THE OEEPE TEST ON INTEGRATED SENSOR ORIENTATION[1]

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ABSTRACT

The European Organisation for Experimental Photogrammetric Research (OEEPE) has embarked on a test investigating 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 direct georeferencing. The second phase deals with the integrated sensor orientation, i. e. the integration of the GPS/IMU data into the bundle adjustment.13 test participants processed the distributed data and returned their results.

In this paper we describe the test incl. the data acquisition and report about the results of phase I. The accuracy potential of direct georeferencing for 1:5.000 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 while these values are larger by a factor of 2 - 3 when compared to standard photogrammetric 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 always possible due to the sometimes relatively large remaining model 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 integration of GPS/IMU data into the bundle adjustment which is the topic of test phase II.

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 eighties and the pioneering work of Mader (1986). In this regard it is interesting to note that in the same year Ackermann predicted that "the performance of new navigation systems will allow in-flight measurements of carrier position and attitude to an accuracy with will change the photogrammetric methods fundamentally" (Ackermann 1986, p. 93).

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 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, for reliability purposes, and possibly for datum transformations. One can distinguish between a loose coupling of photogrammetric and GPS observations, sometimes called the "shift and drift approach" (Ackermann 1994; Jacobsen 1997) and a rigorous GPS/AT combination (Jacobsen, Schmitz 1996; Kruck et al. 1996; Schmitz 1998).

Gyroscopes and accelerometers are the components of an inertial measurement unit (IMU)[2]. Using gyroscopes, one is able to determine the rotation elements of the exterior orientation, the accelerome-

[1] A short version of this paper has been published in the proceedings of the Photogrammetric Week 2001.

[2] 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 realised in software.

ters 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[3], opens up many new applications (Schwarz et al. 1993; Colomina 1999; Skaloud 1999). GPS/IMU measurement can also be used as additional observations within a bundle adjustment; this concept is referred to as 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; 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, and the time synchronisation between the various sensors.

In 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; Habib; Schenk 2001). In this light, also the choice of the object space coordinate system needs a closer look (see e. g. Jacobsen, Wegmann 2001), since the photogrammetric collinearity equations need a Cartesian system, a requirement the 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 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 for the test 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 can be tolerated, however, because we believe that in the long run the technology transfer issue is more important.

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[3] 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.

3 DATA ACQUISITION AND GPS/IMU DATA PRE-PROCESSING

3.1 Criteria for selecting test data

The test was carried out based on especially acquired imagery and GPS/IMU data. In order to enable a fair and meaningful test between the two competing technologies the following selection criteria for the data acquisition were set forward:

- geometrically stable photogrammetric block,
- modern photogrammetric film camera,
- dual frequency GPS receivers using differential carrier phase measurements with a data rate of 0.5 sec, preferably identical receivers for the aircraft and reference station,
- a short base line between aircraft and reference station,
- high quality off-the-shelf navigation grade IMU as typically used in precise airborne attitude determination,
- different image scales suitable for large scale topographic mapping,
- a well-controlled test field with a large number of ground control points.

Given these criteria and a few practical constraints a test field in Fredrikstad, Norway, was selected. The test field Fredrikstad (see figure 1) lies in the south of Norway near the capital Oslo. It is maintained by IKF. The test field has already been used in a prior OEEPE test on GPS-assisted bundle adjustment (Andersen, Ackermann 2001), its size is approximately 5 x 6 km^2. 51 well distributed signalised ground control points with UTM/EUREF89 coordinates and ellipsoidal heights known to better than 0.01 m are available. The ground control point targets have a size of 40 x 40 cm^2.
In order to eliminate influences of long GPS base lines, it was decided to place the stationary receiver necessary for the differential GPS solution directly is the test field. For reasons of redundancy, additional receivers were operated at various distances from the test field.

Figure 1: Test field Fredrikstad, the black triangles indicate the position of the ground control points

3.2 Acqusition of aerial imagery and GPS/IMU data

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 (Hutton, Lithopoulos 1998; Applanix 2001), and IGI mbH of Kreuztal (formerly of Hilchenbach), Germany, with the system AEROcontrol IIb (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; see also table 1). The flight axes of the two calibration flights are presented in figures 2 and 3, those of the actual test flights in figures 4 and 5. These figures also show the ground control points (GCP) and check points. The object space coordinates of the GCP visible in the figures 2 and 3 were distributed to the participants in order to carry out the system calibration (for further detail see below).
Both flying companies had the IMU tightly attached to the photogrammetric camera and have used gyro-stabilised camera platforms. While Fotonor had the PAV30 switched on during the complete

