THE OEEPE-TEST ‘INTEGRATED SENSOR ORIENTATION’
AND ITS HANDLING WITHIN THE
HYBRID BLOCK-ADJUSTMENT PROGRAM ORIENT

Camillo Ressl
Institute of Photogrammetry and Remote Sensing
University of Technology, Vienna
car@ipf.tuwien.ac.at

Abstract
In this paper we present the experiences we made as participants in the OEEPE test ‘Integrated Sensor Orientation’ by using the hybrid block-adjustment program ORIENT. For the calibration phase of this test we will explain the parameter model chosen for the calibration of the participating GPS/IMU systems. The calibration was carried out in the UTM system as well as in a Cartesian tangential system. The differences in the results in these two systems will be examined. During the application phase (1:5.000, 150 mm) direct georeferencing (with fixed exterior orientation) and a combined bundle block were performed and then the intersected tie points were compared, yielding approx. 6 cm in plane and 11 cm in height (s.d.). One problem with GPS/IMU data is their reliability, which also showed up during this test in one gross error and discontinuous changes in the misalignment.

1. Introduction
The first and most important step for doing object reconstruction with a set of (aerial) photographs is image orientation; i.e. the determination of the images exterior orientation (XOR). The interior orientation (IOR) is generally given by means of the protocol of a labor calibration. Up to now this orientation is generally done in an ‘indirect’ way by means of an aerial triangulation (AT) using control and tie points and their observations in the images. In the last few years another – more ‘direct’ – way for image orientation, by means of the Global Positioning System (GPS) and some Inertial Navigation System (INS) (resp. a Inertial Measurement Unit (IMU)), has been developed. This also termed integrated sensor orientation has lots of benefits for Photogrammetry which can result in a large temporal (= financial) gain; (Colomina 1999), (Cramer 2000):

- Theoretically, no control and tie points are required
- Free block geometry
- Reduction of the number of images
- Image interpretation does not require full block triangulation
- Support for matching during automatic aerial triangulation

Besides that, there are also some potential error sources. ‘These include the Kalman filtering of the GPS/IMU data for noise reduction, the determination of parameters for systematic position and attitude corrections of the GPS/IMU data, the stability of these parameters over time, especially the stability of the attitude values between the IMU and the camera (the so-called misalignment), the time synchronization between the various sensors, issues related to the correlation between the interior and the exterior orientation parameters of the imagery, and the quality of the resulting exterior orientation parameters for subsequent stereoscopic plotting’ (Heipke et al. 2000).
To investigate the potential of integrated sensor orientation, the European Organization for Experimental Photogrammetric Research (OEEPE) has initiated a large test in the year of 2000. ‘The test is expected to demonstrate to which extent integrated sensor orientation using GPS and IMU with and without aerial triangulation is an accurate and efficient method for the determination of the exterior orientation parameters for large scale topographic mapping’ (Heipke et al. 2000). The test is carried out with two different GPS/IMU systems. One is the system AeroControl II of IGI mbH from Hilchenbach, Germany, with a Zeiss RMK Top camera (termed as Comp1). The other one is the system POS/AVC 510 DG from Applanix of Toronto, Canada, with a Leica RC 30 camera (termed as Comp2). The principal distance of both analog cameras is approximately 150 mm.

As test field the one of Fredrikstad, Norway, was chosen. It measures approximately 5 x 6 km² and is equipped with 52 well distributed ground control points. The test was split into two phases: Phase 1 was the ‘calibration phase’, during which two calibration flights for each company in the scales 1:5.000 and 1:10.000 were to be handled. In phase 2 another flight in the scale 1:5.000 (termed as test flight) was to be handled with the aim to apply the system parameters determined in phase 1 to this flight and perform a) direct georeferencing and b) a combined AT. All three flights (starting with the two calibration flights) were performed for each company on the same day in October 1999.

Each company processed their own GPS/IMU data.¹ The image measurements (ground control and tie points) were performed using analytical plotters by the Institute for Photogrammetry and GeoInformation (IPI), Hannover, which also acted as a pilot center for the OEEPE test. For each phase, different data were delivered to the test participants and different tasks were to be performed by them. One of these test participants was the Institute of Photogrammetry and Remote Sensing (I.P.F.), Vienna, and in the following it will be presented, how the tasks of this test can be solved using the hybrid block adjustment program ORIENT (Kager 1989), which has been developed at the I.P.F.

2. ORIENT and its functional model²

The hybrid bundle block adjustment program ORIENT is written in FORTRAN and has been developed at the I.P.F. for more than 20 years (Kager 1989). The term hybrid means that ORIENT offers the possibility to simultaneously adjust different kinds of observations by least squares:

- perspective image (frame) coordinates
- coordinates of push and whisk broom scanners (of 1 or 3 lines)
- Synthetic Aperture Radar image coordinates
- control points
- model coordinates
- geodetic (polar) measurements (e.g. tachymeter observations)
- fictitious observations: points belonging to planes or to polynomial surfaces
- fictitious observations: points belonging to straight lines, circles, or to any intersecting curve of two polynomial surfaces

¹ Comp1 discovered a mistake in their data processing and therefore made a 2nd data processing (Heipke et al. 2001), which was delivered to the test participants after the end of phase 1. This data will be termed ‘Comp1b’ in the following and the 1st processed data will be termed ‘Comp1a’.

