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# The OEEPE Test on Integrated Sensor Orientation – Results of Phase I

**CHRISTIAN HEIPKE, KARSTEN JACOBSEN, HELGE WEGMANN, Hannover**

**ABSTRACT**

The European Organisation for Experimental Photogrammetric Research (OEEPE) has embarked on a test investigating integrated sensor orientation using GPS and IMU in comparison and in combination with aerial triangulation. The test consists of two phases. The first phase comprises the system calibration and the determination of the exterior orientation parameters. The second phase deals with the integration of the GPS/IMU data into the bundle block adjustment, i. e. the integrated sensor orientation itself. 13 test participants processed the distributed data and returned their results.
In this paper we shortly describe the test setup and report about the results of phase I. The accuracy potential of direct georeferencing for 1:5000 imagery was found to lie at approximately 5-10 cm in planimetry and 10 – 15 cm in height in object space and at 15 - 20 µm in image space. The most important finding is the fact that direct georeferencing has proven to be a serious alternative to conventional bundle adjustment and currently allows for the generation of orthophotos and other applications with less stringent accuracy requirements. However, stereo plotting is not yet possible due to the relatively large remaining y-parallaxes.
Future developments in the areas of GPS and IMU sensors and data processing will probably also reduce this problem. The best results in terms of accuracy and in particular in terms of reliability are expected from an intergration of GPS/IMU data into the bundle adjustment

## 1. INTRODUCTION

Image orientation is a key element in any photogrammetric project, since the determination of three-dimensional coordinates from images requires the image orientation to be known. In aerial photogrammetry this task has been exclusively and very successfully solved using aerial triangulation since many decades. Over the years, a number of additional sensors were used to directly determine at least some exterior orientation parameters, albeit with little success until the advent of GPS in the late eighties. Today differential kinematic GPS positioning is a standard tool for determining the camera exposure centres for aerial triangulation. Using the GPS measurements as additional observations in the bundle block adjustment a geometrically stable block based on tie points alone can be formed, and ground control points (GCP) are essentially only necessary for calibration, for detecting and eliminating GPS errors such as cycle slips and for reliability purposes (Ackermann 1994; Jacobsen 1997). Applications involving image strips such as highway mapping, however, still need GCP in order to reliably determine the rotation of a plane around the flight axis.
Gyroscopes and accelerometers are the components of an inertial measurement unit (IMU)[1]. Using gyroscopes, one is able to determine the rotation elements of the exterior orientation, the accelerometers provide sensor velocity and position. Thus, in principle a GPS/IMU sensor combination can yield the exterior orientation elements of each image without aerial triangulation. This technology, called direct sensor orientation[2], opens up many new applications for photogrammetry and remote sensing (Schwarz et al. 1993; Colomina 1999; Skaloud 1999). GPS/IMU measurement can also be used as additional observations within the bundle adjustment; this concept is called integrated sensor orientation.
A series of tests and pilot projects has been conducted and has convincingly shown the potential of direct georeferencing and integrated sensor orientation (Skaloud, Schwarz 1998; Wewel et al. 1998;

[1] Note, that we use the term IMU instead of INS (Inertial navigation system). Following Colomina (1999), an INS contains an IMU as a measurement device plus positioning and guidance functions, mainly realized in software.
[2] In contrast to “direct sensor orientation” the term “direct georeferencing” includes not only the determination of the exterior orientation elements but also the subsequent computation of object space coordinates.

Abdullah, Tuttle 1999; Burman 1999; Colomina 1999; Cramer 1999; Toth 1999; Jacobsen 2000). At independent checkpoints on the ground root mean square errors of down to 0.1 to 0.2 m were obtained. These results have proven that both technologies are serious alternatives to conventional aerial triangulation. In addition, potential error sources have been identified. 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 (system calibration parameters), the stability of these parameters over time, especially the stability of the attitude values between the IMU and the camera, the time synchronisation 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.