		Applanix	**IGI**
Flying company		Fotonor	Fjellanger Widerøe Aviation
Photogrammetric camera		Leica RC30	Zeiss RMK Top
Focal length [mm]		153	153
Date of calibration protocol		February-22-1999	Aug-03-1998
Gyro-stabilised camera platform		PAV30, switched on during the complete mission	T-AS, switched on during parts of the mission
Film material		Panchromatic (AP 200)	Panchromatic (AP200)
GPS reference station		Fredrikstad	
GPS receiver		Ashtec Z Surveyor, (L1 and L2)	
data rate		0.5 sec	
GPS/IMU-System		POS / AV 510-DG	AEROcontrol IIb
Accuracies of GPS/ IMU post-processing according to companies	Position	< 0.1 m	< 0.1 m
	roll, pitch	0.005 deg.	0.005 deg.
	yaw	0.008 deg.	0.010 deg.
GPS receiver		Ashtech Z Surveyor, (L1 and L2)	Ashtech Z XII, (L1 and L2)
Data rate		0.5 sec	0.5 sec
Gyroscopes		Litton LN-200	Litef LCR-88
data rate		200 Hz	50 Hz
Flight mission		Oct.-07-99, 7:39-12:43	Oct. -07-99, 9:38-13:17
Sequence of data acquisition		Cal. flight 1:5.000, cal. flight 1:10.000, test flight	Cal. flight 1:10.000, cal. flight 1:5.000, test flight
Calibration flight 1:5.000		2 strips North/South, 2 strips East/West (in opposite dir.)	2 strips North/South, 2 strips East/West (in opposite dir.)
No. of images		2*17 + 2*14 = 62	2*17 + 2*14 = 62
End overlap		l = 60 %	l = 60 %
Flying height [m]		800	800
No. of visible ground control points		25	25
Calibration flight 1:10.000		block with 5 strips followed by 2 strips at a 90 degree angle	block with 5 strips followed by 2 strips at a 90 degree angle
No. of images		5*11 + 2*15 = 85	5*11 + 2*14 = 83
Overlap		l = 60 %, q = 60 %	l = 60 %, q = 60 %
Flying height [m]		1600	1600
No. of visible ground control points		50	50
Actual test flight		block with 9 strips followed by 2 strips at a 90 degree angle	block with 7 strips followed by 1 strip at a 90 degree angle
No. of images		9*17 + 2*14 = 181	7*17 + 1*14 = 133
Overlap		l = 60 %, q = 60 %	l = 60 %, q = 60 %
Flying height [m]		800	800
No. of visible ground control points		50	50

Table 1: Data acquisition details[4]

[4] It should be noted that the GPS/IMU system 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 (Summer 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.