² This chapter is entirely based on the ORIENT introduction as given in (Rottensteiner 2001).
• fictitious observations: points belonging to 3D spline curves
• observed mapping parameters (e.g. projection center or rotational parameters of an image)

Adjustment is based on the Gauss-Markoff-Model – also known as adjustment by indirect observations. ORIENT assumes the observations to be uncorrelated. Additionally, ORIENT offers two blunder detection techniques:
• Robust estimation by iterative re-weighting of observations (using a-priori normalized residuals)
• Data snooping (using a-posteriori normalized residuals)

Since the observations’ weighting depends on their (a-priori) accuracies, ORIENT has included the technique of variance components analysis (VCA) to check the plausibility of the a-priori accuracies.

The mathematical model of adjustment in ORIENT is based on a very strict concept in using basically the same mapping function for all types of observations (except for the 3D splines). This mapping function expresses the relation between the above mentioned observations and the unknowns (i.e. object points and mapping parameters). Since the observations are made in a 3D Cartesian observation coordinate system \((u, v, w)\) and the unknown object points are to be determined in a 3D Cartesian object coordinate system \((X, Y, Z)\), this mapping function is the transformation (depending on the mapping parameters) between these two coordinate systems. The basic formula for this transformation is the spatial similarity transformation. In ORIENT it is formulated in the following way:

\[
p - p_0(a) = \lambda \cdot R^T(\Theta) \cdot (P - P_0)
\]

with

\[
\begin{align*}
p &= (u, v, w)^T : \text{the observed point} \\
p_0 &= (u_0, v_0, w_0)^T : \text{the interior reference point} \\
a &= \text{additional parameters modifying the interior reference point (e.g. camera distortion)} \\
\lambda &= \text{the scale factor between observation and object coordinate system} \\
R(\Theta) &= \text{a } 3 \times 3 \text{ rotational matrix parameterized by three rotational angles } \Theta, \text{ like (Roll, Pitch, Yaw)} \\
P &= (X, Y, Z)^T : \text{the object point corresponding to } p \\
P_0 &= (X_0, Y_0, Z_0)^T : \text{the exterior reference point}
\end{align*}
\]

The mapping parameters are made of \(p_0, a, \lambda, \Theta \text{ and } P_0\). All of these parameters may be determined in the adjustment. Basically, these groups of parameters appear in the mapping functions of all observations types, but they might obtain different interpretations and/or be given constant default values. It shall be emphasized that it is possible to

1. keep single groups of parameters fixed for each observation type,
2. declare several observation coordinate systems to share groups of mapping parameters (e.g., two perspectives may be declared to have the same rotational parameters if the photos were made using a stereo camera) without having to formulate condition equations, just by manipulating the data base.
3. Declare groups of parameters constant for individual observation coordinate systems.

\[3\] The definition of Roll, Pitch and Yaw in ORIENT differs from ARINC 705 in the following way:
\[\begin{align*}
\text{Roll}_{\text{Orient}} &= \text{Roll}_{\text{ARINC 705}}, \\
\text{Pitch}_{\text{Orient}} &= -\text{Pitch}_{\text{ARINC 705}}, \\
\text{Yaw}_{\text{Orient}} &= 100^{\text{gon}} - \text{Yaw}_{\text{ARINC 705}}.
\end{align*}\]
All data in ORIENT are stored in so-called rooms, which are uniquely defined by their types and identifiers: the observations are stored in observation rooms (e.g. PHOTO rooms, MODEL rooms or SPLINE rooms) and the mapping parameters are stored in parameter rooms (e.g. ROT rooms, SCALE rooms, IOR room or APDAR rooms). All rooms that are necessary to describe a particular type of observation in ORIENT are addressed by reference using the identifiers.

If we now stick explicitly to the problem of integrated sensor orientation, the following types of observations occur:

- **perspective image (frame) coordinates**
  
  For this kind of observations, considering equation (1), \( w = 0 \); \((u_0, v_0, w_0)\) is made of the principal point \((u_{pp}, v_{pp})\) and principal distance \(f\); and \(\lambda\) varies from one image point to another (it is pre-eliminated by dividing the first two equations by the third, this way yielding the well known formula of the perspective transformation\(^4\)). Explicitly, \(p_0(\mathbf{a})\) means \(u_0 = u_{pp} + \Sigma a_i du_{0,i}(u', v')\), \(v_0 = v_{pp} + \Sigma a_i dv_{0,i}(u', v')\) and \(w_0 = f + \Sigma a_i dw_{0,i}(u', v')\).

\[
\begin{align*}
  u' &= \frac{u - u_{pp}}{\rho_0} \\
  v' &= \frac{v - v_{pp}}{\rho_0}
\end{align*}
\]

are normalized image coordinates and \(\rho_0\) is a normalization radius. In this way the modification of the interior reference point (e.g. the camera distortion) is described by the sum of polynomial functions \(du_{0,i}, dv_{0,i}\) and \(dw_{0,i}\) of the reduced image coordinates. For each index \(i\) there is such a set of functions and \(a_i\) is the corresponding additional (e.g. distortion) parameter. Table 1 gives the parameters \(a_i\) which were used in the OEEPE test together with the corresponding functions \(du_{0,i}, dv_{0,i}\) and \(dw_{0,i}\) and a geometrical interpretation. As it was already mentioned, additional parameters are stored in ADPAR-rooms.