In conventional bundle adjustment the control information in the form of ground control point coordinates and the quantities to be determined (the coordinates of tie points) are both located on the object surface, and the computation of the unknowns can be thought of as an interpolation task. In direct georeferencing, on the other hand, the control information is measured at the height of the sensors and subsequently transferred down to the object surface. Therefore, direct georeferencing must be considered as an extrapolation, and thus a compensation of different error sources due to a high correlation between the related parameters is much less effective. This fact is particularly true for possible changes in the interior orientation of the camera, which no longer can be compensated for by a change in the exterior orientation (e. g. Schenk 1999). In this light also the choice of the object space coordinate system needs a closer look (see e. g. Jacobsen 2001), since the photogrammetric collinearity equations need a Cartesian system, a requirement most mapping systems do not fulfil.

## 2. TEST OBJECTIVES AND EXPECTED RESULTS

The European Organisation for Experimental Photogrammetric Research (OEEPE) has embarked on a multi-site test investigating integrated sensor orientation using GPS and IMU in comparison and in combination with aerial triangulation (see also Heipke et al., 2000;2001). The Institute for Photogrammetry and GeoInformation (IPI), University of Hannover acts as pilot centre. Data acquisition and pre-processing including the organisation of test flights and the necessary fieldwork was carried out by the Department of Mapping Sciences (IKF), Agricultural University of Norway in Ås.

The focus of the test is on the obtainable accuracy for large scale topographic mapping using photogrammetric film cameras. The accuracy of the results is assessed with the help of independent check points on the ground in the following scenarios:

- conventional aerial triangulation,
- GPS/IMU observation for the projection centres only (direct georeferencing),
- combination of aerial triangulation with GPS/IMU (integrated sensor orientation).

The test is expected to demonstrate to which extent direct georeferencing and integrated sensor orientation are accurate and efficient methods for the determination of the exterior orientation parameters for large scale topographic mapping.

Another test goal is to transfer the technology recently developed within the research arena to potential users. This goal is in line with the mission of OEEPE, and it is the main reason for choosing a multi-site test approach. As a consequence, the duration of the test is somewhat lengthy when compared to a single site investigation. This disadvantage, however, is taken into account, because we believe that in the long run the technology transfer issue is more important.

## 3. TEST SET UP

The test consists of two phases. The first phase comprises the determination of so-called system calibration parameters, i. e. the determination the boresight misalignment (the angular difference between the IMU and the image coordinate systems), and possibly additional parameters modelling GPS shifts, the interior orientation of the camera, GPS antenna offsets, time synchronisation errors etc. The second phase deals with the integration of the GPS/IMU data into the bundle block adjustment, i. e. the integrated sensor orientation itself.

### 3.1. Data acquisition and GPS/IMU pre-processing

Two companies producing suitable GPS/IMU equipment agreed to participate in the test, namely Applanix of Toronto, Canada, using their system POS/AV 510-DG[3] (Hutton J., Lithopoulos E. 1998; Applanix 2001), and IGI mbH of Kreuztal (formerly of Hilchenbach), Germany, with the system AEROcontrol IIb[3] (IGI mbH 2001). The test imagery was acquired in October 1999 by the Norwegian companies Fotonor AS and Fjellanger Widerøe (FW) Aviation AS using photogrammetric cameras equipped with a wide angle lens. For each GPS/IMU system calibration flights in two different scales (1:5.000 and 1:10.000) followed by the actual test flight in 1:5.000 were carried out. All six flights (three per company) were flown over the Fredrikstad test field in Southern Norway maintained by IKF; for further details about the data acquisition see Heipke et al. (2000; 2001)[4].

From the raw GPS and IMU measurements flight trajectories for the camera projection centres in UTM/EUREF89 in zone 32 with ellipsoidal heights and roll, pitch and yaw values in ARINC 705 convention (ARINC 2001) describing a three-dimensional rotation from local level coordinate system to the body frame of the aircraft were computed by Applanix and IGI, respectively. The flight trajectories refer to the camera projection centre, thus the lever arm corrections describing the difference in position between the GPS antenna, the IMU coordinate origin and the origin of the camera coordinate system (more precisely, the entrance node of the camera lens) were taken into account. It should be noted that a few assumptions were introduced into pre-processing:

- The alignment of the EUREF89 and the WGS84 coordinate systems is assumed to be identical.
- No geoid information was introduced, thus the local Z-axis was assumed to be parallel to the local gravity vector, and the deflection of the vertical was assumed to be zero.

Pre-processing details are considered propriety information by IGI and Applanix ; an investigation is beyond the scope of the test. A point of criticism raised by a number of participants was the lack of any information about the quality of the pre-processed GPS/IMU data such as a covariance matrix.