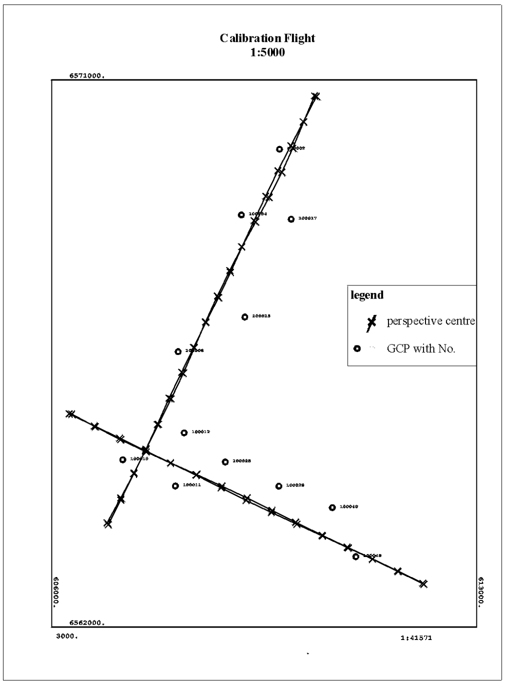

Figure 2: Flight axes of calibration flight 1:5.000

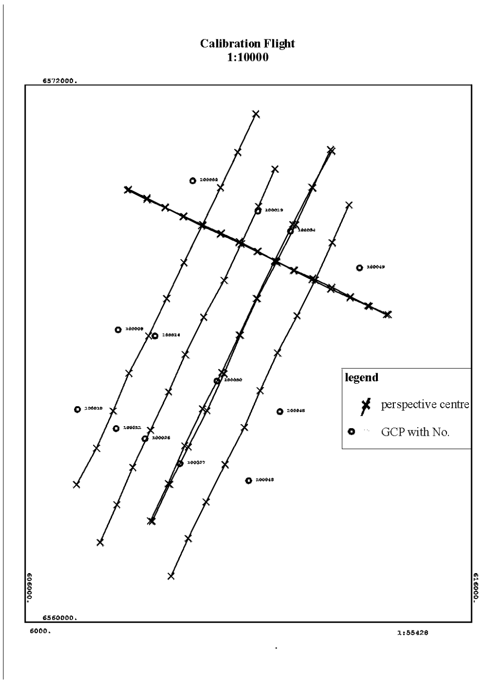

Figure 3: Flight axes of calibration flight

1:10.000

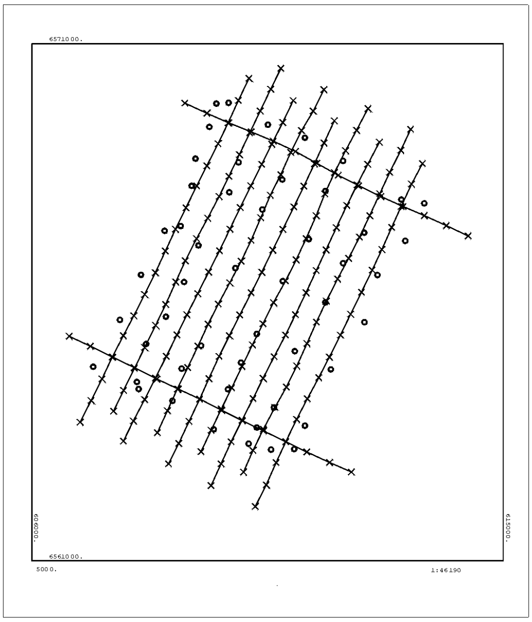

Figure 4: Fotonor/Applanix test flight, 1:5.000

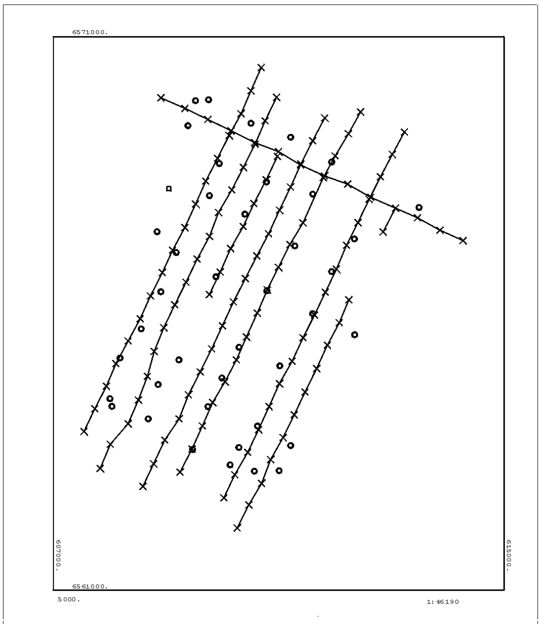

Figure 5: FW/IGI test flight, 1:5.000

mission, FW had turned on the T-AS for parts of the flight only. In both cases movements of the camera with respect to the aircraft were registered and accounted for in post-processing.
Unfortunately, the weather did not permit to have identical conditions for the two test flights. The Fotonor/Applanix flight could be carried out according to plan, all scheduled images were captured, and apart from a short period of time during the calibration flight 1:10.000, a minimum of 9 GPS satellite was visible during the mission. As a result the PDOP value indicating the quality of the GPS observations was below 2 except for parts of the 1:10.000 calibration flight (see also figure 6). The memory card of the on-board IMU become full shortly before the end of the actual test flight and was changed, apparently without any consequences for the data acquisition.
The FW aircraft with the IGI system was operated from an airport further away from the test field. Fog prevented a start as scheduled, and during the second half of the flight clouds started to move into the test field area. The crew slightly changed sequence of image capture, but some of images could not be acquired at all. This fact explains the different number of images of the test flight (see again table 1) and also differences between figures 4 and 5. Also, the film cassette had to be changed during the flight. Finally, for about 50 % of the FW/IGI test flight the number of visible satellites dropped down to 6, resulting in a PDOP value of up to 3.5 (see figure 7). These difficulties during data acquisition have to be taken into account in the interpretation of the test results (see below).

