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Handling Uncalibrated GPS/IMU Data for Medium Scale Mapping

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Summary: The use of GPS/IMU is simplifying aerial photogrammetry and extends the applications, since it generates the exterior orientation directly. Nevertheless, some traditional geoinformation vendors still resist using GPS/IMU data in their projects, since the system is more complex than standard photogrammetry and it has to be calibrated. The special calibration flight, the ground control and the necessary computation of the calibration data, seem to restrict the promised flexibility. Some small flight companies deliver the photos together with GPS/IMU data not improved and validated by calibration. A solution for handling uncalibrated GPS/IMU data is presented, leading to results fulfilling the accuracy requirements for mapping in medium scales, without additional costs.

Zusammenfassung: *Zur Verwendung von nicht kalibrierten GPS/IMU-Daten bei der Kartenherstellung in mittleren Maßstäben.* Der Einsatz von GPS/IMU-Daten vereinfacht die Luftbildphotogrammetrie und erweitert ihre Anwendungsmöglichkeiten, weil die Parameter der äußeren Orientierung direkt bestimmt werden. Dennoch hat sich dieses Verfahren in der Praxis noch nicht überall durchgesetzt, weil es komplexer als die traditionelle Standardphotogrammetrie ist und außerdem eine Kalibrierung benötigt. Der Kalibrierungsflug, die Bestimmung von Passpunkten im Kalibrierungsgebiet und die notwendige Berechnung der Kalibrierungsdaten scheinen die Flexibilität des Verfahrens einzuschränken. Einige Bildfluggesellschaften liefern Bilder in Kombination mit GPS/IMU-Daten, die nicht durch Kalibrierung verbessert und validiert wurden. Dieser Artikel stellt ein Verfahren für die Verarbeitung von unkalibrierten GPS/IMU-Daten vor, welches die Genauigkeitsanforderungen für Kartierungen in mittleren Maßstäben erfüllt und keine zusätzlichen Kosten verursacht.

1 Introduction

Nowadays, mapping by photogrammetry means data acquisition for a geoinformation system. For the required geometric accuracy it involves a sequence of preliminary operations mainly depending upon the representation scale. The image orientation plays the most important role. In aerial photogrammetry for mapping purposes such orientation is traditionally determined by means of aerial triangulation of a block of nearly vertical photos. Based on a set of well distributed ground control points and sufficient number of tie points, the aerial triangulation is an indirect method of determining the position of the projection centres and the attitudes.

The determination of a sufficient number of ground control points in the required location is time consuming, expensive and sometimes not possible.

The late developments in photogrammetry were driven by simplifying the sensor orientation. Since the availability of algorithms and commercial software for the automatic determination of homologous points in aerial photos, the acquisition of

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tie points is, in the most cases, no longer a critical issue. The use of relative kinematic GPS-positioning allowed a reduction of the number of control points. In this method the coordinates of the projection centres are interpolated, for the moment of each exposure, from a GPS determined flight trajectory. Several years of experience confirmed that GPS data included in a combined adjustment, with tie points and some additional crossing flight lines, lead to a relevant reduction in the number of necessary ground control points (Jacobsen 2002). By fixing an Inertial Measuring Unit (IMU) to the sensor and combining this system with the GPS unit, not only the position of the projection centres but also the sensor attitudes can be determined at the instant of exposure. In other words, the exterior orientation can be directly available (and not over ground control points) for every photo of a GPS/IMU supported flight.

The GPS/IMU based sensor orientation, due to its flexibility and independence from block configuration and ground control, expands the fields of application of aerial photogrammetry. For example coastal areas, remote or dangerous regions and also areas of poor contrast like deserts or forests, where the automatic aerial triangulation is not able to provide enough tie points, can be oriented without problems by means of GPS/IMU. So, also photo flights containing just one stripe and those coming from small format cameras can be handled in an economic manner.

