [cm] | North [cm] | Vertical [cm] |
|---|---|---|---|---|---|
| I | 17 | 6.4 | 17.2 | 3.9 | 17.7 |
| II | 40 | 4.6 | 8.3 | 3.3 | 16.0 |
| III | 14 | 4.3 | 8.2 | 3.4 | 23.7 |
| Block | 63 | 6.4 | 11.5 | 3.3 | 13.5 |

Table 2**:** Accuracy of object point determination from HRSC stereo imagery (exterior orientation from Applanix POS/DG system)

| strip | Pts. ChP | $\sigma_0$ [μm] | East [cm] | North [cm] | Vertical [cm] |
|---|---|---|---|---|---|
| I | 17 | 5.9 | 19.4 | 7.8 | 37.6 |
| II | 40 | 5.1 | 12.0 | 4.3 | 18.3 |
| III | 14 | 6.1 | 11.4 | 4.8 | 18.4 |
| Block | 63 | 6.0 | 21.6 | 7.3 | 15.0 |

Table 3: Accuracy of object point determination from HRSC stereo imagery (exterior orientation from *ifp*)

After applying the misalignment and IMU corrections, the accuracies of direct georeferencing as depicted in Tables 12 and 3 were obtained. Table 2 shows the RMS values using the orientations provided by the PosProc software, whereas Table 3 shows the same results (RMS) from the ifp approach using the combined AT to estimate additional error terms to correct the preliminary GPS/inertial orientation parameters. The results were obtained comparing the recalculated check points to their given reference coordinates. The comparisons were done using 14, 17 and 40 check points for the single image strips and 63 check points for the whole block, respectively.

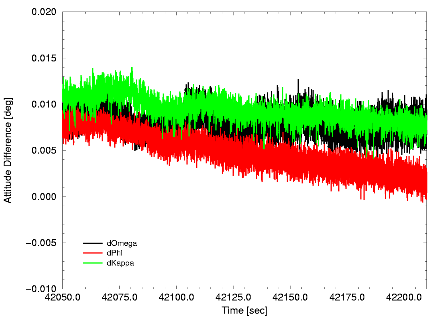


Figure 5: Differences $\Delta\omega, \Delta\varphi, \Delta\kappa$ between attitudes from ifp and Applanix

Figure 6 Rectification, Applanix exterior orientation.

Figure 7 Rectification, ifp exterior orientation.

Using the PosProc orientation parameters, object points could be determined with an accuracy better than one pixel. This can be seen from the estimated $\sigma_0$ a posteriori value after adjustment which is below one pixel in image scale. This high accuracy is transferred to the accuracy of object point determination on the ground. The RMS values are about 10cm for the east component, which corresponds to the flight direction (ground pixel size 17cm) and about 5cm for the north component, perpendicular to the flight direction (ground pixel size 12cm). The maximum deviations did not exceed 30cm for the east, 10cm for the north, and 30cm for the vertical coordinate. Compared to the results from the PosProc orientations, the accuracies of the ifp strip-wise approach given in Table 3 are slightly worse. This is mainly caused by the fact that for this test the unfiltered inertial data are used for the determination of the exterior orientation. This introduces noise on the attitude data and results in larger maximum errors in object space. Therefore, the maximum deviations obtained for the exterior orientations from the ifp approach are about 50cm for the east, 20cm for the north and 50cm for the vertical coordinates, the RMS values are about 20cm for the flight direction, 10cm perpendicular to the flight and 20 cm for the height component. The differences between the attitudes from the combined AT to the values obtained from the GPS/inertial Kalman filtering are depicted in Figure 5. After three iteration steps the empirical standard deviations of the attitude differences are about $4''$, $7''$ and $5''$ for the roll, pitch and heading, respectively. As mentioned above, these remaining differences are mainly due to the fact, that for the inertial data used in the ifp approach no prefiltering was applied, whereas the inertial data is filtered during Kalman filtering by the Applanix software to estimate the influence of data smoothing implemented in the PosProc software. Additionally, there are still some small offsets and some remaining linear effects between the two solutions.