### 3.2. Phase I: System calibration and direct georeferencing

The first test phase deals with the determination of the system calibration parameters from the information of the calibration flights. Phase I also comprises the direct sensor orientation of the actual test flight based on the GPS/IMU data and the results of system calibration and – as part of

[3] It should be noted that the equipment used for the test represents the state-of-the-art technology of 1999, and is a little out of date at the time of writing (June 2001). For instance, while in the AEROcontrol IIb from IGI dry-tuned gyros were used, they have been replaced by fibre optics gyros in the current system AEROcontrol IId. Similar developments have taken place at Applanix.

[4] Unfortunately, the weather did not permit to have identical GPS conditions for the two test flights. While good GPS visibility (6-7 satellites) existed throughout the whole Fotonor/Applanix flight, fog prevented a start of the FW aircraft with the IGI system as scheduled, and consequently for most of the second half of this flight only fewer satellites were visible.

the analysis of the results (see chapter 4) - the derivation of object space coordinates. Thus, all elements of direct georeferencing are contained in phase I.
The test scheme of phase I is depicted in figure 1. From the pre-processed GPS/IMU values and the instant of exposure the pilot centre interpolated the position and roll, pitch, yaw angles for each

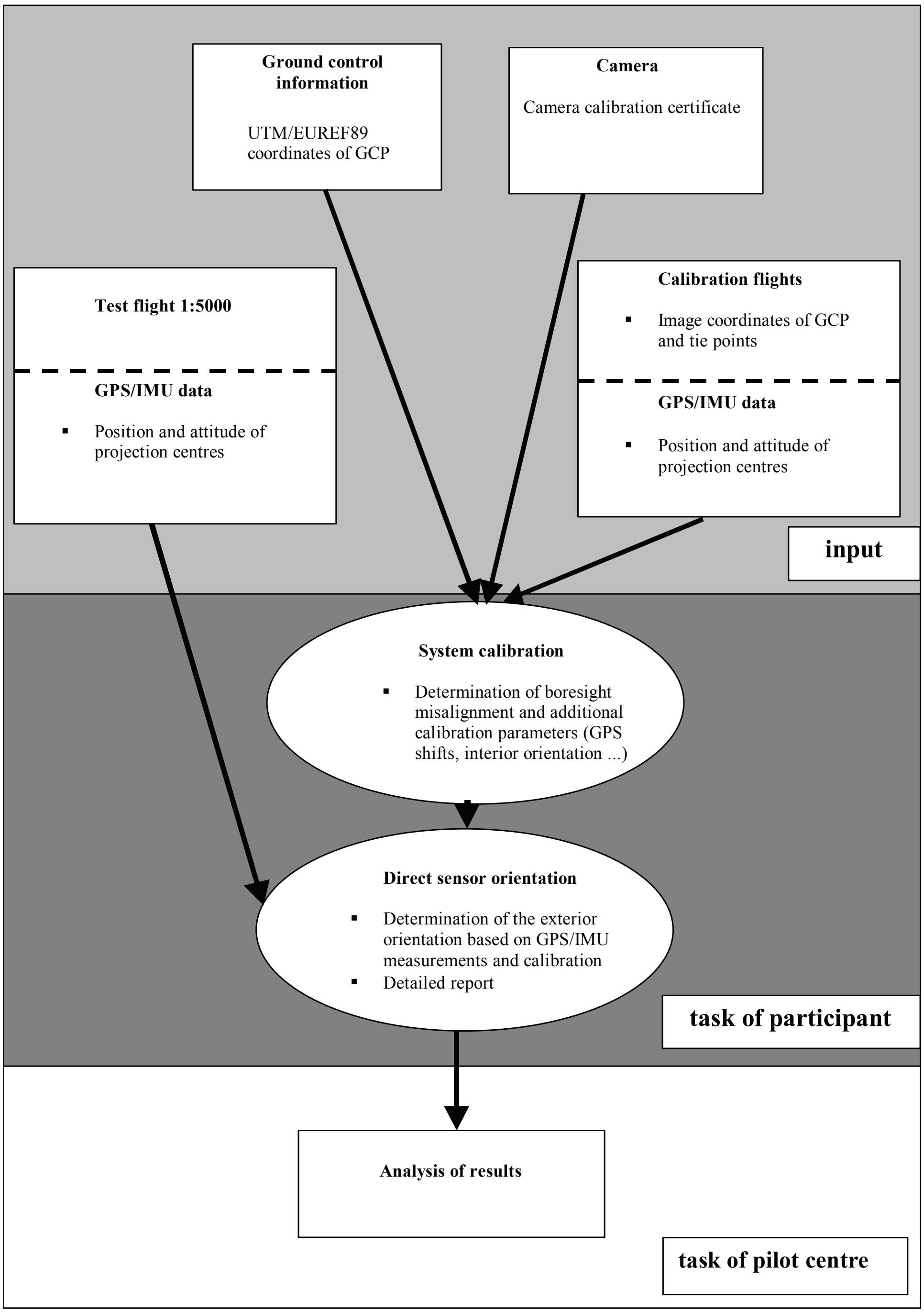


Figure 1: Flowchart of phase I

image. The pilot centre also measured the image coordinates of the GCP and 25 tie points in each of the calibration flight images using an analytical plotter. The object space coordinates of the GCP as determined by IKF were given in UTM/EUREF89 with ellipsoidal heights, the camera calibration protocol was provided by the flight companies.

All these data were sent out to the test participants[5]. The derived calibration parameters together with the orientation parameters for the calibration flights and the test flight and a detailed report about the work carried out were to be delivered back to the pilot centre.
34 potential test participants asked for the data, 13 participants returned their results in time to be included into this paper[6], refer to table 1. As can be seen, besides the two companies having provided the GPS/IMU sensor systems, three software developers (GIP, inpho, LH Systems), one National Mapping Agency (ICC), one commercial user (ADR) and four university institutes (DIIAR, IPF, IPI and ifp) have taken part in the test. Thus, with the exception of the University of Calgary, which carried