Nevertheless, the system composed by the camera/sensor, the IMU and the GPS unit has to be calibrated. That means, the space relation between the three units must be known. Usually, this calibration is done by comparison of indirect and direct determined orientation parameters for the same set of photos. The indirect determination, as mentioned above, is done by means of aerial triangulation with ground control points. That means, GPS/IMU does also need some ground information. Fortunately, this fact doesn't restrict too much the flexibility of the technique, because the reference area with ground control for the calibration doesn't have to be located in the project area, as long as certain aspects are considered. For instance, the influence of the map projection and the Geoid undulation differ from calibration site to project site and that must be taken into account. In case of different flying heights, the effects on the focal length shall also be considered (Jacobsen 2004a, Yastikli & Jacobsen 2005).

Summarizing, the use of GPS/IMU offers, theoretically, a lot of advantages: full sensor orientation for every photo without aerial triangulation and without ground control points (except for the system calibration), saving of time and therefore reduction of the global data acquisition costs. What about the practical results? Assuming that the conditions for a good operation of the GPS/IMU system on the plane are guaranteed, including an initialization of the system before the photo acquisition by flying an eight shaped curve and avoiding extremely long stripes without further initializations (Jacobsen 2004a), the quality of the results depends mainly on the system calibration.

Furthermore, other aspects must be considered. Handling GPS/IMU data requires experience and education (Jacobsen 2004a). Unfortunately, not every user is immediately able to handle the data that some flight companies deliver. Several map producing companies are not ready to pay the additional costs of such data since they do not know how to handle it to get reasonable results. The most frequent problem is that the necessary system calibration is sometimes incomplete or missing. On the other hand, small flight companies are also not ready to fly extra stripes and to acquire ground control points, when it is not guaranteed that the customer buys the data at a price that covers the extra expenses. Besides, in small countries, flight companies seldom have the structure and the necessary know-how for carrying out a calibration beyond the flight. Although both parts know that a calibration is absolutely necessary, each part alleges that it is a task for the other one. Uncalibrated photo flights with GPS/IMU data are not as rare as one might suppose. So, how

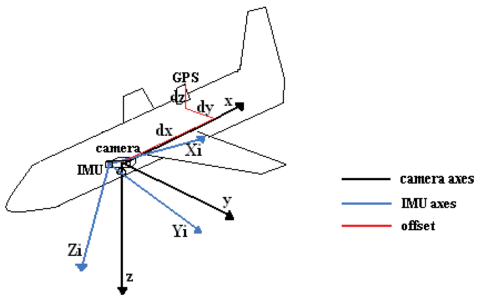

Fig. 1: Offset and Misalignment.

to recover the calibration data? A method how to handle not calibrated GPS/IMU flight data is shown in the following chapters.

2 Calibration Data

Exterior orientation parameters consist on the projection centre coordinates and three attitude angles defining the rotation of the camera coordinate system in relation to the object coordinate system. The relative kinematic GPS positioning yields the object coordinates of the centre of the GPS antenna. Projection centre and antenna centre are separated in space by the offset vector (Fig. 1). Usually, this vector can be measured and its components are available in the camera coordinate system. The effect of this offset on the object coordinates of the projection centre differs from photo to photo, depending on the attitude of the camera. The antenna offset has to be considered as a part of the calibration data.

On the other hand, the Inertial Measuring Unit is fixed to the camera and yields, based on the accelerometers and gyroscopes, three attitude angles and the position of the IMU. Usually IMU origin and camera projection centre are not coincident and the system axes of the IMU are not parallel to the camera coordinate axes (Fig. 1). That means, for getting the exterior orientation parameters of the camera from IMU data, the shift between IMU axes origin and projection centre, as well as the misalignment of the axes must be considered. Unlike antenna offset and IMU shift, the misalignment can't be measured. It has to be determined indirectly by comparison between IMU data and exterior orientations coming from a reliable source. In addition, this so called boresight misalignment may not be stable in time, so that for projects with high accuracy level it is advisable to determine it at the day of the flight. Shift of the coordinates and misalignment of the axes are elements of the calibration data.

