Role of Tie Points in Integrated Sensor Orientation for Photogrammetric Map Compilation

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Abstract

Direct measurement of exterior orientation parameters has been a challenge in photogrammetry for many years. Direct sensor orientation using a calibrated GPS/INS system can potentially eliminate the need for ground control points and aerial triangulation, and consequently, result in a great reduction in the cost and time of aerial photogrammetry. Previous studies have shown that, compared to conventional aerial triangulation, direct sensor orientation yields larger errors in the image and object space. It has also been shown that including a number of tie points within an integrated orientation approach can result in a reduction of errors in the image space. In this paper, the influence of the number and distribution of tie points on integrated orientation is investigated. Experiments with various numbers of tie points regularly as well as randomly distributed are presented. Results indicate that an increase in the number of tie points up to one point per model results in a considerable reduction of the errors in the image space.

Introduction

Ground control survey and aerial triangulation are the most costly and time-consuming stages in photogrammetric mapping projects. Direct measurement of exterior orientation parameters by a thoroughly calibrated GPS/INS system can potentially eliminate the need for ground control points and aerial triangulation, and consequently, result in a great reduction in the cost and time of aerial photogrammetry (Khoshelham and Eslami, 2007; Mostafa and Schwarz, 2001; Skaloud, 1996; Toth, 2002). With the direct measurement of the position and attitude of the camera perspective center at exposure times, the object-space coordinates of the image points can be computed using a least-squares forward intersection. This method is referred to as direct sensor orientation (Cramer and Stalnann, 2001; Yestikli and Jacobsen, 2005a).

While direct sensor orientation is a promising method that can potentially reduce the photogrammetric mapping process to photography and stereo plotting, in practice, the range of accuracies obtained using this method is generally lower than that of conventional photogrammetry. Previous experiments with commercially available GPS/INS systems have shown that direct sensor orientation in the scale of 1:5 000 reaches accuracies that are two to three times lower when compared to the results of conventional aerial triangulation (Heipke et al., 2002; Khoshelham et al., 2007).

An alternative approach to determining sensor orientation parameters and transforming the image-space coordinates to the object space is integrated sensor orientation (Ip, 2005; Jacobsen, 2004). In this approach, tie points in overlapping images contribute to the refinement of the directly measured exterior orientation parameters through a bundle adjustment. It has been shown that the introduction of tie points leads to a considerable improvement of the accuracy in the image space (Heipke et al., 2002). In effect, improved accuracy in the image space means lower y-parallax in the stereo-models, which is of great significance in photogrammetric map compilation. It is well known that the stereo compilation of a pair of images with a y-parallax of larger than 20 microns is very inconvenient for the operators. Therefore, the potential of integrated sensor orientation approach in reducing the y-parallax is particularly worthwhile in photogrammetric mapping applications. From an economic point of view, integrated sensor orientation can be seen as a trade-off between direct orientation and conventional aerial triangulation since it eliminates the need for ground control points but still requires the measurement of tie points in overlapping images.

An important issue in integrated sensor orientation is the number and distribution of the tie points. Despite the availability of automated point extraction and matching algorithms, still many mapping organizations rely on the manual measurement of the tie points. To minimize the amount of this manual procedure, it is essential to know whether an acceptable range of y-parallax in stereo images can be obtained with a minimum number of tie points. Although previous studies have shown the effect of including a certain number of tie points, it is not known how the accuracy is influenced by variations in the number and distribution of the points. The objective of this research is to investigate the influence of the number and distribution of tie points on the accuracy of integrated sensor orientation.
sensor orientation. The focus will be on airborne frame cameras, as these are more commonly used in aerial mapping applications.

The paper is structured in five sections. The next section describes the calibration of integrated GPS/INS system followed by the transformation of points from the image to the object space through direct and integrated sensor orientation. Experiments with various numbers of the points in integrated sensor orientation are then presented followed by conclusions.