out much of the pioneering work in direct georeferencing (Schwarz 1993; 1995), most parties currently active in this area are represented in the test. Nearly all participants used existing bundle block adjustment programmes, partly augmented by additional software development. In this way, besides demonstrating the state-of-the-art in integrated sensor orientation, the distributed data also served as test data for refinements of the existing software, which is well within the goal of technology transfer.

| Test participant | Abbreviation | Used software |
|---|---|---|
| IGI, Germany | IGI | AEROoffice tools and BINGO |
| Applanix, Canada | Applanix | POS tools |
| ADR, BAE Systems, USA | ADR | BLUH |
| GIP, Germany | GIP | BINGO |
| ICC Barcelona, Spain | ICC | GeoTex/ACX |
| inpho, Germany | inpho | inBlock |
| LH Systems, USA | LHS | ORIMA |
| Politecnico di Milano, Italy | DIIAR | own development |
| Technical University Vienna, Austria | IPF | ORIENT |
| University of Hannover, Germany | IPI | BLUH |
| University of Stuttgart, Germany | ifp | PAT B and own development |

Table 1: List of test participants, phase I (note that the same software name does not necessarily imply the same version and thus the same results)

### 3.3. Phase II: Integrated sensor orientation

The second phase deals with the integration of the GPS/IMU data into the bundle block adjustment in order to obtain an optimum, i. e. the most accurate solution. After having returned the results of phase I the participants have received image coordinates of tie points and GCP of the test flight images. Together with the system calibration parameters determined in phase I they have then performed an integrated sensor orientation, refining the exterior orientation (and partly also the system calibration parameters), and estimating the object space coordinates of the tie points and the GCP. These values have subsequently been returned to the pilot centre together with a detailed report describing the adopted model for the integration. Analysis of the phase II results is currently under way.

[5] The GPS/IMU data from IGI sent out at first contained an error due to inappropriate consideration of the initial alignment process during GPS/IMU pre-processing. This error was detected by IGI shortly afterwards, and corrected GPS/IMU data were subsequently distributed to the participants. The results presented in this paper refer exclusively to the second data, the first incorrect data set is not further considered.
[6] A few results arrived at the pilot centre too late to be included in this paper. They are currently being processed and will be published in the final test report.