The inner orientation of a camera usually is determined under laboratory conditions. Under flight conditions it can change (Jacobsen & Wegmann 2001). As far as stereo models are oriented by means of control points, the discrepancies between the laboratory values and the real ones have only a limited influence on the derived ground coordinates because the ground point determination is mainly an interpolation in relation to the control points.

When GPS/IMU data is used for direct georeferencing, the ground coordinates of a new point are determined by extrapolation from the projection centre coordinates. Discrepancies of the inner orientation parameters have here a stronger influence in the derived ground coordinates as in the previous case. If the calibration is determined in a different flying height as the project flight, we will have different inner orientations for each flight. So, it is advisable to determine how the inner orientation changes with the height to be able to correct it for the project flying height.

3 Requirements for the calibration flight

The calibration flight must cover an area with a sufficient distribution of well determined ground control points. The control point distribution can be like for a conventional aerial triangulation with a distance of 3 to 4 base length from each other. At least two stripes flown in opposite directions are required for the boresight calibration when the IMU shift and the misalignment are intended to be determined. If the calibration and the project flights do have the same scale, the mentioned configuration is sufficient. Otherwise it is also necessary to adjust the actual focal length for the project flight and that requires one more stripe in a different flying height (Jacobsen 2001).

4 Project Southeast

The project "Southeast" is located in the southern part of Portugal. The photo flight was part of an extensive coverage for mapping purposes in 1 : 25000 and consists of four stripes with a north-south orientation, covering an extension of about 10 km × 55 km with in total 112 aerial photos with an average scale of 1 : 22700, 60 % end lap and 30 % side lap. The analogue colour photos were scanned with 14 µm pixel size.

GPS/IMU data from an Applanix POS/AV 410 unit were supplied for all four strips with a set of UTM coordinates, height, geographic coordinates, attitude angles as omega, phi, kappa and GPS time for each photo. The accuracy of the unit is given by the producer as being 0,008 degrees (roll and nick) to 0,015 degrees (heading) for the angles and 5 to 30 cm for the projection centres (Sandau 2005).

The initial assumption that the supplied GPS/IMU data corresponds to the exterior orientation parameters of the photos soon revealed to be wrong. To worsen the situation, neither calibration values, nor signalised ground control points were available.

5 Recovering calibration information

To correct the available GPS/IMU data it was necessary to process a calibration. That means, part of the block should be triangulated based on ground control points. From the so achieved exterior orientations and the GPS/IMU data for that part of the block, we could obtain corrections for the rest of the data.

According to the requirements for a calibration flight having the same scale as the project flight, the two central strips of the block "Southeast" with 55 photos were chosen as reference area (Fig. 2).

As the area is densely covered by ground triangulation points (Fig.3), it would be an economic solution to use them as ground control, avoiding additional field work. The disadvantage of those points is that they are marked by monuments built to be seen from the earth and not necessarily from the air. Consequently the identification in the photos was difficult and in most of them the floating mark couldn't be set to the ground.

An automatic aerial-triangulation was made for the whole block. The 19 triangulation points in the reference sub-block were handled as ground control in a national coordinate system.

5.1 *Object coordinates*

An analysis of the delivered GPS/IMU data and the available ground control data revealed that several steps had to be done before any calibration elements could be determined.

As a matter of fact (see Tab. 1), only the reference ellipsoid was common to both data sets. First of all, the heights must be transformed to a common reference level.

Tab. 1: Coordinate definitions of used data sets.

Data set	GPS/IMU	Ground control
Coordinate System	national coordinates 1/ Geographic	national coordinates 2
Map Projection	UTM	TM Local
Ellipsoid	WGS84	WGS84
Height Reference	Ellipsoid	Geoid
Central meridian	$\lambda = 351°$ (9° W Gr.) X = 500 000 m	$\lambda = 351{,}86689139°$ X = 200 000 m
Equator	Y = 0 m	Y = – 4092695,273 m
Scale at central meridian	1 : 0,9996	1 : 1,000

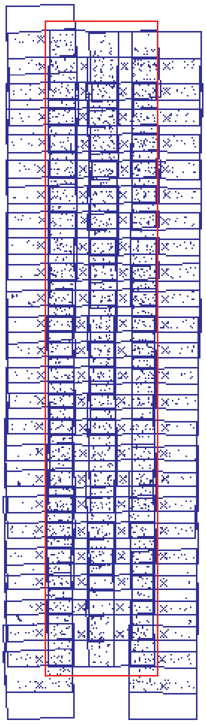

Fig. 2: Project "Southeast": Footprints and reference sub-block.