Calibration of GPS/INS for Airborne Frame Cameras

The calibration of GPS/INS is basically a comparison of exterior orientation parameters measured directly by GPS/INS with those obtained by using a reference method (Forlani and Pinto, 2002; Honkavaara, 2004; Yastikli and Jacobsen, 2005b). The discrepancies are modeled by computing calibration parameters that relate GPS/INS position and attitude to the reference exterior orientation parameters. Bundle adjustment of the aerial triangulation is most often used as the reference method for the computation of exterior orientation parameters. Therefore, the determination of calibration parameters requires one or more test flights over a test field with preferably signalized control points. There are two main approaches to the computation of calibration parameters: one-step approach and two-step approach (Heipke et al., 2002). In the one-step calibration approach, a bundle adjustment of all available information in the image and object space is performed. The image space is related to the object space using the well-known collinearity condition equations augmented with a set of calibration parameters that establish the relation between the INS, the GPS receiver, and the camera (Skaloud, 1999). The main calibration parameters include the unknown lever arm distance between the GPS/INS and the camera perspective center and the three misalignment angles that model the relative orientation of the INS with respect to the camera. Ideally, the camera exposure must be precisely synchronized with the GPS/INS; nevertheless, a possible time delay can be modeled by adding a synchronization offset to the time of the GPS/INS measurements. Parameters such as the lever arm distance, the misalignment angles, and the synchronization offset are all estimated in this calibration procedure, provided that the INS and GPS/INS attitude measurements are navigation angles, roll, pitch, and yaw, which define the relative orientation of the IMU body with respect to the navigation coordinate system. In order to be used in the calibration procedure, navigation angles must be converted to photogrammetric angles, omega (ω), phi (φ), and kappa (κ), which determine the relative orientation of the camera with respect to the local coordinate system. Figure 1 depicts the coordinate systems that are used in navigation and photogrammetry. The conversion of navigation angles to photogrammetric angles can be expressed as a sequence of rotations:

\[
R_{E} = R_{N} \cdot R_{P} \cdot R_{L}
\]

where \(R_{E}\) is a rotation matrix that contains photogrammetric angles, \(ω, φ, \) and \(κ\), and brings the camera axes parallel to the local coordinate system; \(R_{N}\) denotes the rotation from the navigation to the local system; \(R_{P}\) denotes the rotation from the camera to the IMU body, and \(R_{L}\) is the rotation from the body to the navigation system and contains navigation angles, roll, pitch, and yaw. As illustrated in Figure 1,

where variables with \(\text{GPS/INS}\) subscript denote \(\text{GPS/INS}\) measurements, those with \(\text{AT}\) subscript denote aerial triangulation estimate of the exterior orientation parameters, \(i\) subscripts denote the polynomial coefficients, \(t\) is time, and \(n\) is the order of the polynomials.

The polynomial coefficients play the role of calibration parameters. A zero order polynomial incorporates only three GPS shifts and three misalignment angles. This basic set of six parameters can properly calibrate the \(\text{GPS/INS}\), if a comparison of aerial triangulation estimate of exterior orientation parameters and \(\text{GPS/INS}\) measurements shows discrepancies that remain within a limited constant range over time. Otherwise, an increase or decrease of the discrepancies over time indicates that additional drift parameters must be taken into account, thus a higher order of the polynomial should be used.

Conversion of Navigation Angles to Photogrammetric Angles

A basic requirement for the calibration procedure is the conversion of navigation angles to photogrammetric angles. GPS/INS attitude measurements are navigation angles, roll, pitch, and yaw, which define the relative orientation of the IMU body with respect to the navigation coordinate system. In order to be used in the calibration procedure, navigation angles must be converted to photogrammetric angles, omega (ω), phi (φ), and kappa (κ), which determine the relative orientation of the camera with respect to the local coordinate system. Figure 1 depicts the coordinate systems that are used in navigation and photogrammetry. The conversion of navigation angles to photogrammetric angles can be expressed as a sequence of rotations:

\[
R_{E} = R_{N} \cdot R_{P} \cdot R_{L}
\]
The rotation from the navigation to the local coordinate system, however, is not constant during the flight, because the origin of the navigation system is at the center of the IMU, which moves with the aircraft. In other words, while the local system remains fixed, the navigation system slightly rotates with the movement of the aircraft to keep one axis towards north. Thus, in order to express the rotation from the navigation system at a given location to the local system, an initial navigation system, \( N^a \), at a hypothetical location above the local coordinate system is assumed (Figure 1).