<table>
<thead>
<tr>
<th>i</th>
<th>(du_{0,i}(u', v'))</th>
<th>(dv_{0,i}(u', v'))</th>
<th>(dw_{0,i}(u', v'))</th>
<th>Geometric interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>(u'(r^2-1))</td>
<td>(v'(r^2-1))</td>
<td>0</td>
<td>Radial distortion; 3(^{\text{rd}}) degree</td>
</tr>
<tr>
<td>5</td>
<td>(r^2+2u'^2)</td>
<td>(2u'v')</td>
<td>0</td>
<td>Tangential (asymmetric) distortion</td>
</tr>
<tr>
<td>6</td>
<td>(2u'v')</td>
<td>(r^2+2v'^2)</td>
<td>0</td>
<td>Tangential (asymmetric) distortion</td>
</tr>
<tr>
<td>41</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>Interior GPS excenter(^5)</td>
</tr>
<tr>
<td>42</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>Interior GPS excenter</td>
</tr>
<tr>
<td>43</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>Interior GPS excenter</td>
</tr>
</tbody>
</table>

Table 1: Some of the additional parameters in ORIENT \((r^2 = u'^2 + v'^2)\).

- **ground control points**
  
  For this kind of observations, considering equation (1), \(p_0(\mathbf{a})\) and \(P_0\) both equal to \((0, 0, 0)\) (or to a special reduction point), \(\lambda = 1\) and \(\Theta = (0, 0, 0)\).

---

\(^4\) See e.g. (Kraus 1997), which also gives a general introduction to the topic of bundle block adjustment.

\(^5\) The effect of this interior GPS excenter is identical to the lever arm correction.
• observed projection centers (realized in ORIENT as models)
  For this kind of observations, considering equation (1), \( p_0(a) \) is constant (and merely serves as a reduction point for numerical considerations). The seven remaining parameters describe a spatial similarity transformation of the GPS/IMU projection centers and can be interpreted as corrections for remaining errors after the datum’s transformation between WGS84 and EUREF89, but only \( P_0 \) was considered, whereas \( \lambda \) and \( \Theta \) were fixed to 1 resp. \((0, 0, 0)\). Since this \( P_0 \) describes a translation of the GPS/IMU projection centers as a whole, \( P_0 \) will be termed as exterior GPS excenter in the following.

• observed rotational parameters (realized in ORIENT as observed mapping parameters)
  For this kind of observations, considering equation (1), \( \lambda \equiv 1, \Theta \) and \( P_0 \) both equal to \((0, 0, 0)\). The interpretation of \( p \) and \( P \) has a bit changed. They don’t mean points in the usual sense, but stand for triples of rotation angles. \( p \) holds the observed GPS/IMU Roll, Pitch and Yaw values, whereas \( P \) holds the unknown rotation angles of the respective photo. \( p_0(a) \) is used as additional excenter for the rotations’ observations (misalignment).

3. Phase 1 – The calibration of the systems

Both companies made two calibration flights at scales 1:5,000 (2 + 2 strips with 60 images totally) and 1:10,000 (5 + 2 stripes with 85 images totally). The data delivered to the test participants in August 2000 included the image measurements for the calibration flights performed by IPI (fiducial transformed and distortion corrected) together with the IOR \((0, 0, f)\), the GPS/IMU processed data (linearly interpolated for exposure time and lever-arm corrected, so yielding observations for the images’ XOR) and the coordinates of 20 ground control points, with an accuracy of \(\pm 1.5\) cm. The aim of phase 1 was to compute the system calibration for each company and to return the results to the pilot center till the end of October 2000.

For each company a separate ORIENT project was created. The observed projection centers for each of the 11 strips were imported into ORIENT as 11 separate models. The observed rotation angles were realized as special rooms, which are addressed by each photo in ORIENT. Because the accuracies for the image measurements and the GPS/IMU data were missing, it was first tried to get some plausible estimates for them. The accuracies for the image measurements were obtained by computing the relative orientation for all images of each company (with fixed IOR). This yielded an accuracy of 4.1 \(\mu m\) for the images of Comp1 (Zeiss RMK Top) and 5.6 \(\mu m\) for those of Comp2 (Leica RC 30). Due to this relatively large difference of 1.5 \(\mu m\) between these two cameras, it was tried to improve the results by including distortion parameters. For the Zeiss RMK Top only one radial distortion parameter (adp3) was found to be significant (with very small effects of 1 \(\mu m\) as average and a maximum of 8 \(\mu m\)) resulting in an image accuracy of 4.0 \(\mu m\). For the Leica RC 30, however, large tangential distortion parameters (adp5&6) were found. The adp6 had effects of 16 \(\mu m\) as average and a maximum of 40 \(\mu m\). Furthermore it would have induced a significant change in the y-coordinate of the principal point in the range of 60 \(\mu m\). Since these quantities are highly improbable for metric cameras (and as it turned out later, adp6 differs between phase 1 and phase 2) it was finally decided not to include these two tangential distortion parameters (adp5&6) – although this simple model of two additional parameters improved the image accuracy of the Leica camera to a value of 4.7 \(\mu m\). After
phase 1 a summary paper by the IPI was published (Heipke et al. 2001) where the worse accuracy of the Leica camera was ascribed to the poorer image quality.