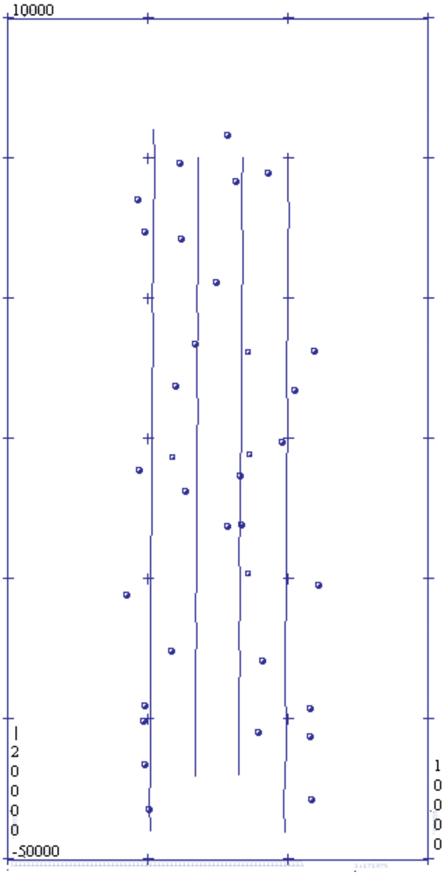

Fig. 3: Stripe lines and ground net points in the project area.

Using the module UNDULE of the Hannover Program System BLUH and a Geoid data set covering Europe, the heights of the control points have been corrected by the Geoid undulation to ellipsoidic heights.

The objective of determining the calibration data by differences between exterior orientations obtained, on one hand, from GPS/IMU and, on the other hand, from a ground controlled aerial triangulation gives rise to some problems. So, a block adjustment based on control points leads to flying heights above ground that are affected by the same scale factor as the national coordinates of the ground control, while the heights from GPS/IMU data have the scale factor 1.0 (Jacobsen 2004a). In addition, the

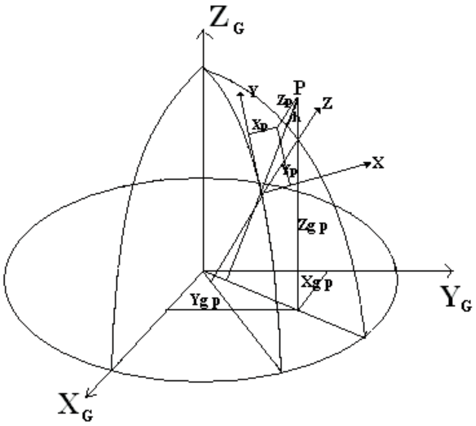

Fig. 4: Tangential orthogonal (X,Y,Z) and geocentric (XG,YG,ZG) coordinate systems.

used map projections have different central meridians, so the directions of grid north in both map projections are not parallel.

A method to avoid the effects caused by different map projections is a transformation to a common tangential coordinate system (HEIPKE et al. 2001). Opposite to the national coordinate systems this is a Cartesian system (Fig. 4). The Y axis is coincident with the geographic north direction at the tangential point and the scale is homogeneous along all three axes.

5.2 *Determining the Antenna Offset*

Before the boresight misalignment and IMU shift can be determined, the GPS/IMU data has to be corrected from the offset of the GPS antenna. In the present project no reliable information was available about measured offset components or whether the data was already corrected from offset. So it had to be checked.

Therefore, a combined aerial triangulation was processed with program BLUH, with ground control points and projection centres coming from the GPS/IMU together with the photo coordinates set of the chosen calibration strips.