## 4. ANALYSIS OF PHASE I RESULTS

The results delivered back to the pilot centre have been analysed and are presented in this chapter. As was to be expected the different participants have used different approaches for computing the results. The most noticeable distinctions are (see also table 2):

- Determination of the system calibration parameters in a combined bundle adjustment run with the image coordinates of the calibration flights, the GPS/IMU data and the GCP coordinates as input (denoted as "1 step" in table 2) vs. a comparison of the exterior orientation derived from a bundle adjustment (with only the image coordinates and the GCP information) and the GPS/IMU measurements ("2 steps"). IPI and ifp introduced the GPS measurements into the bundle adjustment in which the three GPS shifts were determined; the misalignment angles were derived in a separate step.
- UTM vs. local tangential coordinate system: Most participants carried out all computations in the UTM system; LHS transformed the input data into a local tangential system, computed the results, and subsequently transformed them into the UTM system (denoted by * in table 2); DIIAR and ifp delivered results in the local tangential system, IPI delivered results in both systems.
- Number of system calibration parameters estimated in the adjustment: Many participants used the six standard parameters (3 GPS shifts, 3 misalignment angles), which can be computed from only one calibration flight. Some participants also corrected for the parameters of interior orientation and the additional parameters known from camera self-calibration. DIIAR also improved the time synchronisation between the attitude values and the exposure time by estimating a constant time shift (see Skaloud 1999 for details of this method).
- Input information used: some participants used the image coordinates of both calibration flights in one simultaneous adjustment, others performed separate adjustments and subsequently combined the results, while yet others used one calibration flight only. In some cases, the GPS shifts were determined from only one flight while the boresight misalignment was derived from both. Some participants also deleted the first and the last few images from the computations, arguing that the corresponding GPS/IMU data were not suited for the calibration. Unfortunately, the exact procedure was not always revealed in detail.

| Participant | Procedure | Object space coordinate system used for the computations | Number of system calibration parameters |
|---|---|---|---|
| IGI | 1 step | UTM | 6 |
| Applanix | 1 step | UTM | 6 |
| ADR | 2 steps | UTM | 6 |
| GIP | 1 step | UTM | 6 |
| ICC | 1 step | UTM | 21 (6 + 3 f. int. ori. + 12 add. param.) |
| inpho | 1 step | UTM | 9 (6 + 3 f. int. ori; only 6 for company 1) |
| LHS | 1 step | Local tangential* | 6 |
| DIIAR | 2 steps | Local tangential | 6 + time synchronisation |
| IPF | 1 step | UTM | 11 (6 + 3 f. int. ori + 2 f. rad. distortion) |
| IPI | 2 steps | Local tangential and UTM | 21 (6 + 3 f. int. ori. + 12 add. param.) |
| ifp | 2 steps | Local tangential | 6 |

Table 2: Information on system calibration

While it is obvious that in object space a comparison between the computed coordinates and those of independent check points can serve to judge the results, it is not clear a priori how to assess the derived orientation parameters themselves. Rather than trying to analyse the GPS/IMU measurements and to quantify their accuracy we have taken a users´ perspective for this test and have looked at remaining y-parallaxes in the resulting stereo models. The reason for this approach was that the most sensitive application for the image orientations in terms of accuracy is that of stereo plotting, which relies on parallax-free models. Thus, if the determined exterior orientation is accurate enough for this task, it is also good enough for other tasks.

In order to analyse the participants´ results we have carried out a conventional bundle adjustment for the test flight 1:5000 in which the image coordinates of the GCP of the test field together with 25 tie points per image and a number of object space coordinates served as input. All image coordinates were measured using the analytical plotter Planicomp P1. The standard deviation of the image coordinates after the bundle adjustment was 4.8 µm for the IGI dataset and 6.2 µm for the Applanix data. These values lie in the expected range; the difference can be explained by the somewhat poorer image quality of the Applanix images. In a second step, we transformed the image coordinates of the GCP into object space via a least-squares forward intersection with the exterior orientation of the participants being introduced as constant values. The resulting object space coordinates were then compared to the known values of the GCP yielding RMS differences, and the residuals in image space were interpreted as remaining y-parallaxes in stereo models formed using the participants´ exterior orientation. Statistical results of this procedure are given in table 3, graphical representations revealed that no major local systematic effects are present in the data. In order to compare them with the conventional photogrammetric accuracy without GPS/IMU data the corresponding results are also shown.

