SYSTEM CALIBRATION OF AERIAL CAMERA/GPS/IMU SYSTEMS – PROCEDURES AND EXPERIENCES

Jens Kremer

IGI mbH, Langenauer Strasse 46, 57223 Kreuztal, Germany – j.kremer@igi-systems.com

ABSTRACT:
The application of integrated GPS/IMU systems to directly measure position and orientation of aerial images or to aid other orientation methods became a widely used method over the last years. Especially the appearance of all-digital sensors accelerate the introduction of this technology. Nevertheless, some users of those systems had to undergo a –more or less– difficult learning process before they were able to get the full benefit of this technology.
Most of these experienced difficulties are not caused by malfunctions of the GPS/IMU systems or by mistakes during the flight missions, but by a not optimal introduction of the directly measured orientations and positions into the photogrammetric workflow. Especially the ambiguous use of the term CALIBRATION of aerial sensors equipped with GPS/IMU systems may cause confusion. In this paper, the different meanings of CALIBRATION are discussed for the case of a camera/GPS/IMU system. Different workflows are suggested for different applications and a result of the calibration of a camera/GPS/IMU system is given.

1. INTRODUCTION

The application of integrated GPS/IMU systems to directly measure position and orientation of aerial images or to aid other orientation methods became a widely used method over the last years. Besides the spread of scanning sensors, like line scanners or LIDAR systems, where an IMU system is a necessity, the potential to increase productivity and to reduce costs during the photogrammetric workflow lead to the increasing application of GPS/IMU systems together with aerial cameras.
Especially the appearance of all-digital imaging sensors accelerates the introduction of this technology. The successful introduction of a GPS/IMU system to a user's workflow requires more than the (necessary) correct mounting of an IMU to the aerial sensor. To obtain the full benefit of the technology, the correct handling of the different unknown parameters of the system - in other words – the *calibration* is crucial. Unfortunately, the term *calibration* of aerial sensors equipped with GPS/IMU systems is ambiguous. In this case, the *calibration* may be divided into the determination of groups of parameters of

- the aerial sensor,
- the IMU,
- the installation in the aircraft and
- the geodetic datum.

Looking at the final product of the georeferencing process, it is important to take into account that the effects of many of these parameters are strongly correlated and difficult to determine independently from each other. Some of these parameters only have a negligible effect on the final result; others may ruin the mission success if they are not handled correctly. For the daily photogrammetric production it is not necessary to make these considerations for each single project because a few workflows have proven to lead reliably to good results.

In this paper, a possible calibration procedure for the task of small and medium scale mapping and typical orthophoto projects (Direct Georeferencing) and a calibration method for large scale mapping projects (Integrated Sensor Orientation) are described. An example for the misalignment calibration for a Direct Georeferencing project is presented.

2. CALIBRATION PARAMETERS

In the following list, possible calibration parameters for a camera/GPS/IMU system are described and the typical method for their determination is given (It is NOT aspired to create a complete list!).

2.1 Camera Parameters

The parameters of an aerial camera are given by the camera manufacturer or a calibration office in a calibration certificate. They have to be determined in regular intervals. For the method of “Direct Georeferencing” (paragraph 3.1), the user should be careful to take the “constants” from the calibration certificates, if he wants to obtain highest accuracies. This calibration mostly has been done in a calibration laboratory in a very controlled environment. The environment in a survey aircraft, e.g. the temperature, can differ from these conditions strongly. Especially the focal length of the aerial camera can be affected by these different conditions.

2.2 IMU Parameters

The parameters of the IMU, like biases or scale factors of the sub sensors, or like adjustments to the orthogonality of the sensor assembly are either estimated by a Kalman filter process during the data processing, or they are determined by the manufacturer and taken into account during the data processing. The “normal” user does not need to take care of these parameters.

2.3 Installation Parameters

The installation parameters can be divided into two different groups:

2.3.1 The Parameters of the Installation of the IMU and the GPS Antenna(s) in the Aircraft

These parameters are the orientation of the IMU relative to aircraft axes and the relative position of the GPS antenna(s) to the IMU. These parameters of the installation do not change as long as the installation does not change. They can be determined either by direct measurements or they can be estimated during the GPS/IMU data processing.