Since the existence of antenna offset is reflecting in a flight direction dependent systematic influence, the additional parameters that reveal corrections in the position of the projection centres were separately calculated for each strip, so that this influence and its amount could be detected.

The results (Tab. 2) showed that a not considered offset was causing significantly different shifts in the projection centres from strip to strip, being similar within each strip (indicated by similar standard deviation). Of course an offset in the flight direction may not be just caused by the distance between GPS-antenna and the projection centre. Constant synchronisation errors have a similar effect. Nevertheless, for the practical handling of the data the cause of the offset is less important than its detection.

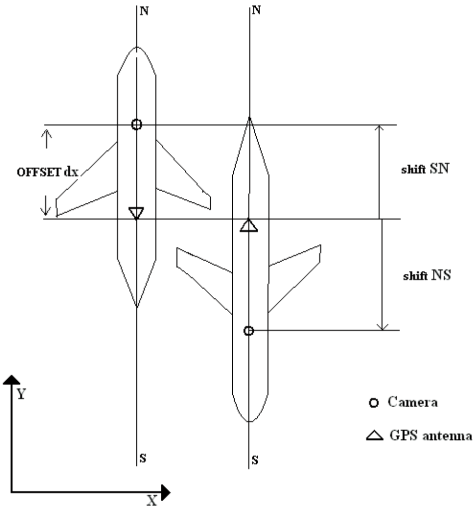

Fig. 5: Effect of dx-offset.

To determine the offset vector components in the camera coordinate system (dx,dy,dz), it was necessary to analyse how the camera axes were oriented in the XYZ object space, during the flight (Fig. 5). A shift in Y, for instance, is caused by an dx-offset (x is located in the flight direction – in this case in North-South direction).

The intention of this first step was to get approximate values for the dx and dy components of the offset vector so that the whole GPS/IMU data set could be corrected from the biggest part of its influence. Unlike dx and dy, the dz offset only influences the Z-shift of the coordinates and can be included also later in the computation of the general Z-shift between IMU and object coordinate systems. So, the size of dx was assumed to be about half of the Y-shift differences between the stripes ([– 2,7 + 1,0]/2 = – 1,7/

Tab. 2: Shift in projection centres (mean values). GPS data minus result of bundle adjustment.

	Projection centre shift [m]			standard deviation [m]		
	X	Y	Z	SX	SY	SZ
STRIP 1	– 6.315	**– 2.728**	**– 1.364**	0.058	0.154	0.082
STRIP 2	– 6.476	**– 0.998**	**– 0.382**	0.061	0.143	0.080

2 = 0.75 m), as far as they exceeded the a priori standard deviation for the GPS coordinates (± 30 cm). The dy component was assumed to be 0. An approximate offset of x = − 0.75 m, y = 0 m, z = 0 m was then used for a flight direction dependent correction of the whole GPS/IMU data set.

5.3 *Reference orientation*

For computing the exterior orientation by bundle block adjustment well distributed and well defined ground control points shall be used. Because the accuracy of the available control points in this project could not be guaranteed, the computed exterior orientations could not be assumed as a reference. As a solution for this problem, a two step adjustment was applied as follows.

Since the GPS projection centre coordinates were more accurate than the existing ground control (Tab. 3), a combined adjustment was computed in the first step, in the reference sub-block. Self calibration with additional parameters was considered in the adjustment including shift parameters for the projection centres. On the second step, the object coordinates resulting from the previous adjustment (over 2000 points) were considered as ground control for a conventional aero triangulation (without GPS). So, a set of orientation parameters has been estimated that was not so much dependent upon the GPS projection centre coordinates.

The use of this strategy has advantages when the quality of the ground control is poor (Jacobsen 2004b). The resulting exterior orientation parameters were finally used as reference orientation data set.

5.4 *Boresight Misalignment*

To assure that the angles of both data sets coming from IMU and from block adjustment were comparable, particular attention was paid to the rotation sequence in each data set. The IMU angles, which were delivered in the ω, φ, κ sequence, have been first transformed to the φ, ω, κ rotation sequence used by BLUH and then analysed with the Hannover program GPSPL.