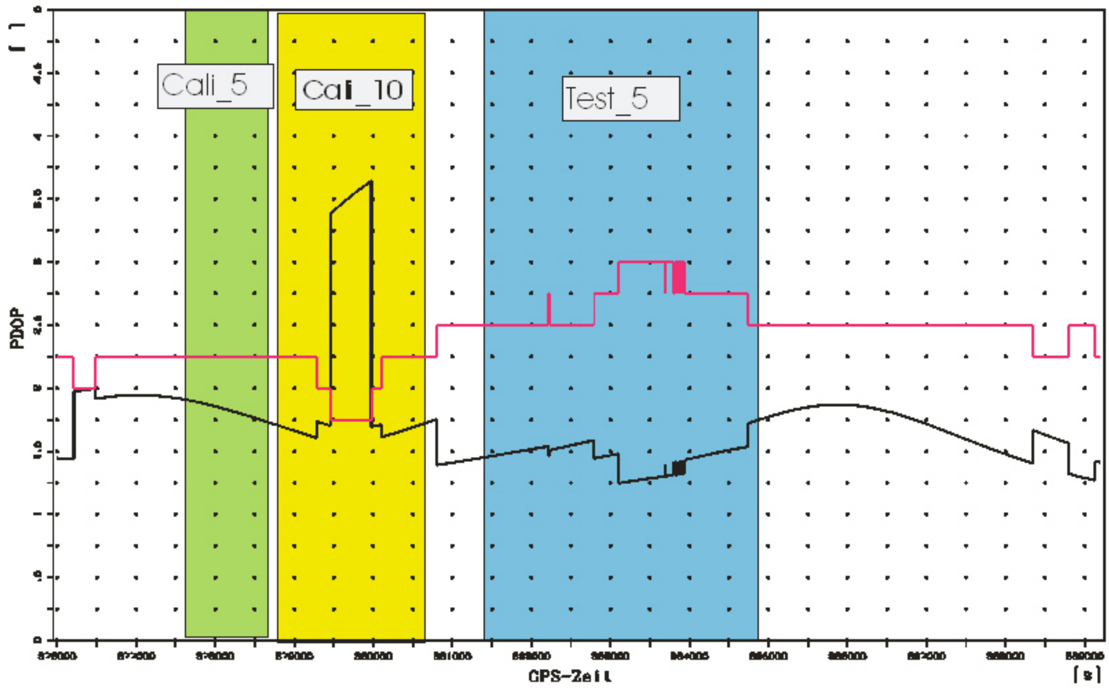

Figure 6: Number of visible satellites (red) and resulting PDOP value (black), Fotonor/Applanix flight (elevation mask 5°, SNR >2, signals actually received simultaneously at the reference station and the receiver in the aircraft)

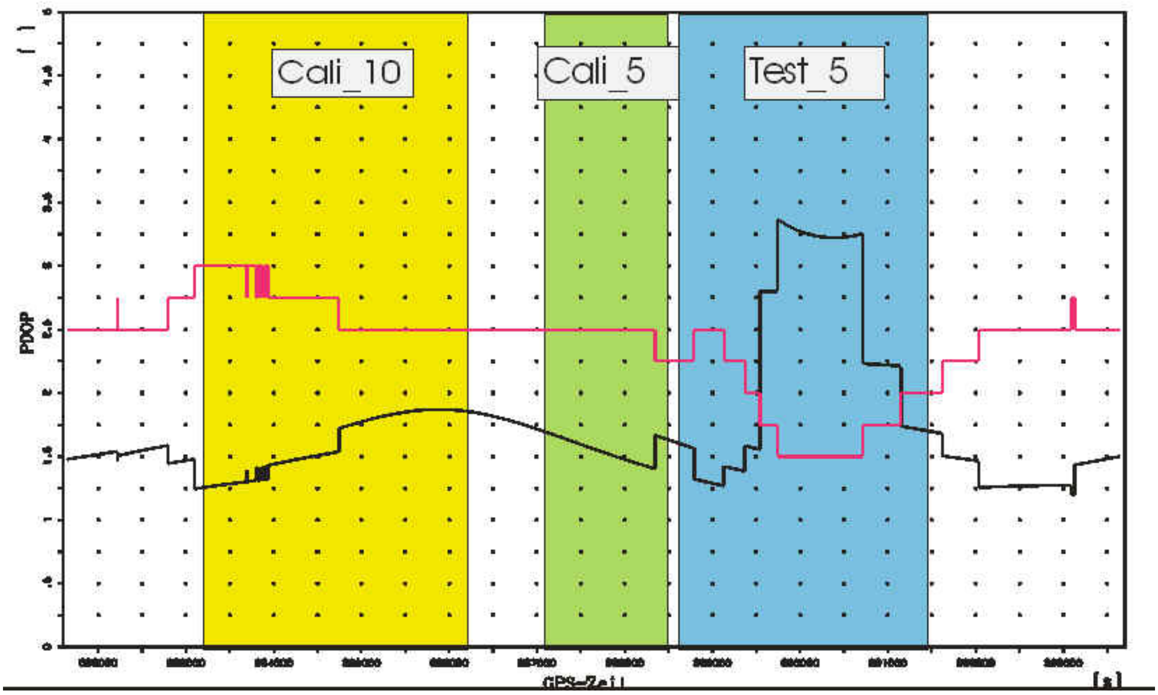

Figure 7: Number of visible satellites (red) and resulting PDOP value (black), FW/IGI flight (elevation mask 5°, SNR >2, signals actually received simultaneously at the reference station and the receiver in the aircraft)

3.3 GPS/IMU pre-processing

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. 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, thus the deflection of the vertical was assumed to be zero.

Pre-processing details are considered propriety information by both, Applanix and IGI. Consequently, within the arrangements made for the test, pre-processing was carried out by the two companies. As mentioned, GPS data were recorded at different reference stations. Initially, four of these GPS data sets were processed to make sure that no problems had occurred during data collection. IMU measurements were not use during these checks. Applanix and IGI judged the results of reference station Fredrikstad, located within the test field, to be well suited for the further investigations. Therefore, it was decided to only use this data set within the OEEPE test. Subsequently, GPS/IMU pre-processing was carried out by Applanix and IGI, respectively. Position and attitude data for the test flights were then delivered to the pilot centre, unfortunately without any information about the quality of the pre-processed GPS/IMU data such as a covariance matrix.

Raw GPS and IMU data were not made available by the companies. Therefore, an investigation into pre-processing, and also into rigorous GPS/IMU/AT approaches must be postponed to a later stage (see, however, Schmitz et al. 2001 for such an approach using the OEEPE test data, albeit with other reference stations).

4 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 of 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. and direct sensor orientation. The second phase deals with the integration of the GPS/IMU data into the bundle adjustment, i. e. the integrated sensor orientation itself.