The accuracies for the GPS/IMU data were found by an adjustment with GPS excenters and ROT excenters for each of the 11 strips, so that no systematic errors in the GPS/IMU data could disturb the results. Using the above mentioned VCA, the arbitrary chosen a-priori accuracies were adapted to fit to the a-posteriori ones. The IOR was kept fixed at their given values, since any errors in the IOR would be compensated by the free GPS/IMU excenters. For this adjustment (and all the following ones) the data of both flights were used. In Table 2 the estimated accuracies are listed:

<table>
<thead>
<tr>
<th></th>
<th>Comp1a</th>
<th>Comp1b</th>
<th>Comp2</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHO $\sigma_x = \sigma_y$</td>
<td>4 µm</td>
<td>4 µm</td>
<td>6 µm</td>
</tr>
<tr>
<td>GPS $\sigma_x = \sigma_y = \sigma_z$</td>
<td>5 cm</td>
<td>5 cm</td>
<td>5 cm</td>
</tr>
<tr>
<td>IMU</td>
<td>35/35/110°</td>
<td>35/35/80°</td>
<td>35/35/80°</td>
</tr>
<tr>
<td>GCP $\sigma_x = \sigma_y = \sigma_z$</td>
<td>1.5 cm</td>
<td>1.5 cm</td>
<td>1.5 cm</td>
</tr>
</tbody>
</table>

Table 2: Estimated accuracies for the observations of phase 1

Then, with these accuracies, the next step was to choose the appropriate model for the system calibration. Since both scales (more precisely, the paths) of the calibration flights were suitable for doing the calibration (except for the determination of the principal distance, which had to rely on both) the appropriateness of a chosen model could be checked, by comparing the results obtained for both scales. Due to the combined processing of the GPS and IMU data, the observations for the images’ projection centers and rotation angles were assumed to be free of gross errors (due to cycle slips etc.), so for all ORIENT-models (containing the observations for the projection centers) of one height level only one common (exterior) GPS excenter was specified. The same was done with the observed rotation angles. The IOR was fixed at (0, 0, $f$). This model will be termed $M_1$. Table 3 holds the values for the GPS and IMU excenters of both scales. Table 3 is followed by the plots (Figure 1) of the GPS residuals (shifted for better distinction) and of the IMU residuals (with the excenter included).

<table>
<thead>
<tr>
<th>scale</th>
<th>exterior GPS-exc. (X/Y/Z) [m]</th>
<th>ROT-exc. (Roll/Pitch/Yaw) [gon]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comp1a 5k</td>
<td>0.045, -0.075, 0.100</td>
<td>0.0947, 0.0044, -0.1201</td>
</tr>
<tr>
<td>Comp1a 10k</td>
<td>0.034, -0.101, 0.270</td>
<td>0.0915, 0.0023, -0.1017</td>
</tr>
<tr>
<td>Comp1b 5k</td>
<td>0.036, -0.077, 0.095</td>
<td>0.1029, 0.0100, -0.0670</td>
</tr>
<tr>
<td>Comp1b 10k</td>
<td>0.021, -0.092, 0.272</td>
<td>0.1013, 0.0108, -0.0663</td>
</tr>
<tr>
<td>Comp2 5k</td>
<td>-0.016, 0.000, -0.130</td>
<td>-0.1329, 0.0599, 0.1989</td>
</tr>
<tr>
<td>Comp2 10k</td>
<td>-0.058, 0.013, -0.148</td>
<td>-0.1324, 0.0628, 0.1969</td>
</tr>
</tbody>
</table>

Table 3: Exterior GPS excenter and ROT excenter of model $M_1$

Outstanding attributes in Table 3 and in the plots are the strip characteristics in the GPS plane residuals in both companies (although the GPS excenter’s plane components in both scales do not differ very much – perhaps due to averaging effects) and the jump in the GPS excenter’s height component of Comp1 (indicating a wrong principal distance). It is also
interesting to see how the IMU accuracy of Comp1 improved by the 2nd data processing.6

The existence of a strip systematicness in the GPS plane residuals implies rather the existence of an interior GPS excenter (defined in the system of the camera and therefore changing its effect in the object system in dependence of the flight direction) than an exterior GPS excenter.

So, in the 2nd model M2 the exterior GPS excenter is replaced by an interior one. In ORIENT, this means that the GPS-model’s exterior reference point P0 is fixed and all images of the same scale point to the same ADPAR-room, which includes the adpars 41-43 (c.f. Table 1). The IOR remains fixed at (0, 0, f). Table 4 holds the values for the GPS and IMU excenters of both scales. Table 4 is followed by the plots (Figure 2) of the GPS residuals (shifted for better distinction). The plots of the IMU residuals do not differ much from the ones above.