Since the Inertial Measuring Unit originally delivers the attitude of the sensor in terms of pitch, roll and yaw (Fig. 6), with yaw as primary rotation and referred to geographic north, the boresight misalignment has also to be determined in this angle definition, corresponding to the physical rotation that may be affected by systematic errors (Jacobsen 2002).

Therefore, the angles of both data sets are at first converted to pitch, roll and yaw and then compared with each other. The results (Tab. 4) include corrections to these angles and not to φ, ω, κ. The convergence of the meridians must be computed for each projection centre and used for the angle conversion.

The first line of Tab. 4 includes the mean values of the differences between both data

Tab. 3: Results of adjustment steps 1 and 2.

	ground points	GPS points	σ_o [μm]	RMS X [m]		RMS Y [m]		RMS Z [m]	
				ground	GPS	ground	GPS	ground	GPS
1. AT(GPS)	19	46	5.06	0.447	0.080	0.528	0.198	0.690	0.053
2. AT	2216	–	5.59	0.069	–	0.103	–	0.187	–

Tab. 4: Angle and coordinate differences.

	pitch[grads]	roll[grads]	yaw[grads]	X [m]	Y [m]	Z [m]
misalignment	− 0.00952	− 0.08722	− 0.02018	7.248	1.714	0.984
square mean of differences after bias correction	0.0042	0.0058	0.0042	0.169	0.221	0.082

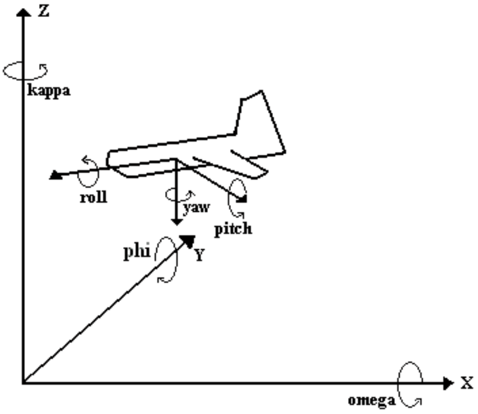

Fig. 6: Rotation angles: Kappa origin = grid north, Yaw origin = geographic north.

sets. Not only the misalignment of the axes is computed but also the shift of the GPS/IMU coordinates to the camera projection centre coordinates.

The last line shows the root mean square of the differences after bias correction. It is in the range of 4 to 6 milligrads for the attitudes and ±20 cm for the projection centres. Consequently, the first line can be assumed as the estimated boresight misalignment and the XYZ values indicate a datum shift between IMU and local coordinate systems (not just a shift between IMU and camera systems). These values will be used to correct the data of the project flight.

6 Evaluating the results

Using GPSPL once again, the misalignment angles were transformed back to the photogrammetric φ, ω, κ and the corrections were applied to the whole GPS/IMU data set already corrected from the antenna offset. Because the applied method wasn't based on reliable ground control, it is more reasonable to name it corrected GPS/IMU data instead of "calibrated data".

In order to evaluate the quality of the so achieved orientation data, several approaches were done with the complete block.

A set of check points was composed of the whole set of 29 ground net points. Their standard deviation is in the range of 0.6 m. Another set consisted of the object coordinates derived from a combined adjustment with GPS projection centres in the whole block. This adjustment was independent from the attitude data.

At first the object coordinates have been determined by spatial intersection based on the direct sensor orientation (corrected GPS/IMU data). This was followed by an Integrated Sensor Orientation where the orientation parameters have been adjusted based on the photo coordinates and including the direct sensor orientation as observation, in order to reduce y-parallaxes in the stereo models. No ground control was used.

As expected (Tab. 5) the discrepancies at the ground control points are in the range of the estimated control point accuracy. Better results are achieved in relation to the ground coordinates of the combined adjustment. The integrated sensor orientation has improved the results only slightly.