4.1 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 the analysis of the results (see chapter 5) - 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 8. 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 image. The pilot centre also measured image coordinates of GCP and about 25 tie points in each of the calibration flight images using the analytical plotter Planicomp P1. These measurements were checked by the pilot centre using photogrammetric bundle adjustments, and also by Applanix and IGI by performing a system calibration. The object space coordinates of some 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 then 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 2. 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 five research institutes (DIIAR, FGI, 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 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. For reports of the individual participants see e. g. Alamùs et al. (2001), Forlani, Pinto (2001), Jacobsen, Wegmann (2001), and Ressl (2001).

[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 set, the first incorrect data set is not further considered.

[6] A few results arrived at the pilot centre too late to be included into this paper. They are currently being processed and will be published in the final test report.

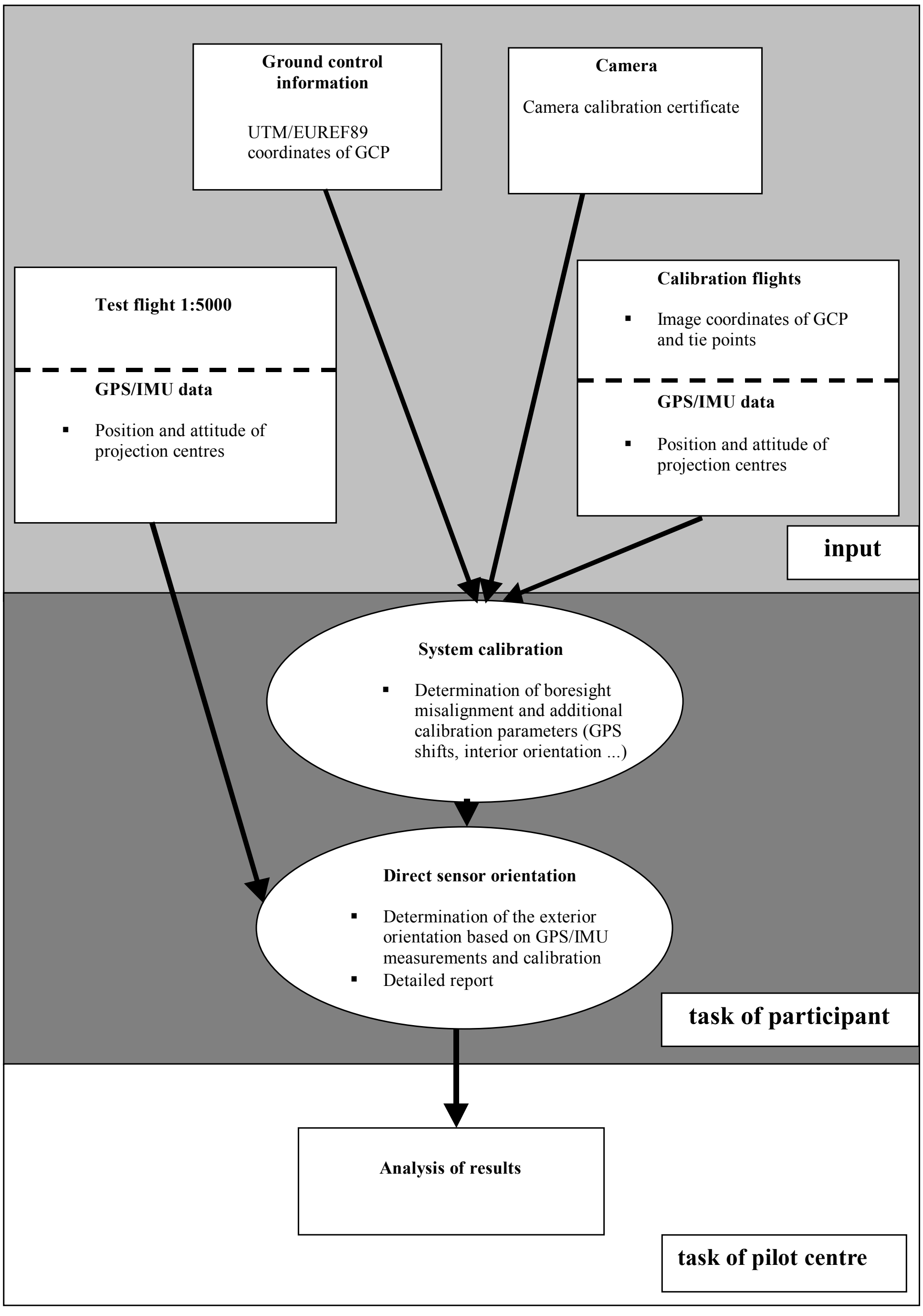

Figure 8: Flowchart of phase I

Test participant	Abbreviation	Used software
Applanix, Canada	Applanix	POS tools
IGI, Germany	IGI	AEROoffice tools and BINGO
ADR, BAE Systems, USA	ADR	BLUH
Finnish Geodetic Institute, Masala	FGI	own development, called FGIAT
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 2: List of test participants, phase I (note that the same software name does not necessarily imply the same version and thus the same results)