In the residual plots, it can be clearly seen, that the strip systematicness is removed. But now it is interesting to see, that the y-component (orthogonal to the flying direction) of the interior GPS excenter in both scales differs by a factor 2. This implies, that rather a change in the principal point is necessary. So, in the 3rd model M3 the interior GPS excenter’s plane components are fixed at (0, 0) and the principal point in each scale is allowed to be free (while f still being fixed). Table 5 holds the changes in the principal point, the interior GPS excenter’s z-component, and the IMU excenters of both scales.

From Table 5 it can be seen, that the y-coordinate of the principal point in both scales fit together much better than the y-component of the interior GPS excenter in M2. On the other hand, the x-coordinates of the principal points differ in the range of factor 2, whereas the x-components of the interior GPS excenter in M2 show almost no differences. This means, that not only a change in the principal point needs to be modeled but also the x component of the interior GPS excenter (which can be interpreted as an error in the time synchronization of the GPS/IMU system and the camera).

---

6 As it can be clearly seen in the IMU residual plot, there had to be an error in the 1st processing of Comp1’s GPS/IMU data. This data, however, had to be calibrated somehow, so as a makeshift, for Comp1a the GPS/IMU data of the first strips were not used for the calibration phase.
<table>
<thead>
<tr>
<th>scale</th>
<th>Interior GPS-excenter [m]</th>
<th>ROT-excenter [gon]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comp1a 5k</td>
<td>0.0740 -0.056 -0.095</td>
<td>0.0939 0.0033 -0.1201</td>
</tr>
<tr>
<td>Comp1a 10k</td>
<td>0.065 -0.135 -0.276</td>
<td>0.0882 0.0018 -0.1018</td>
</tr>
<tr>
<td>Comp1b 5k</td>
<td>0.068 -0.062 -0.093</td>
<td>0.1021 0.0092 -0.0670</td>
</tr>
<tr>
<td>Comp1b 10k</td>
<td>0.049 -0.138 -0.273</td>
<td>0.0989 0.0102 -0.0665</td>
</tr>
<tr>
<td>Comp2 5k</td>
<td>0.108 0.115 0.124</td>
<td>-0.1307 0.0579 0.1990</td>
</tr>
<tr>
<td>Comp2 10k</td>
<td>0.141 0.291 0.155</td>
<td>-0.1269 0.0603 0.1970</td>
</tr>
</tbody>
</table>

Table 4: Interior GPS excenter and ROT excenter of model M2

The results of the models M1 – M3 led to the final model, which is made of the parameters in Table 6 common for both scales (and whose values where determined by a bundle adjustment using the data of both calibration flights).

<table>
<thead>
<tr>
<th>scale</th>
<th>princ. point [mm]/int. GPS-excenter z[m]</th>
<th>ROT-excenter [gon]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comp1a 5k</td>
<td>0.014 -0.010 -0.095</td>
<td>0.0939 0.0033 -0.1201</td>
</tr>
<tr>
<td>Comp1a 10k</td>
<td>0.006 -0.013 -0.276</td>
<td>0.0882 0.0018 -0.1018</td>
</tr>
<tr>
<td>Comp1b 5k</td>
<td>0.013 -0.011 -0.093</td>
<td>0.1021 0.0092 -0.0670</td>
</tr>
<tr>
<td>Comp1b 10k</td>
<td>0.005 -0.014 -0.273</td>
<td>0.0988 0.0102 -0.0665</td>
</tr>
<tr>
<td>Comp2 5k</td>
<td>0.021 0.023 0.124</td>
<td>-0.1307 0.0579 0.1990</td>
</tr>
<tr>
<td>Comp2 10k</td>
<td>0.014 0.029 0.154</td>
<td>-0.1268 0.0603 0.1970</td>
</tr>
</tbody>
</table>

Table 5: Principal point, interior GPS excenter’s z and ROT excenter of the model M3

<table>
<thead>
<tr>
<th>IOR [mm]</th>
<th>Glob GPS exc. [m]</th>
<th>Loc [m]</th>
<th>ROT exc. [gon]</th>
<th>Adp [ ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>y</td>
<td>z</td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>Comp1a</td>
<td>-0.003</td>
<td>-0.013</td>
<td>153.693</td>
<td>-0.051</td>
</tr>
<tr>
<td>Comp1b</td>
<td>-0.003</td>
<td>-0.013</td>
<td>153.692</td>
<td>-0.037</td>
</tr>
<tr>
<td>Comp2</td>
<td>0.010</td>
<td>0.027</td>
<td>153.387</td>
<td>-0.025</td>
</tr>
</tbody>
</table>

Table 6: Values of the final calibration model (computed in the UTM)
All computations during this calibration phase were carried out in two systems: the UTM system (zone 32) and a Cartesian tangential system (*TangSys*) defined at the center of the test area. In both systems the same values for the interior GPS excenter, the ROT excenter, the Adpars and the planar components of the IOR and the exterior GPS excenter were obtained, whereas in UTM the height component of the exterior GPS excenter were smaller by less than 1 cm (which is negligible), but the principal distances were larger by approx. 40 µm.