Figure 6 and Figure 7 show the result of the rectification process, which is applied to the scanner imagery in order to eliminate distortions caused by attitude variations of the camera during the flight. For this 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 from both methods. Apparently, very fine structures at the roof are better rectified in Figure 7, it seems that currently the PosProc smoothing process eliminates real high-frequency movement of the camera. Thus, there is still some potential left to improve the current accuracy of the georeferencing process. It also should be stated clearly, that only Kalman filtering as applied in the Applanix approach has the potential of direct georeferencing. In principle the boresight alignment has to be calibrated only once, whereas for the DPA approach unknowns have to be estimated for each image strip. Nevertheless, the feasibility of the ifp software could be verified in this study.

## 4 DTM GENERATION

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. Within this so-called rectification step distortions in the original images resulting from the high frequency motion of the aircraft are eliminated. These distortions not only affect the visual impression, they also prevent the stereo viewing and result in problems for automatic image matching procedures.

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 20m) is rather small compared to the base in the direction of flight, the effect for stereo viewing and image matching is negligible. Nevertheless, for airborne scanner images only quasi-epipolar images can be generated, remaining small vertical parallaxes must be expected during stereo processing. These images are used for parallax measurement in the DTM.

### 4.1 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. As depicted in Figure 8 corresponding points $P_1$ and $P_2$, which can be measured in the rectified (quasi-epipolar) images refer to one point $P$ in 3D object space. Due to the difference between the average terrain height used for rectification and the true height $Z_P$ these points have incorrect coordinates in object space. Their planimetric coordinates $P_1(X_1, Y_1)$ and $P_2(X_2, Y_2)$ are different whereas the component $Z = Z_1 = Z_2$ corresponds to the height of the rectification plane. The correct position in 3D object space can be derived by back projection of the corresponding points $P_1$ and $P_2$ into the original image space $P'$ and $P''$ by collinearity condition. The following spatial intersection of the corresponding rays using exterior orientation results in the correct object coordinates $X_P, Y_P, Z_P$ for the object point. Compared to the processing of full frame imagery the back pro-

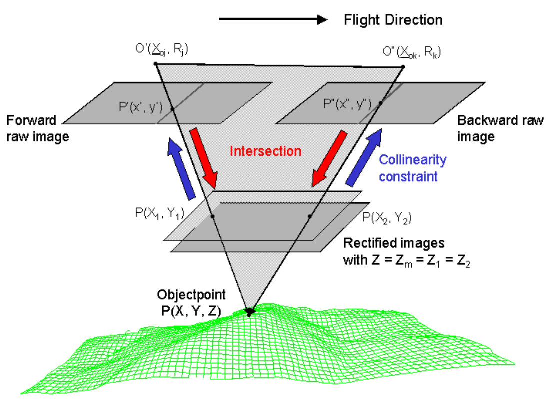


Figure 8: Point determination from rectified imagery

jection 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.

### 4.2 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 the previous section. For computational reasons it can be better, to apply a ortho image generation by the direct method, similar to 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. Nevertheless, for this task also an iterative procedure is required.

## 5 CONCLUSION

Image acquisition based on airborne pushbroom scanners has become a mature technology and therefore is currently entering the mainstream of photogrammetry. The main difference to full frame imagery, results from the fact that the direct measurement of position and attitude of the imaging sensor is vital for airborne scanner applications. 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 aerial triangulation has already become standard within the past decade. The application of the different components GPS, IMU and aerial triangulation enables a reliable, accurate and very operational georeferencing of image data. Hence, by the integration of inertial data a further change of photogrammetric techniques similar to the appearance of GPS can be expected also for the processing of full frame imagery. For pushbroom systems the cheaper costs of CCD line is overlaid by costs for GPS/inertial system, on the other hand the potential of direct georeferencing is an advantage as such. There is no question that the results of photogrammetric processing of data collected by digital photogrametric cameras based on the pushbroom principle are equivalent to the result of frame based system in terms of accuracy. Thus the question, which philosophy will be generally accepted is more related to problems like the overall costs of a complete system (including software) and the quality and performance of commercially available software solutions.

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