We have:

\[
R^N_{B} = R^N_{B} \cdot R^N_{C}
\]  

(5)

where the rotation matrix from the initial navigation system to the local system, \( R^N_{C} \), can now be obtained by a 180° rotation around the \( Z \) axis followed by a -90° rotation around the \( Z \) axis, which results in:

\[
R^N_{C} = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & -1 \end{bmatrix}
\]  

(6)

Finally, the rotation from the navigation system at an arbitrary location to the initial navigation system, \( R^N_{B} \), is carried out by making use of a geocentric coordinate system, \( G \), as an intermediate system:

\[
R^N_{B} = R^G_{B} \cdot R^N_{G}
\]  

(7)

where the rotation from the navigation system at geographic coordinates \((\Lambda, \Phi)\) to the geocentric coordinate system is:

\[
R^N_{G} (\Lambda, \Phi) = \begin{bmatrix} -\sin \Phi \cos \Lambda & -\sin \Lambda & -\cos \Phi \cos \Lambda \\ -\sin \Phi \sin \Lambda & \cos \Lambda & -\cos \Phi \sin \Lambda \\ \cos \Phi & 0 & -\sin \Phi \end{bmatrix}
\]  

(8)

and \( R^G_{B} (\Lambda_B, \Phi_B) = R^G_{B} (\Lambda_B, \Phi_B) \).

Direct and Integrated Orientation

Once determined, the calibration parameters are used to correct the GPS/INS measurements of the exterior orientation parameters. In this direct orientation approach, the object-space coordinates of all the image points can be computed using a least-squares forward intersection procedure, with no need for ground control or tie points (Khoshelham et al., 2007). The exterior orientation parameters corrected by the calibration parameters are treated as constants in the forward intersection estimation model. In other words, no further corrections are applied to the position and attitude of the perspective centers, and only the positions of the points in the image and object space are adjusted.

In the integrated orientation approach, a further correction of the exterior orientation parameters of the camera is permissible. This is achieved by a simultaneous adjustment of a number of tie points within a bundle adjustment model with additional constraints for refining the exterior orientation parameters. Since every tie point appears in at least two images, integrating a number of tie points in the estimation model results in a redundancy of observations that allows for the correction of the exterior orientation parameters. The introduction of tie points in the integrated orientation approach provides the means for exploiting the strength of the bundles for the refinement of the exterior orientation parameters. Since in the estimation model sum of the squared residuals of the image coordinates are minimized, one can expect that the integrated orientation approach results in an improved accuracy in the image space, and consequently, reduced Y-parallax in the stereo models.

The assignment of suitable weights to the exterior orientation parameters is a determinant factor in the refinement of the calibrated position and attitude parameters of the camera. If the exterior orientation parameters are assigned very large weights as compared to the image coordinates, then the result of the estimation model would be very similar to that of direct orientation. In other words, the corrections to the exterior orientation parameters would be very small, and the object space coordinates of the tie points would be similar to those obtained from direct orientation. On the other hand, if the exterior orientation parameters are assigned weights that are too small, then large corrections would be estimated for these parameters, which may result in a greater error in the coordinates of the points in the object space.

Experimental Analysis of the Role of Tie Points

To experiment with the integrated orientation approach and investigate the influence of the tie points, a test dataset of EuroSDR (formerly DEEP) acquired by an Applanix integrated GPS/INS system was used. The data acquisition was comprised of a calibration flight at an image scale of 1:10 000, and a test flight at 1:5 000 over a test field with 40 signalized control points located in Norway. The dataset consists of the following data:

- Position and attitude measurements made by GPS/INS;
- Ground coordinates of the control points in EUROPEAN/UTM system with heights over the WGS84 ellipsoid;
- Image coordinates of control points and a number of tie points.