These differences are caused by the different scales in height and plane in UTM. The scale in height is 1:1 (meaning the ellipsoidal heights are used in UTM 'as they are'), whereas the planar scale is caused by the distortions of the UTM projection and depends on the location of the project’s area relative to the central meridian of the specific zone. So, for the center of the given area the scale factor is approx. \( \tau = 0.99975 \), meaning that the planar situation in the projection is compressed. In the adjustment, these two different scales are realized in plane and height by the ground control points and the GPS observations for the projection centers. If this scale difference is not removed, height errors may occur. With the free principal distance \( f \), however, the height scale can be aligned to the planar one and \( f \) is changed into \( f/\tau \). For more details concerning this problem see (Ressl 2001).

Another interesting result: the (by the pilot center resp. calibration protocol) given value for the principal distance \( f \) for the Leica RC 30 camera (Comp2) fitted closely to the computed value in the Cartesian tangential system, whereas the given value for the Zeiss RMK top (Comp1) fitted closely to the computed value in UTM.

After the system calibration the GPS/IMU data of the test flight (which was also delivered to the test participants) were corrected by the calibration parameters and returned (along with the calibration parameters) to the pilot center.

### 4. Phase 2 – Integrated bundle block adjustment

The aim of phase 2 was to apply the system calibration of phase 1 to an independent flight. This third flight (the test flight), made of 9 + 2 strips, was flown by each company directly after the 2nd calibration flight. Its scale is 1:5.000 and it consists of 180 images for Comp2 and a smaller number of 130 images for Comp1 (due to bad weather conditions). Phase 2 started in March 2001 and the results where due at the end of May. The GPS/IMU data of this flight were already delivered to the test participants together with the data for phase 1. The only data that were additionally delivered, were the measurements in the images of the test flight (approx. 25 tie points per image); but not for all images. Out of all images a sub-block (5 + 1 strips) of 50 images and a single strip of 17 images were selected by the pilot center – both were to be handled separately.

All throughout phase 2 the phase 1 corrected GPS/IMU data of the test flight were used. For the block and strip data of each company the following three scenarios were applied:

1. The GPS/IMU data of the test flight are kept fixed and are used as the XOR of the images. Then an overdetermined spatial intersection for the tie points is computed (direct georeferencing).

2. A combined AT is performed, using the GPS/IMU data together with the image measurements. Here the GPS/IMU data are used as observations for the images’ XOR.

---

*The IMU rotations are related to a temporary system of the aircraft (local horizon, ARINC 705). For UTM the Roll and Pitch angels were adopted and the Yaw angels were corrected by the actual value of the meridian convergence. For the TangSys all three angels had to be transformed.*
3. Same as 2); additionally a change in the misalignment is modeled. Afterwards the coordinates of the intersected tie points of scenarios 1 and 3 were compared.

4.1 Overdetermined spatial intersections with fixed XOR and IOR (direct georeferencing)
For this scenario the corrected GPS/IMU data was used as the XOR of the images and kept fixed. The overdetermined spatial intersection for the tie points resulted in the following $\sigma_0$ (µm in the image):

\[
\begin{array}{|c|c|c|}
\hline
& \text{Comp1a} & \text{Comp1b} & \text{Comp2} \\
\hline
\sigma_0/\text{Block} & 43 & 27 & 17 \\
\hline
\sigma_0/\text{Strip} & 17 & 11 & 14 \\
\hline
\end{array}
\]

Since the GPS/IMU data are disturbed by accidental (or even systematic) errors and are kept fixed, the residuals of the image coordinates have to compensate for these GPS/IMU errors and thus will result in larger image residuals and hence a large $\sigma_0$. If one compares these values with the accuracy of the image measurements of approx. 6 µm, one discovers a decrease in accuracy of 200 % - 700 %. This comparison, however, is not correct since the functional model in these two adjustments are different (free vs. fixed XOR) (see also section 4.4). Further, it is interesting to see, that the strip version of Comp1 yielded significantly smaller $\sigma_0$ – the reason for this will be explained at the end of section 4.3.

4.2 AT with free and observed XOR and IOR
For this scenario, the XOR and (common) IOR for the images are allowed to be free. The GPS/IMU data are used as observations for the XOR (with the accuracies of Table 2). The calibrated values of the IOR (determined in phase 1) are used as observations for the IOR ($x_0 \pm 0.002 / y_0 \pm 0.002 / f \pm 0.003$). The following reference standard deviations $\sigma_0$ (µm in the image) were obtained:

\[
\begin{array}{|c|c|c|}
\hline
& \text{Comp1a} & \text{Comp1b} & \text{Comp2} \\
\hline
\sigma_0/\text{Block} & 6.2 & 5.8 & 6.1 \\
\hline
\sigma_0/\text{Strip} & 3.7 & 3.6 & 6.2 \\
\hline
\end{array}
\]

These values can be compared with the accuracy of the image measurements of 6 µm (for Comp2) and 5 µm (for Comp1). During the bundle block for each company, the a-priori accuracies of the GPS/IMU measurements were checked using ORIENT’s VCA. It delivers for each group of observations a factor, which describes the ratio between the a-priori and a-posteriori accuracies. If these factors are 'close' to 1, one can be quite sure, that the assumed a-priori accuracies are plausible and that finally the weighting of the observations is correct.