| **Participant** | **IGI** | | | | **Applanix** | | | |
|---|---|---|---|---|---|---|---|---|
| | **$\sigma_0$** [µm] | **RMS differences to GCP** | | | **$\sigma_0$** [µm] | **RMS differences to GCP** | | |
| | | **X [cm]** | **Y [cm]** | **Z [cm]** | | **X [cm]** | **Y [cm]** | **Z [cm]** |
| convent. bundle adjustm. | 4.8 | 2.8 | 2.6 | 4.3 | 6.2 | 2.2 | 2.0 | 6.0 |
| IGI | 36.7 | 15.9 | 16.1 | 23.0 | - | - | - | - |
| Applanix | - | - | - | - | 22.2 | 5.9 | 11.9 | 32.0 |
| ADR | 55.5 | 19.9 | 16.8 | 28.8 | 32.2 | 13.4 | 12.7 | 18.1 |
| GIP | 28.1 | 11.6 | 12.0 | 15.1 | 30.2 | 13.4 | 12.3 | 11.8 |
| ICC | 24.1 | 9.0 | 12.3 | 22.9 | 14.4 | 5.1 | 3.0 | 22.4 |
| inpho | 27.0 | 10.3 | 9.8 | 14.6 | 14.8 | 4.7 | 3.3 | 8.2 |
| LHS | 44.6 | 13.8 | 13.1 | 17.9 | - | - | - | - |
| DIIAR | 22.9 | 8.8 | 11.8 | 13.5 | 12.4 | 3.9 | 2.5 | 8.4 |
| IPF | 42.6 | 12.0 | 11.7 | 14.6 | 19.5 | 7.0 | 3.3 | 12.0 |
| IPI (local tang.) | 38.5 | 11.1 | 15.4 | 16.5 | 16.2 | 5.5 | 4.0 | 7.9 |
| IPI (UTM) | 36.7 | 11.3 | 14.7 | 16.3 | 16.1 | 8.5 | 3.3 | 12.3 |
| ifp | 35.5 | 14.9 | 15.6 | 25.0 | 31.3 | 11.1 | 8.7 | 15.1 |

Table 3: Numerical results of phase I for each participant ("-" denotes that the result was not delivered to the pilot centre or is still being processed)

The following results can be derived from the figures given in table 3:

- The accuracy potential of direct georeferencing lies at approximately 5-10 cm in planimetry and 10 – 15 cm in height when expressed as RMS values at independent check points, and at 15 - 20 µm when expressed as remaining y-parallaxes in image space.
- These values are larger by a factor of 2 - 3 when compared to standard photogrammetric results.
- IGI and Applanix have not obtained the best results for their respective data sets. This finding suggests that a refinement of the calibration models and software delivered together with the GPS/IMU hardware has a potential to improve the obtained results.
- The results do not significantly depend on the way of computing the boresight misalignment (one or two steps).

- For the IGI data the results do not depend on the chosen object space coordinate system (see the two IPI results), the situation is different, however, for the Applanix data. Here, the RMS values for planimetry and in particular for the height are significantly better in the more rigorous local tangential system than in the UTM system.
- Whereas in the IGI data a dependency on the chosen calibration model was not found, the Applanix results significantly depend of the number of parameters estimated during system calibration. Allowing for a change in the calibrated focal length and the position of the principal point improves the results approximately by a factor 2, a further refinement using self calibration parameters does not lead to significantly better results.
- The best results for Applanix are better by approximately a factor of 2 when compared to those of IGI. While a conclusive explanation for these differences cannot be given, the used hardware (dry-tuned vs. fibre optics gyros) and the less favourable GPS conditions during the IGI flight are possible reasons; see also footnotes no. 3 and 4 on the third page of the article.
- Excellent results were obtained by DIIAR, the only participant to explicitly investigate a possible time synchronisation error. Unfortunately, DIIAR did not give the size of the detected shift, but they stated that no significant time shift was detected in the data. Based on these results a more detailed analysis of the time synchronisation effects is necessary.
- The results are not homogeneous with respect to the number of estimated calibration parameters, especially if only six calibration parameters are used; different results are obtained (compare e. g. the results of ADR, GIP, and ifp), but also for more refined calibration models (compare e. g. the results from ICC and inpho for the Applanix data). While a conclusive reason for these differences cannot be given due to lacking information about the details of the system calibration, the actual procedures and input data do differ. These differences can account for the differences in the obtained results.