The calibration of the system was carried out using the data of the 1:10 000 flight. A bundle adjustment aerial triangulation of the image coordinates and control points was performed using PAT-B aerial triangulation software. No GPS/INS data were introduced at this step, and the exterior orientation parameters computed within the bundle adjustment were used as reference in the calibration procedure. All the computations at this stage and subsequent stages were carried out in the UTM projection system, where the effects of the projection were compensated for by applying a correction to the local length corresponding to the local scale (Jacobsen, 2002). The two-step approach was implemented for the estimation of the calibration parameters. A comparison of the camera position and attitude parameters obtained from the bundle adjustment with those measured by GPS/INS showed discrepancies that did not largely vary over time; therefore, the basic set of six calibration parameters consisting of three GPS shifts and three misalignment angles was adopted for the calibration.
For the experiments with direct and integrated orientation, the data of the 1:5 000 flight were used. A bundle adjustment aerial triangulation of these data was performed so that the results can serve as reference for the evaluation of the direct and integrated orientation approaches. The data of the bundle adjustment included the ground coordinates of 13 control points evenly distributed in the block. No control points were introduced in the computations of the direct and integrated orientation. Computed ground coordinates for 18 checkpoints were used for the evaluation of the accuracy of the bundle adjustment as well as the direct and integrated orientation approaches in the object space. Figure 2 depicts the perspective centers of a total of 161 photographs taken at the scale 1:5 000 along with the control and checkpoints.

To investigate the influence of the tie points, ground coordinates of the checkpoints were computed using the three aforementioned methods with various numbers of tie points. Obviously, all the tie points contributed in the bundle adjustment aerial triangulation, and no tie points were introduced in the direct orientation approach. In the integrated orientation approach, seven schemes for the selection of the tie points were designed. Table 1 summarizes the tie point selection schemes. In addition, for each selection scheme two distribution schemes were taken into account. In the regular distribution scheme, an even distribution of the tie points across the block was desired; whereas, in the random distribution scheme, tie points were designed. Table 1 presents the tie point selection schemes. In addition, for each selection scheme two distribution schemes were taken into account. In the regular distribution scheme, an even distribution of the tie points across the block was desired; whereas, in the random distribution scheme, tie points were randomly distributed within the block. For example, in the selection scheme S-1 with regular distribution a tie point at the center of the overlapping area of every pair of consecutive images was selected, which resulted in 172 tie points evenly distributed across the block. Thus, in the selection scheme S-1 with regular distribution, 172 tie points at random positions within the block were selected. The tie points were measured in all the images where they appeared. In the 

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**TABLE 1. TIE POINT SELECTION SCHEMES**

<table>
<thead>
<tr>
<th>Selection Scheme</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-1/10</td>
<td>1 tie point in every 10th model</td>
</tr>
<tr>
<td>S-1/5</td>
<td>1 tie point in every 5th model</td>
</tr>
<tr>
<td>S-1/3</td>
<td>1 tie point in every 3rd model</td>
</tr>
<tr>
<td>S-1/2</td>
<td>1 tie point in every 2nd model</td>
</tr>
<tr>
<td>S-4</td>
<td>4 tie points in every model</td>
</tr>
<tr>
<td>S-2</td>
<td>2 tie points in every model</td>
</tr>
</tbody>
</table>

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Figure 2. Perspective centers of the images of 1:5 000 flight along with the control and check points. Arrows indicate the direction of the flights.
affected by the increase in the number of tie points. The changes in the \( \sigma_0 \) values obtained by integrated orientation indicate that by including a sufficient number of tie points in the computations the \( Y \)-parallax in the image space can be reduced to values that are two to three times lower than those obtained by direct orientation.

Figure 5 shows the obtained image-space errors versus various tie point selection and distribution schemes. As can be seen, by increasing the number of tie points up to one point per model (scheme S-1) the \( \sigma_0 \) values decrease almost linearly. The selection schemes S-2 and S-4 result in only a slight improvement of the accuracy in the image space.
TABLE 2. RESULTS OF USING VARIOUS NUMBERS OF TIE POINTS WITH REGULAR DISTRIBUTION IN THE INTEGRATED ORIENTATION APPROACH