For the block versions of Comp1a and Comp1b the VCA delivered factors in the range of 3 for the Roll and Yaw angles, whereas for Comp2 these factors where close to 1. These high factors for Comp1 implied a change in the misalignment, for that reason another bundle block with an additional misalignment for each company was computed. For the strip versions of Comp1, the VCA-factor were always close to 1. The strip of Comp2, however, yielded a higher factor of 1.6 for Pitch and Yaw.
4.3 AT with free and observed XOR and IOR and an additional misalignment

With an additional misalignment in the adjustment the following $\sigma_0$ ($\mu$m/image) were obtained:

<table>
<thead>
<tr>
<th></th>
<th>Comp1a</th>
<th>Comp1b</th>
<th>Comp2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_0$/Block</td>
<td>5.0</td>
<td>5.0</td>
<td>6.1</td>
</tr>
<tr>
<td>$\sigma_0$/Strip</td>
<td>3.4</td>
<td>3.4</td>
<td>5.9</td>
</tr>
</tbody>
</table>

Now for all companies the VCA delivered factors close to 1, except for the Yaw of the block version of Comp1b. Since this was a little bit surprising, the residuals of the rotations angles were plotted.

These plots clearly show the following facts:

- In both data processings of Comp1 irregularities in the Yaw angle occur at the strip endings. In all three angles a linear trend can be seen clearly. For Roll and Pitch this linear trend can effectively be replaced by an additional misalignment. Comparing the Yaw-residuals of the 1st (erroneous) and 2nd (correct) data processing, it is interesting to see, that the mean value of the Yaw-residuals got closer to zero (which was expected), whereas the extent of the Yaw-residuals (max – min) increased (which was not expected). So, as a makeshift, the accuracy of the Yaw angles of the 2nd data processing was set from 80°c to 160°c.
- The Yaw angles of Comp2 included one gross error (the value for image 2279), which was eliminated during all adjustments.

The following table holds the values for the additional misalignments ($\pm$ 15°c).

<table>
<thead>
<tr>
<th>[gon]</th>
<th>Comp1a</th>
<th>Comp1b</th>
<th>Comp2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block</td>
<td>0.0163/0.0083/0.0348</td>
<td>0.0141/0.0052/0.0098</td>
<td>-0.0005/0.0015/-0.0068</td>
</tr>
<tr>
<td>Strip</td>
<td>0.0000/0.0045/0.0141</td>
<td>0.0000/0.0019/-0.0095</td>
<td>0.0000/0.0052/0.0112</td>
</tr>
</tbody>
</table>

These (strip by strip) irregularities in the IMU-data of the block version of Comp1 are the reason, why in section 4.1 the $\sigma_0$ is larger than the one of Comp2 (which has no such irregularities). They also explain why the strip version of the direct georeferencing (in section 4.1) for Comp1 yielded significantly smaller $\sigma_0$ than the block version, since in one single strip no such irregularities occur. On the other hand, for Comp2, whose IMU-data is systematic free, the strip and block version of direct georeferencing yielded similar $\sigma_0$.

Another interesting fact could be observed with the IOR of Comp1. The value for $y_0$ computed in phase 1 did not fit to the data of phase 2 ($\Delta y_0 = 25 \mu$m). This is not a result of
the additional misalignment in Roll, since y₀ of phase 1 doesn’t fit to phase 2 either, when all angle observations are excluded from the adjustment and only the GPS observations are used. So, perhaps, there was an error in the GPS data. The y₀ coordinate of the principal point, however, was allowed to be free, although – perhaps – it only removes the symptoms but not the cause.

4.4 Comparison of the intersected tie points of the direct georeferencing with the tie points of the AT with additional misalignment

The following table holds the statistics of the differences of the tie points of scenario 1 and 3. For Comp2 637 (block) and 322 (strip) tie points were compared, for Comp1 549 (block) and 257 (strip).

<table>
<thead>
<tr>
<th>[m]</th>
<th>Comp1a</th>
<th>Comp1b</th>
<th>Comp2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>σ₀ = 43</td>
<td>σ₀ = 27</td>
<td>σ₀ = 17</td>
</tr>
<tr>
<td>Y</td>
<td>-0.020</td>
<td>-0.013</td>
<td></td>
</tr>
<tr>
<td>Z</td>
<td>-0.018</td>
<td>-0.018</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.098</td>
<td>0.087</td>
<td>0.125</td>
</tr>
<tr>
<td>Std. dev.</td>
<td>0.098</td>
<td>0.087</td>
<td>0.125</td>
</tr>
<tr>
<td>Strip</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>σ₀ = 11</td>
<td>σ₀ = 11</td>
<td>σ₀ = 14</td>
</tr>
<tr>
<td>Y</td>
<td>0.026</td>
<td>0.055</td>
<td>0.003</td>
</tr>
<tr>
<td>Z</td>
<td>0.003</td>
<td>0.003</td>
<td>0.003</td>
</tr>
<tr>
<td>Mean</td>
<td>0.012</td>
<td>0.028</td>
<td>0.004</td>
</tr>
<tr>
<td>Std. dev.</td>
<td>0.051</td>
<td>0.078</td>
<td>0.075</td>
</tr>
</tbody>
</table>

For the block version, the standard deviations for Comp2 are the smallest (6 cm in plane, 11 cm in height), for the 2nd data processing of Comp1 they are larger by approx. 3 cm. The mean values of Comp2 are caused by the small additional misalignment. The reason why the data of Comp2 yielded the smallest differences in the tie points is, that its GPS/IMU data are only disturbed by accidental errors, whereas the data of Comp1 is affected by discontinuous changes in the misalignment.