Especially when highest accuracies have to be achieved, it is important to take changes of these parameters during the flight mission into account. These changes can get quite large, if the sensor-mount corrects the drift of the aircraft or if the sensor-mount is stabilized. The effect of the sensor-mount movement on the lever-arm can easily be estimated:
If the GPS antenna and the IMU are located centered in the aircraft and the GPS antenna is mounted one meter behind the IMU and one meter above the IMU, a corrected drift of 10deg would result in an offset perpendicular to the aircraft axis of $\sin(10°)*1m = 0.17m$. If two neighboring strips that were flown in opposite directions are compared, this makes a position offset of $2*0.17m = 0.34m$! A compensated roll angle of 5deg would lead to an offset of about half that size.

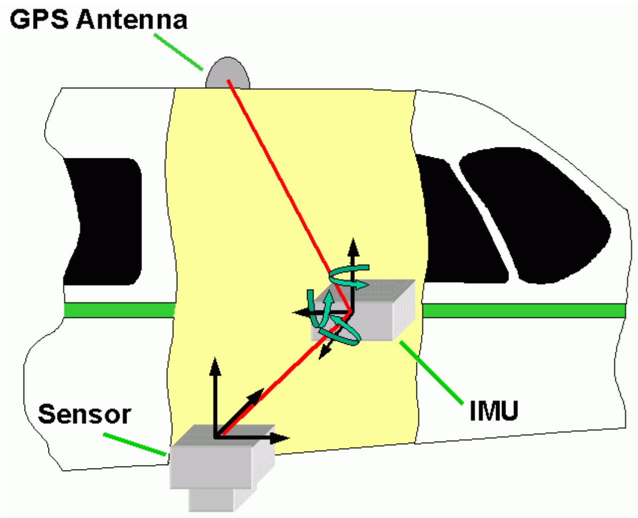

Figure 1: Lever-arm from the IMU to the GPS antenna and from the IMU to the camera

This effect is the same if no IMU, but only airborne GPS is operated. If the results of such a system are used for a GPS assisted AT, these effects show up as “GPS shift and drift parameters”. For all common stabilized sensor mounts it is now possible to readout the mount angles to correct for these effects.

2.3.2 The Parameters of the Installation of the IMU in/on the Camera

These parameters describe the relative orientation and position of the camera coordinate system to the coordinate system of the GPS/IMU results. The position offset can directly be measured. In the case of the calibration of a frame camera, the “boresight” or “misalignment” angles are determined by the comparison of the Exterior Orientation Parameters (EO) measured by the GPS/IMU system to the EO obtained by an Aerial Triangulation (AT). This comparison can happen explicitly to obtain the misalignment angles for further processing, or it can happen as one (for the user invisible) step in an Integrated Sensor Orientation process. As the example in paragraph 4 confirms, the misalignment angles stay sufficiently constant, as long as the mechanical integration of the IMU and the camera is done correctly. It is obvious, that changes in the mechanical installation create the need to review the misalignment calibration.

The comparison of the AT results with the directly measured EO does not only give the misalignment angles, but also a position offset. In theory, this offset should be insignificant, if all other parameters have been determined correctly, and if there were no systematic errors in the GPS measurements. An existing significant position offset can be caused by different effects:

A constant height offset:

A constant offset for height can be caused by an insufficient transformation of the WGS84 GPS coordinates of the GPS/IMU system to the target coordinate system. Another possible reason is the effect of a variation in the real focal length of the camera compared to the used focal length from the camera calibration. In the daily work, the much more trivial reasons like an incorrect height of the GPS base station or a wrong or unknown base station GPS antenna may cause an offset.

A horizontal position offset common to all flight lines:

Such an offset is caused by an insufficient transformation of the WGS84 GPS coordinates of the GPS/IMU system to the target coordinate system.

A horizontal position offset dependent on the direction of the flight lines:

Such an offset may be caused by a wrongly introduced position difference between IMU and GPS antenna(s). This error can be caused by drift or roll angle compensation of the sensor mount. Another reason could be a problem in the timing between the “instant” of the exposure and the recorded time stamp. A wrong principal point of the camera definition in the AT would have the same effect.

A position offset between the AT results and the directly measured EO are mostly not caused by a real spatial offset of the IMU and the camera, but caused by wrongly determined parameters described in paragraphs 2.1 and 2.4.

2.4 Datum Transformation Parameters

The target coordinate system for geo-referenced images is often not the same as the original coordinate system of the GPS/IMU data. The parameters of the transformation of the positions and angles to correct coordinate system have to be exactly known to avoid the introduction of additional errors. In some cases, the transformation parameters are not accessible or generally not known with a sufficient accuracy. In these cases the determination of these parameters is done as a part of the system calibration, although they are not really parameters of the camera/GPS/IMU system.