<table>
<thead>
<tr>
<th>Method</th>
<th>Scheme</th>
<th>No. of tie points</th>
<th>RMSE_X (cm)</th>
<th>RMSE_Y (cm)</th>
<th>RMSE_Z (cm)</th>
<th>$\sigma_o$ (\mu m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bundle AT</td>
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<td>2294</td>
<td>3.3</td>
<td>3.5</td>
<td>10.5</td>
<td>4.1</td>
</tr>
<tr>
<td>Direct Orientation</td>
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<td>0</td>
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<td>7.7</td>
<td>14.7</td>
<td>36.19</td>
</tr>
<tr>
<td>S-1/10-Reg</td>
<td></td>
<td>17</td>
<td>7.6</td>
<td>7.5</td>
<td>12.2</td>
<td>26.2</td>
</tr>
<tr>
<td>S-1/5-Reg</td>
<td></td>
<td>33</td>
<td>7.6</td>
<td>7.6</td>
<td>12.2</td>
<td>23.2</td>
</tr>
<tr>
<td>S-1/3-Reg</td>
<td></td>
<td>59</td>
<td>7.6</td>
<td>7.6</td>
<td>12.2</td>
<td>20.1</td>
</tr>
<tr>
<td>S-1/2-Reg</td>
<td></td>
<td>87</td>
<td>7.6</td>
<td>7.6</td>
<td>12.2</td>
<td>18.5</td>
</tr>
<tr>
<td>S-1-Reg</td>
<td></td>
<td>172</td>
<td>7.7</td>
<td>7.4</td>
<td>11.9</td>
<td>15.0</td>
</tr>
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<td>S-2-Reg</td>
<td></td>
<td>296</td>
<td>7.7</td>
<td>7.4</td>
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<td>12.6</td>
</tr>
<tr>
<td>S-4-Reg</td>
<td></td>
<td>516</td>
<td>8.4</td>
<td>7.0</td>
<td>11.9</td>
<td>13.1</td>
</tr>
</tbody>
</table>

TABLE 3. RESULTS OF USING VARIOUS NUMBERS OF TIE POINTS WITH RANDOM DISTRIBUTION IN THE INTEGRATED ORIENTATION APPROACH

<table>
<thead>
<tr>
<th>Method</th>
<th>Scheme</th>
<th>No. of tie points</th>
<th>RMSE_X (cm)</th>
<th>RMSE_Y (cm)</th>
<th>RMSE_Z (cm)</th>
<th>$\sigma_o$ (\mu m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bundle AT</td>
<td></td>
<td>2294</td>
<td>3.3</td>
<td>3.5</td>
<td>10.5</td>
<td>4.1</td>
</tr>
<tr>
<td>Direct Orientation</td>
<td></td>
<td>0</td>
<td>6.7</td>
<td>7.7</td>
<td>14.7</td>
<td>36.19</td>
</tr>
<tr>
<td>S-1/10-Rand</td>
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<td>17</td>
<td>7.6</td>
<td>7.5</td>
<td>12.2</td>
<td>26.2</td>
</tr>
<tr>
<td>S-1/5-Rand</td>
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<td>33</td>
<td>7.6</td>
<td>7.6</td>
<td>12.2</td>
<td>23.2</td>
</tr>
<tr>
<td>S-1/3-Rand</td>
<td></td>
<td>59</td>
<td>7.6</td>
<td>7.6</td>
<td>12.2</td>
<td>20.1</td>
</tr>
<tr>
<td>S-1/2-Rand</td>
<td></td>
<td>87</td>
<td>7.6</td>
<td>7.6</td>
<td>12.2</td>
<td>18.5</td>
</tr>
<tr>
<td>S-1-Rand</td>
<td></td>
<td>172</td>
<td>7.7</td>
<td>7.4</td>
<td>11.9</td>
<td>15.0</td>
</tr>
<tr>
<td>S-2-Rand</td>
<td></td>
<td>296</td>
<td>7.7</td>
<td>7.4</td>
<td>11.7</td>
<td>12.6</td>
</tr>
<tr>
<td>S-4-Rand</td>
<td></td>
<td>516</td>
<td>8.4</td>
<td>7.0</td>
<td>11.9</td>
<td>13.1</td>
</tr>
</tbody>
</table>

Figure 5. Error values in image space obtained for various selection and distribution schemes.