For the strip version the standard deviations of the 2nd data processing of Comp1 are the smallest. For Comp2 quite large mean values and standard deviations in the tie point differences can be spotted. They are caused by the changes in the misalignment of Pitch and Yaw. The Yaw residuals also show a clear linear trend for Comp2 (plot not included).

As it was already mentioned in section 4.1 the σ₀ of direct georeferencing may not be compared with the σ₀ of the bundle scenario (~ 6 µm). Due to the different functional models (fixed vs. free XOR) the cofactors for these scenario will be different. The cofactors, which depend on the geometric properties of the point determination, will be smaller for direct georeferencing in general. For this test, the mean of their roots was smaller by ~ 40 %.

The fact, that for Comp2 (block) the direct georeferencing scenario delivers similar results to the bundle scenario, does not mean, that the latter can be fully replaced by the former one. Two reasons mainly speak against that:

---

8 The estimated accuracy σₓ for an unknown X determined during the adjustment depends on the reference standard deviation σ₀ and the corresponding diagonal element Qᵢᵢ of the cofactor-matrix (the inverse of the matrix of the normal equations): σₓ = σ₀ ⋅ Qᵢᵢ.
• Direct georeferencing does not deliver useful accuracy estimates. As we saw, the direct results appear much more accurate than one may deduce from their \( \sigma_0 \).

• If systematic errors (like for Comp1) or gross errors (like for Comp2) are in the GPS/IMU data, then the intersected points will be false according to that. These types of errors can be detected using conventional bundle methods (when at least three images are used at once).

5. Conclusions

In this article it was presented how the task of the OEEPE test ‘Integrated Sensor Orientation’ can be solved using the hybrid bundle block adjustment program ORIENT. The results of the two phases can be summarized in the following way. The main result of this test is:

• The usage of GPS/IMU data free of systematic errors as fixed values for the images’ XOR (direct georeferencing) yields for the given block with the scale 1:5,000 coordinates for the tie points similar to those of the corresponding integrated AT (standard deviations of the differences: 6 cm in plane and 11 cm in height). One must be aware of the fact, however, when adapting these results for other projects of direct georeferencing, that the results during this test were obtained by performing an overdetermined intersection for the whole block – which is perhaps not what a novice may understand as ‘direct georeferencing’, who would rather use the GPS/IMU data to perform stereo restitution from image pairs right away (cf. end of this section).

Among the secondary results the following can be stated:

• The IMU data of the block version showed one gross error (for Comp2) and partly linear trends together with clear discontinuities in the misalignment at strip endings (for Comp1). The IMU data of the strip version showed a linear trend for the Yaw values of Comp2.

• The IOR of Comp1 showed a somewhat peculiar behavior. The \( y_0 \)-coordinate, that was determined for Comp1 during the calibration phase, did not fit to the data of the test flight in phase 2 and changed by \( \Delta y_0 \approx 25 \mu m \). We assume, that this is rather a compensation for some error in the GPS data of phase 2, since \( \Delta y_0 \) occurs independently on the usage of the IMU data.

This OEEPE test demonstrated the high potential of integrated sensor orientation and it is undoubt able that its importance in image orientation will increase over the next years. Today, however, there are still some open problems this technique has to cope with (see section 1), including the reliability of the GPS/INS data and the stability of the misalignment as the most important ones. These latter problems showed up also during this test. As a consequence, total direct georeferencing without any tie and control points by immediate stereo restitution using GPS/IMU data is still not possible (due to the large \( y \) parallaxes in the image (Heipke et al. 2001)).

A thinkable solution would be to perform a calibration flight (in two scales) before and after each project to determine the misalignment and its linear trend and to interpolate the misalignment for each time of exposure. Discontinuous changes in the misalignment during the project flight, however, can not be detected by this method, either. This calibration flight is also inevitable regarding the IOR, since the principal distance may differ largely from its labor calibrated value because of atmospheric influences. After all, system calibration (including IOR and GPS/INS parameters) must be carried out as precise as possible because direct georeferencing acts like an extrapolation (since the control points are only on the level
of the plane), during which system errors have a very strong impact on the determined points on the ground; whereas conventional AT acts like an interpolation (since the control points are on the ground, where new points are to be determined); (Heipke et al. 2001). And, as it emanated during this test, also the choice of the underlying coordinate system (map projection vs. Cartesian tangential system) is of importance concerning direct georeferencing.

6. References


Acknowledgment

This work was supported by the Austrian Science Fund (FWF) – P13901INF.

9 An revised English version of this paper (preliminary title ‘Direct Georeferencing of aerial images in conformal map projections’) will be submitted to the ISPRS Commission III Symposium 2002, Sept. 9 – 13, Graz, Austria.