3. CALIBRATION METHODS

For the daily photogrammetric production it is not always aspired to find the physically correct value for all relevant calibration parameters, but to find methods to cancel out the effects of not correctly known parameters. This should be demonstrated with the following example:

For a photogrammetric block flown in an approximately constant height over ground, the AT of a small sub-block shows a small but significant height offset. In this case, it makes no difference for the final result of the complete block, if the used focal length for the camera would be adjusted, if the position of the GPS base station would be moved, or if the datum transformation would be changed (as long as the block is not too large). For this block all three methods would give practically the same result, but if the parameters should be transferred to other projects flown in different areas and different scales, it would make a large difference. For the daily photogrammetric production the following methods have proven to be useful:

3.1 Direct Georeferencing

The use of directly measured image EO for photogrammetric data processing without conducting an AT over the entire image block or strip can be called Direct Georeferencing (DG).

The advantages of DG are obvious: No AT, no tie point measurements and no Ground Control Points (GCPs) are needed for the complete block. These advantages lead not only to substantial cost reductions compared to traditional georeferencing using AT or GPS assisted AT, but also to shorter processing times.

On the other hand, for this method the determination of the calibration parameters, as described in paragraph 2.1 have to be done with care. The reason is the missing redundancy in the DG process. This implies that the not correct determination of some of the parameters described in paragraph 2.1 would affect the final result without a clear “warning” to the operator.
If the method of DG shall be used, the minimal calibration would be to determine the misalignment angles (see paragraph 2.3.2) at least once. The misalignment angles that result from the misalignment calibration do not depend on the position of the calibration area or on the photo scale. They do not even depend on the availability of GCPs! This misalignment calibration can be done with a special calibration field, but in most cases it makes more sense to use a small sub-block of the actual mission area. To use a small part of the mission area for the calibration has the advantage that no extra flying time and no extra photos are wasted. If at least one GCP is available, a possible datum shift can be detected inside the area and not somewhere else.
To process a part of the area with an AT to do the misalignment calibration has the additional advantage, that the result of the complete system is checked.
If a part of a block should be used that was flown with a standard side-overlap of 30%, the configuration for the calibration should include at least three flight lines, the middle line should be flown in the opposite direction. The determination of the angles does not depend on GCPs but if the correct height and possible datum shifts shall be checked, it is useful to have at least four, if possible six GCPs like shown in the example (for an ULTRACAM$_D$) in Figure 2. If a separate calibration field should be operated, the minimal configuration would be two lines, but with minimum 60% side-overlap.

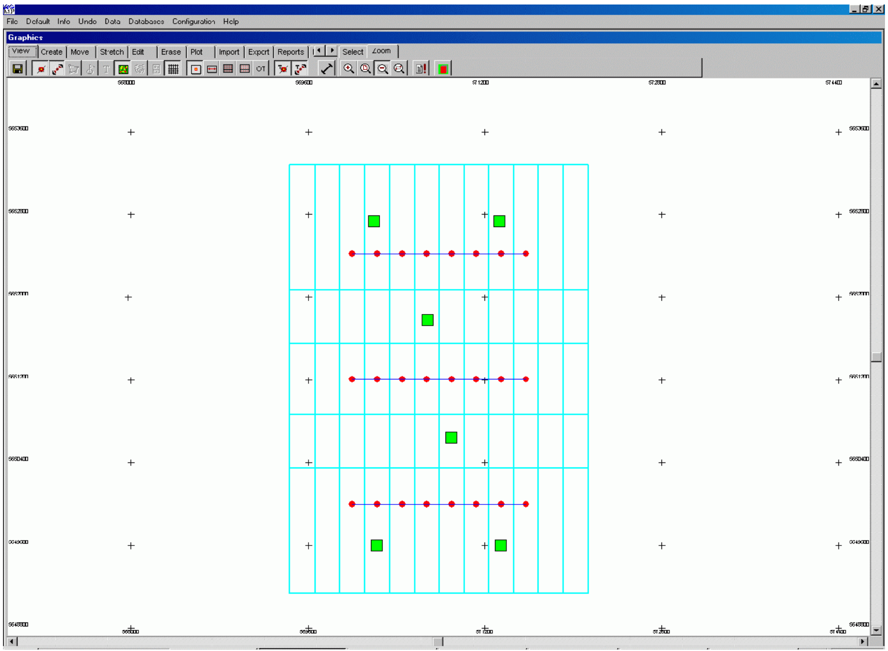

Figure 2: Example for a calibration sub-block

The AT of the calibration field should use the at least positions, but better positions and angles of the direct EO as additional measurements. In other words, the calibration AT for DG should be an Integrated Sensor Orientation of the calibration area. To be able to detect a possible shift, it is important that the AT includes the position offset (or global shift) as free parameters.
The user should keep in mind, that the misalignment angles obtained with this procedure are stable for a long time (depending on the physical installation), but the possible position offsets may be different for a different project in a different scale and a different area. If the position offsets shall be used for another project, the result should be checked with known points in the area.