It is worth noting that regular and random distributions of the tie points yield very similar results. This suggests that the accuracy in the image space is not influenced by the distribution of the tie points. One exception, however, is the scheme S-4, where the $\sigma_o$ value associated with random distribution is a noticeable 2 \mu m smaller than that of regular distribution.

The error vectors at check points were also examined for the presence of systematic errors in the object space. Table 4 summarizes the mean values of the error vectors as a measure of systematic effects in the object space. As can be seen, the direct orientation approach results in a noticeable 7.8 cm shift in Z, whereas systematic shifts in the integrated orientation approach (with various numbers of tie points distributed regularly within the block) remain within a small range comparable to the results of the bundle adjustment. Also, the mean error values do not show a correlation with the number of tie points in the integrated orientation approach.

Conclusions

In this paper the influence of the number and distribution of tie points on the integrated orientation of an aerial frame camera was investigated. The integrated orientation approach was implemented through a bundle adjustment of a number of tie points with additional constraints for refining the exterior orientation parameters. The number of tie points varied across experiments from 17 (one point in every 10th model, selection scheme S-1/10) to 516 (four points in each model; selection scheme S-4). Experiments were also conducted with regularly distributed tie points as well as randomly distributed ones. The main findings of the experiments can be summarized as the following:

- The inclusion of tie points in the integrated orientation approach, regardless of their number and distribution, does not substantially improve the accuracy in the object space (as measured by checks at check points), and the results are similar to those obtained by the direct orientation approach.
- In the image space, an increase in the number of tie points up to one point per model results in a considerable reduction of the residuals of the image coordinates. This
Table 4. Mean Errors at Checkpoints as a Measure of Systematic Shifts in Object Space

<table>
<thead>
<tr>
<th>Method</th>
<th>No. of tie points</th>
<th>Mean_X (cm)</th>
<th>Mean_Y (cm)</th>
<th>Mean_Z (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bundle AT</td>
<td>2204</td>
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<td>0.1</td>
<td>1.6</td>
</tr>
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<td>Direct Orientation</td>
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<td>-1.3</td>
<td>-1.9</td>
<td>-7.8</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>1.6</td>
<td>-0.1</td>
<td>-0.2</td>
</tr>
<tr>
<td></td>
<td>33</td>
<td>1.6</td>
<td>-0.1</td>
<td>-0.2</td>
</tr>
<tr>
<td>Integrated Orientation</td>
<td>58</td>
<td>1.6</td>
<td>0.0</td>
<td>-0.6</td>
</tr>
<tr>
<td></td>
<td>87</td>
<td>1.6</td>
<td>-0.1</td>
<td>-0.6</td>
</tr>
<tr>
<td></td>
<td>172</td>
<td>1.8</td>
<td>-0.1</td>
<td>-0.1</td>
</tr>
<tr>
<td></td>
<td>296</td>
<td>2.2</td>
<td>-0.2</td>
<td>-0.2</td>
</tr>
<tr>
<td></td>
<td>516</td>
<td>2.3</td>
<td>-0.5</td>
<td>-0.4</td>
</tr>
</tbody>
</table>

suggested that including a minimum of one tie point per model can be recommended for practical applications since it leads to a considerable reduction of Y parallax in the image space:

- The distribution of the tie points does not have an influence on the accuracy in the image space since both the regular and random distributions of the tie points result in a similar range of the residuals of the image coordinates;
- Unlike the direct orientation approach, systematic shifts in the integrated orientation approach are very small and are comparable to the results of the bundle adjustment aerial triangulation.

In conclusion, the presented results indicate the potential of GPS/INS in the orientation of aerial frame cameras without control points. In the context of photogrammetric map compilation, tie points play a key role in reducing the Y parallax within the integrated orientation approach. In the absence of automated point extraction and matching algorithms, a minimum of one tie point per model can reduce the Y parallax to values that are sufficiently small for map compilation.

Acknowledgments

I would like to thank Professor Karsten Jacobsen of the University of Hannover for providing the dataset used in the experiments. The dataset included GPS/INS measurements acquired by the Applanix Company, which is also gratefully acknowledged. This research was partially supported by a grant from the Research Centre of the National Cartographic Centre of Iran.

References