4.2 Phase II: Integrated sensor orientation

The second phase deals with the integration of the GPS/IMU data into the bundle adjustment. After having returned the results of phase I the participants have received image coordinates of tie points and GCP of a subset of the test flight images, namely from a small block and one strip. It should be noted that no object space coordinates of GCP were distributed, and that GCP used in phase I were not used as tie points in phase II. Thus, the participants received only information in image space, but no object space information. This decision was made, because we wanted to explore the advantage of combining GPS/IMU measurements with tie points alone, since (1) tie points can be generated automatically using image matching techniques (see approaches automatic aerial triangulation), and (2) as soon as GCP are included, their influence starts to dominate the results, and thus we end up with a GPS-assisted photogrammetric bundle adjustment.
Combining the received information with the system calibration parameters determined in phase I, the participants 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 ANALYSIS OF PHASE I RESULTS

5.1 System calibration approaches

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 system calibration parameters. A description of the standard approach can be found e. g. in Skaloud (1999 and Forlani, Pinto 2001), it will not be repeated here. Although the exact procedures adopted by the participants were not always released in detail, a number of noticeable distinctions could be observed (see also table 3):

- 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.

- 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 object coordinates as input (denoted as "1 step" in table 3) vs. a comparison of the exterior orientation derived from a conventional bundle adjustment and the GPS/IMU values ("2 steps"), see also Mostafa (2001). Some participants averaged the differences of the photogrammetric and the GPS/IMU result, others used a more sophisticated computational scheme. DIIAR, for example, weighted the influence of the photogrammetrically determined exterior orientation parameters based on the corresponding theoretical standard deviations derived from the bundle adjustment (see Forlani, Pinto 2001). 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.
- 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 (Ebner 1976; Jacobsen 1980). DIIAR also investigated the time synchronisation between the attitude values and the exposure time by estimating a constant time shift (see Skaloud 1999), but found that no correction needed to be applied (see again Forlani, Pinto 2001). ifp did not consider the computed GPS shifts as calibration parameters and only used the three angular misalignment values.
- 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 3); DIIAR and ifp processed and delivered results in the local tangential system, IPI processed and delivered results in both systems[7].

Participant	**Procedure**	**Object space coord. 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
FGI	2 steps	UTM	18 (6 + 12 add. par.) for IGI ; 19 (6 + focal length + 12 add. par.) for Applanix
GIP	1 step	UTM	21 (6 + 3 f. int. ori. + 12 add. param.)
ICC	1 step	UTM	21 (6 + 3 f. int. ori. + 12 add. param.)
Inpho	1 step	UTM	6 for IGI; 9 (6 + 3 f. int. ori. for Applanix)
LHS	1 step	Local tangential*	6
DIIAR	2 steps	Local tangential	6
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	3

Table 3: System calibration approaches followed by the different participants

[7] The IPI results in table 4 slightly differ from previously published results due to an editing error. The results given here are correct.

5.2 Analysis procedure and overall results

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 y-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 1:5.000 in which the image coordinates of the GCP of the test field (49 GCP for Applanix, 41 GCP for IGI) together with 25 tie points per image and a number of object space coordinates served as input. All image coordinates were measured manually, again using the 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 Fotonor/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. The residuals in image space are accumulated in the σ_o value of the adjustment and can be thought of as a measure for remaining y-parallaxes in stereo models formed using the participants´ exterior orientation (see below for a more detailed discussion). Statistical results of this procedure are given in table 4. In order to compare them with the conventional photogrammetric accuracy without GPS/IMU data the corresponding results are also shown.

Participant	**No. of cal. parameters**	**Applanix**				**IGI**			
		σ_o [µm]	RMS differences at GCP			σ_o [µm]	RMS differences at GCP		
			X [cm]	Y [cm]	Z [cm]		X [cm]	Y [cm]	Z [cm]
Convent. bundle adjustment		6.2	2.2	2.0	6.0	4.8	2.8	2.6	4.3
Applanix	6	22.2	5.9	11.9	32.0	-	-	-	-
IGI	6	-	-	-	-	36.7	15.9	16.1	23.0
ADR	6	32.2	13.4	12.7	18.1	55.5	19.9	16.8	28.8
FGI	19/18	13.6	9.8	10.8	9.2	27.4	11.8	10.1	18.6
GIP	21	14.8	10.7	11.2	8.1	22.9	8.1	8.3	11.2
ICC	21	14.4	5.1	3.0	22.4	24.1	9.0	12.3	22.9
Inpho	9/6	14.8	4.7	3.3	8.2	27.0	10.3	9.8	14.6
LHS	6	-	-	-	-	44.6	13.8	13.1	17.9
DIIAR	7	12.4	3.9	2.5	8.4	22.9	8.8	11.8	13.5
IPF	11	19.5	7.0	3.3	12.0	42.6	12.0	11.7	14.6
IPI (local tang.)	21	16.2	5.5	4.0	7.9	43.0	12.7	12.6	18.4
IPI (UTM)	21	16.1	8.5	3.3	12.3	42.8	12.9	15.7	18.7
Ifp	3	31.3	11.1	8.7	15.1	35.5	14.9	15.6	25.0

Table 4: 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 4:

- 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 σ_o values of the over-determined forward intersection 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 their calibration models and software may lead to improved 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 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 especially in height, as was to be expected a further refinement using self calibration parameters does not lead to significantly better results. These findings are also reflected in the results presented in table 5 in which for two participants (GIP and IPI) the results for different sets of calibration parameters under otherwise identical conditions are presented. An exception to these findings, however, is the results obtained by DIIAR, as they only used 6 calibration parameters and still obtained excellent results. This may have to do with the weighing scheme used when computing the calibration parameters, however, at this point in time, no conclusive explanation is available for this result.
- The best Applanix results are better by approximately a factor of 2 when compared to the IGI results. 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 (see chapter 3) are possible reasons; see also the discussion below.
- 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, inpho and LHS for the IGI flight), but also for more refined calibration models (compare e. g. the results from ICC and inpho for the Applanix data). Again, a conclusive reason for these differences cannot be given due to lacking information about the details of the system calibration.

Participant	**No. of cal. parameters**	**Applanix**				**IGI**			
		σ_o [µm]	RMS differences at GCP			σ_o [µm]	RMS differences at GCP		
			X [cm]	Y [cm]	Z [cm]		X [cm]	Y [cm]	Z [cm]
GIP	6	30.2	13.4	12.3	11.8	28.1	11.6	12.0	15.1
	21	14.8	10.7	11.2	8.1	22.9	8.1	8.3	11.2
IPI (local tang.)	6	33.7	10.3	11.0	16.6	43.8	13.3	13.4	19.2
	9	17.1	6.1	3.8	8.0	43.0	12.7	12.6	18.4
	21	16.2	5.5	4.0	7.9	43.0	12.7	12.6	18.4

Table 5: Detailed results for a varying number of calibration parameters, GIP and IPI

5.3 Local systemtic effects

The results presented so far give a good overview of the potential of direct georeferencing, and the RMS differences are surprisingly small. Thus, direct georeferencing must be seen as a promising candidate for 3D point positioning from airborne platforms. However, tables 4 and 5 contain only average values for the whole block. Next, a more detailed analysis aiming at detecting local systematic effects in location and/or time was carried out. To this end the RMS values in object space where plotted in the XY plane. The plots of one participant (GIP) are presented in the figures 9-12. The figure 9 and 10 show the results for Applanix and IGI achieved with 6 calibration parameters, while figures 11 and 12 show the same information obtained from a calibration with 21 parameters. In the Applanix data set a systematic effect can clearly be seen in the 6 parameter solution, while it has vanished when using 21 parameters. For the IGI results no such systematic effect is visible.

These observations could also be made for other participants´ results and can thus be regarded as representative. The systematic effect shown in figure 9 and its absence in figure 11 conform well with the discussion about the necessary number of calibration parameters above, as does the similarity of figures 10 and 12. Thus, these results again suggest to introduce parameters in the calibration procedure, taking care of differences between the nominal and the actual values for the interior orientation.

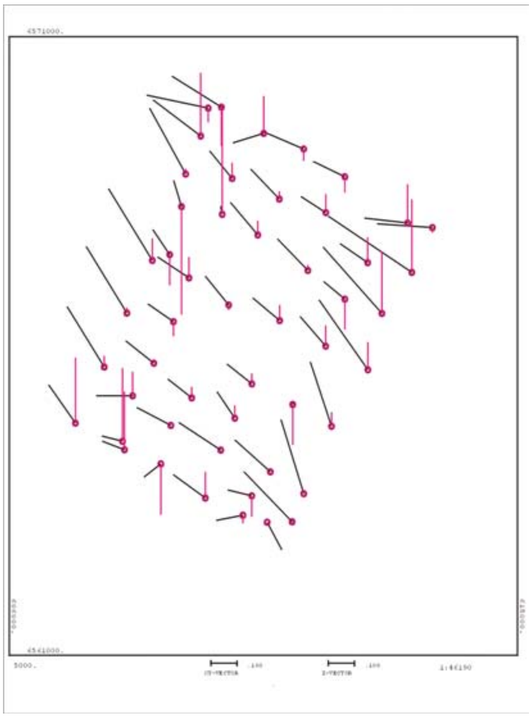

Figure 9: Difference vectors in object space (black: planimetry, red: height), Fotonor/Applanix flight, Participant GIP, 6 calibration parameters

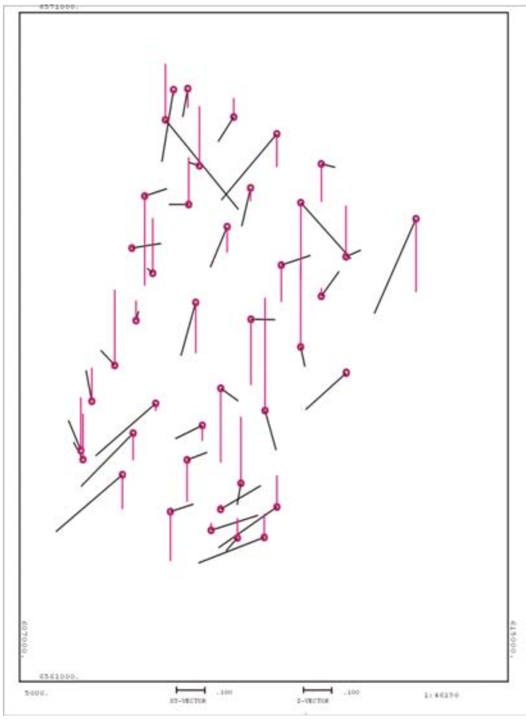

Figure 10: Difference vectors in object space (black: planimetry, red: height), FW/IGI flight, Participant GIP, 6 calibration parameters