3.2 Integrated Sensor Orientation

The simultaneous processing of GPS/IMU results and image information for the determination of the EO in an extended aerial triangulation is referred to as Integrated Sensor Orientation (ISO).
For ISO the advantage of not needing AT and tie point measurements is traded for an easier and more error tolerant orientation procedure. This procedure eliminates the need for a special misalignment calibration, because the parameters described in 2.1, 2.3 and 2.4 can be calculated inside the AT. Since each method, the AT

and the direct measurement are capable to determine the EO alone, the combination of both brings a maximum reliability and error tolerance.
Especially in an all-digital workflow, the disadvantage to need tie-point measurements for the complete project becomes less important, because the matching process of an Automatic Aerial Triangulation can be improved and accelerated by using the “raw” EO from the GPS/IMU. For a digital camera equipped with a GPS/IMU system, the ISO can be a highly integrated and robust procedure with only a minimum of human interaction.

4. MISALIGNMENT CALIBRATION OF A DIGITAL AERIAL CAMERA/GPS/IMU SYSTEM

The following example shows the results of the misalignment calibration of a digital aerial camera together with a GPS/IMU system for a DG project.

In April 2005 NODIC, Nordostdeutsche Ingenieurconsult, Neubrandenburg, Germany flew several photo missions to cover an area of about 6500 km^2 with digital images of a ground sample distance of 20cm for the “Landesvermessungsamt Mecklenburg-Vorpommern”. The flight operations were conducted by Weser Bildmessflug, Bremerhaven, Germany. In three missions, a special calibration field was flown to fulfill the given formal requirements.

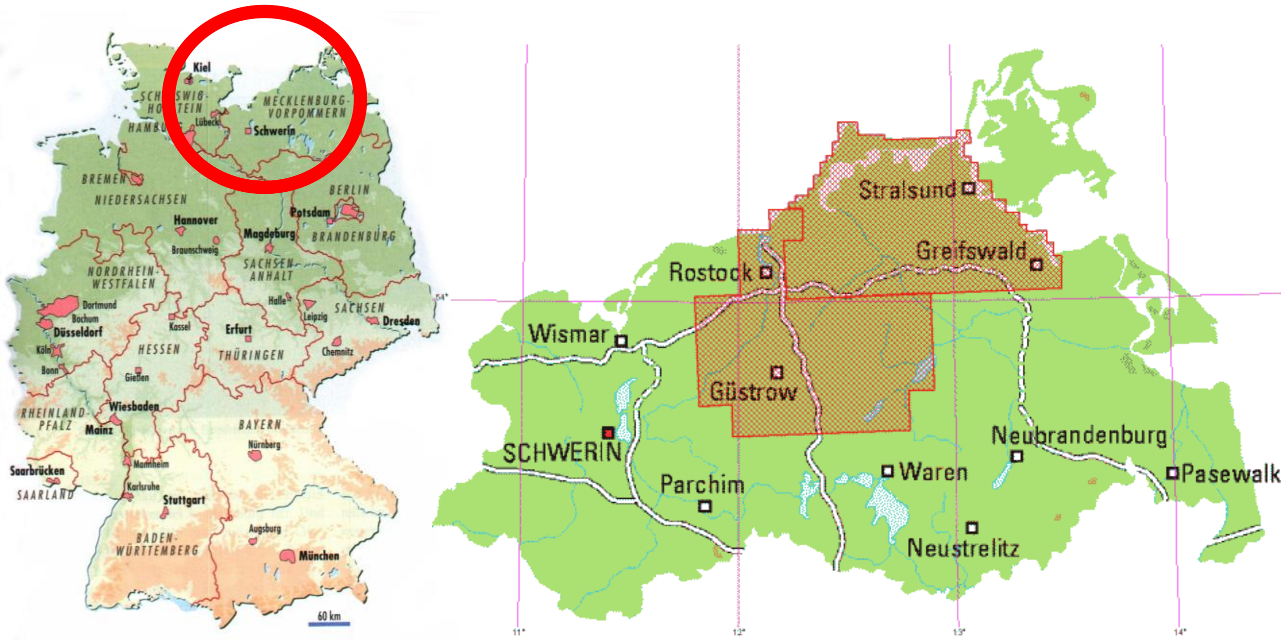

Figure 3: Project “NODIC, Mecklenburg Vorpommern”