Recalling the objective of the project, the mapping in scale 1 : 25000, requiring in planimetry 0,1 mm × 25000 = 2,5 m and in altimetry 1/3 of contour interval = 10 m/3

Tab. 5: Results from the spatial intersection and from the integrated sensor orientation.

root mean square differences (+/−) at check points	spatial intersection ($\sigma_o = 13.2\,\mu m$)			integrated sensor orientation ($\sigma_o = 7.1\,\mu m$)		
	SX	SY	SZ [m]	SX	SY	SZ [m]
ground control points (29 points)	0.645	0.721	0.839	0.640	0.754	0.785
ground points of the combined adjustment (2761 points)	0.438	0.279	0.441	0.419	0.262	0.398

Tab. 6: Discrepancies of attitude data.

Square mean of differences [grad] (97 projection centres)	Sφ	Sω	Sκ
Corrected GPS/IMU – Comb. Adjustment	0.0077	0.0049	0.0058
Integrated Sensor Orientation – Comb. Adjustment	0.0084	0.0058	0.0025
Integrated Sensor Orientation – Corrected GPS/IMU	0.0057	0.0057	0.0045

= 3,3 m, it can be concluded that the improved GPS/IMU data assures the geometric accuracy requirements.

Assuming the worst value in Tab. 5 as the geometric accuracy for an orthophoto, the corrected GPS/IMU data could be also used for the production of orthophotos up to the scale of 1 : 9600. Considering that the data based on the combined adjustment with GPS projection centres are more reliable, even a scale of 1 : 5000 could be produced (0,1 mm in the ortho = 0,5 m on the ground).

As for the attitudes, the values shown in Tab. 6 for the square mean of the differences existing between the orientation angles yield by each method are within the measuring accuracy of the GPS/IMU system. The Integrated Sensor Orientation is mainly improving the κ-value. This has an influence to the model orientation sensitive for κ. Although y-parallaxes are irrelevant for automatic DEM generation, it disturbs the human operator if their values are exceeding 20 microns. Near this value vanishes, in general, the stereo perception (JACOBSEN & WEGMANN 2001, YASTIKLI & JACOBSEN 2002). So, also the y-parallaxes have been checked by intersection model by model.

Tab. 7: Frequency of points per model.

Points/Model	10–30	31–50	51–70	> 70
Number of Models	15	45	33	2

Tab. 8: Number of models with RMS y-parallaxes exceeding given limits.

Coordinate system	Origin of orientation parameters	Remaining Y-parallax (RMS)	
		> 10 µm	> 20 µm
Tangential system	Corrected GPS/IMU	7	0
Tangential system	Integrated Sensor Orientation	0	0
National system	Corrected GPS/IMU	48	0
National system	Integrated Sensor Orientation	37	0

Usually the mapping will be made in the national coordinate system. That means, the corrected orientation data have to be back transformed from the tangential to the national coordinate system of the ground net points. By this reason, the analysis of remaining y-parallaxes in the models was done in both coordinate systems (Tab.7 and 8).

As already mentioned, the Integrated Sensor Orientation reduces the y-parallaxes in the models, usually caused by the κ-values (JACOBSEN 2004a). Consequently there are fewer models with remaining y-parallax over 10 microns when the improved exterior orientations are used (lines 4 and 6 in Tab. 8). The results are significantly better in the tangential coordinate system than in the national system. Nevertheless, both approaches guarantee that there are no models in this block with remaining RMS y-parallaxes exceeding 20 microns. Therefore, every model can be handled by human operators without parallax problems.

7 Conclusion

Although GPS/IMU supported photo flights allow a great flexibility to photogrammetric projects, they usually require an additional system calibration. This causes some resistance from the user side.

In the present project, the orientation of a block for mapping in the scale 1 : 25000, supported by GPS/IMU was achieved without calibration data or well defined ground control points.

By means of the Hannover Program System BLUH it was possible to combine several observation sets in order to determine the offset and boresight misalignment. The ground information came from several not well defined net points existing in the covered area.

The results of the used strategy show that not only the required geometric accuracy for the pretended mapping scale but also the requirements for a parallax free stereo plotting were fulfilled. Using the so achieved exterior orientation data even orthophotos up to the scale 1 : 5000 could be produced.

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