The most important finding is the fact that based on the obtained results direct georeferencing has proven to be a serious alternative to conventional bundle adjustment and currently allows for the generation of orthophotos and other applications with less stringent accuracy requirements. However, stereo plotting is not possible due to the relatively large remaining y-parallaxes, and the reliability of the results remains uncertain due to a lack of redundancy in absolute orientation Systematic errors in the GPS/IMU measurements cannot be detected without the introduction of GCP coordinates.

When analysing the presented figures in more detail it must be kept in mind that a refinement of the interior orientation parameters during the calibration does not necessary mean that the camera calibration protocol contains incorrect values. It only implies that the more general models better explain the given input data. For instance, a change in the x-direction of the principal point has the same effect onto the results as a constant error in the time synchronisation between the GPS/IMU sensor and the camera. The same is true for a change in the calibrated focal length and the GPS shift in Z. Only if two calibration flights in distinctly different flying heights are available (as was the case in this test), the latter two parameters are independent and can both be determined.

As mentioned the reason for the better results with the Applanix data is probably the difference in the GPS conditions during the test flights and the use of dry-tuned gyros in the (today outdated) IGI system, while Applanix had already used a fibre optics gyro. The better accuracy level of the Applanix data may explain why the results are more sensitive to the chosen calibration model and the object space coordinate system: while the IGI results are dominated by sensor effects, the Applanix data are more effected by the chosen mathematical model and coordinate system. To confirm this hypothesis a more detailed analysis is necessary.

Based on the obtained results it is recommended to include the interior orientation parameters into the system calibration whenever possible. With the DIIAR figures in mind a detailed and explicit consideration of possible time synchronisation effects also seems worthwhile. If it is not feasible to

use two different calibration flights, the calibration should be carried out in the same scale as the actual project. In this case, the GPS shift will also take care of possible changes in the focal length.
As for the object space coordinate system, preference should be given to a local tangential system, because in this case the approach is mathematically more rigorous. If for whatever reason a project has to be carried out in a non-cartesian mapping system, however, also the calibration needs to be performed in this system (for details see Jacobsen 2001).
It should also be noted that the test results have been obtained immediately after calibration. Within the test, no statement can be made concerning the stability of the system calibration parameters over time. Currently, it is generally recommended to carry out the system calibration before and possibly also after each block. Since the actual physical reasons for the GPS shift and the possible changes in the interior orientation of the camera are unknown, this recommendation should be followed, at lest for high accuracy work.

## 5. CONCLUSIONS

In the first phase of the OEEPE test on integrated sensor orientation an accuracy potential of direct geo-referencing for 1:5000 imagery of approximately 5-10 cm in planimetry and 10 – 15 cm in height when expressed as RMS values at independent check points, and of 15 - 20 µm when expressed as remaining y-parallaxes in image space was found. While these values are larger by a factor of 2 - 3 when compared to standard photogrammetric results, they prove that direct georeferencing has proven to be a serious alternative to conventional bundle adjustment and currently allows for the generation of orthophotos and other applications with less stringent accuracy requirements. Stereo plotting, on the other hand, is currently not yet possible with such data due to the relatively large y-parallaxes.
In summary, it can be stated and comes as no surprise that the system calibration itself is more complex than one might think at first. This statement is motivated not only by the fact that direct georeferencing is equivalent to an extrapolation as explained in chapter 1 and therefore comes with all associated difficulties, but also by the fact that not all test participants have given full details of the actual procedure used for investigating the test data. While it is of course understandable that some crucial information is kept secret, in particular in the commercial arena, this lack of information renders a conclusive interpretation of the results more difficult. Nevertheless, we feel that we could reach the goals set out for phase I of the test.
Future developments in the areas of GPS and IMU sensors and data processing will probably also reduce this problem. The best results in terms of accuracy and in particular in terms of reliability are expected from an integration of GPS/IMU data into the bundle adjustment  A point, which needs to be addressed in this regard, is the choice of a proper stochastic model for the GPS/IMU data. Integrated solutions are investigated in phase II of the OEEPE test; results will be available shortly.

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http://www.ipi.uni-hannover.de/htm-deutsch/forschung/laufend/oeepe-gps-imu/index.html