The operated camera/GPS/IMU system was a Vexcel Imaging ULTRAM$_D$ together with a CCNS/AEROcontrol from IGI. The misalignment calculation was done with AEROoffice 5.0b with GrafNav 7.5 and the integrated BINGO30 AT software. GPS base station data was taken from the permanent station in Güstrow operated by the SAPOS network (www.sapos.de).
The calibration area consisted of two flightlines flown in opposite directions with a side overlap of 60%. Each line had 14 Images with a forward overlap of 60%. 18 GCPs were distributed in the area. The same base station was used and all other parameters stayed constant for all three days.

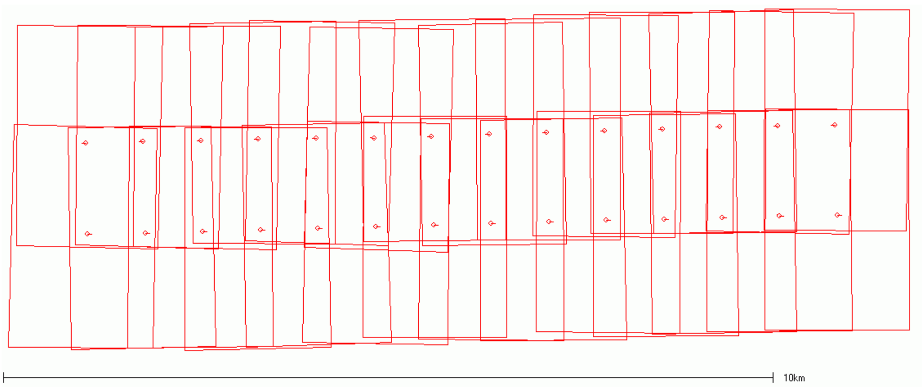

Figure 4: Calibration field

Table 1 shows the position offset and the misalignment angles obtained from the three calibrations flown on the April 20th, 21st and 24th 2005.

	East [m]	North [m]	Up [m]	Roll [deg]	Pitch [deg]	Yaw [deg]
20.4.2005	-0.002	0.024	-0.115	0.1415	0.2269	-0.1055
21.4.2005	-0.029	-0.072	-0.329	0.1438	0.2275	-0.1056
24.4.2005	0.005	0.016	-0.001	0.1441	0.2254	-0.0980

Table 1: Results of the Misalignment Calibration of three different days

The misalignment angles for roll, pitch and heading, as well as the horizontal position offsets are within the specifications of the system. The height offset between the different missions is 32cm.
One possible reason for at least a part of this difference might have been a variation in the effective focal length of the camera. At the used flying height of 2800m, a height difference of 32cm would be caused by a focal length change of about 11μm. If the optics would be (very roughly) estimated by an aluminum tube with the length of the focal length of 100mm, this length change could be caused by a temperature change of only 5K.

The results of the three misalignment calibrations show, that the misalignment angles stayed constant within the accuracy that is possible to determine with this configuration. As expected, there was no significant horizontal offset. The result for the position offset indicates that the height of the final results has to be treated with more care than the horizontal components. If a height error of the order experienced in this example is not acceptable, a final quality control of result would be important.

5. CONCLUSIONS

The use of EO parameters, directly measured with a GPS/IMU system, leads to huge savings in the photogrammetric processing of aerial images. To obtain optimal results, the calibration of the system has to be treated carefully. If the results of the GPS/IMU system should be used directly to georeference the images, the knowledge of the correct system parameters is crucial. If they should be treated as additional measurements in an extended aerial triangulation an explicit knowledge of most parameters is not needed.
The given example shows, that (for the given camera/GPS/IMU combination) the misalignment parameters are sufficiently stable and the calibration method is sufficiently repeatable to obtain excellent results with direct georeferencing. The example and a simple estimation of the effect of temperature changes also indicates that the height results have to be treated with more care than the horizontal positions.

6. ACKNOWLEDGEMENTS

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