Also, the deviations in image space represented by the σ_o values in tables 4 and 5 deserve a closer look. First, we assessed individual models rather than relying on the results of multi-ray points. We computed relative orientations for all models which could be formed from the two test blocks (178 models for Applanix, 106 models for IGI). Table 6 contains the results: the σ_o values from table 5, the average of the RMS y-parallaxes per model, called $\sigma_{o,\,rel}$ and the percentage of models with RMS y-

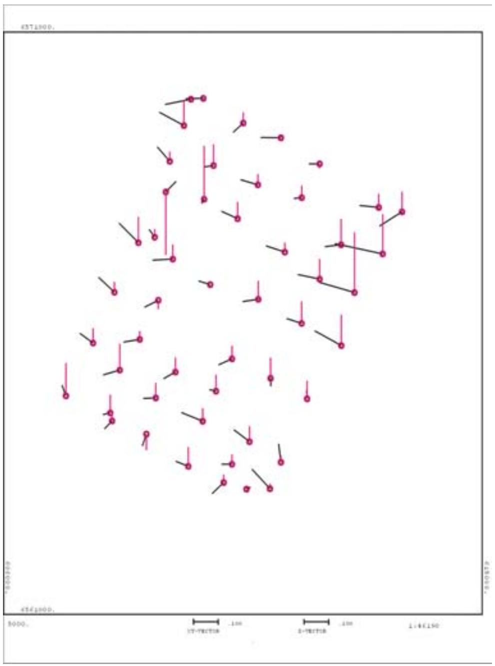

Figure 11: Difference vectors in object space (black: planimetry, red: height), Fotonor/Applanix flight, Participant GIP, 21

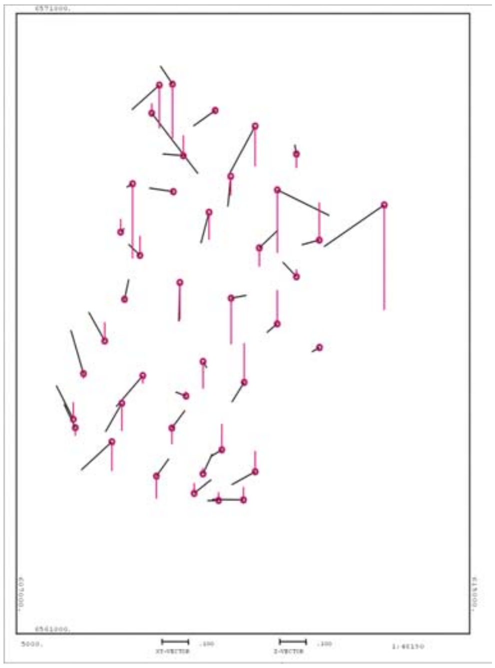

Figure 12: Difference vectors in object space (black: planimetry, red: height), FW/IGI flight, Participant GIP, 21 calibration parameters

parallaxes larger than 10 and 20 µm. These thresholds were chosen because in models with y-parallaxes larger than 10 µm stereo plotting becomes less comfortable, and even cumbersome with y-parallaxes larger than 20 µm.

Participant	**Applanix** (178 models)				**IGI** (106 models)			
	σ_o [µm]	$\sigma_{o,\,rel}$ [µm]	% of models with RMS y-parallaxes		σ_o [µm]	$\sigma_{o,\,rel}$ [µm]	% of models with RMS y-parallaxes	
			> 10 µm	> 20 µm			> 10 µm	> 20 µm
Applanix	22.2	20.2	89	31	-	-	-	-
IGI	-	-	-	-	36.7	36.6	86	55
ADR	32.2	22.6	90	34	55.5	57.5	100	86
FGI	13.6	13.6	85	13	27.4	26.9	75	35
GIP	14.6	16.4	88	15	27.8	27.3	74	36
ICC	14.4	15.4	84	13	24.1	27.0	75	35
inpho	14.8	15.6	86	12	27.0	27.0	74	34
LHS	-	-	-	-	44.6	43.3	98	78
DIIAR	12.4	15.1	79	13	22.9	27.0	74	33
IPF	19.5	16.4	85	15	42.6	43.3	98	78
IPI (local tang.)	16.2	19.3	86	27	43.0	45.4	90	61
ifp	31.3	19.0	76	17	35.5	36.8	86	53

Table 6: Model accuracy in image space, all models of the test blocks

Besides the fact that σ_o indeed seems to be a good approximation for the model accuracy, because in most cases and σ_o and $\sigma_{o,\ rel}$ agree rather well, table 6 suggests that while a number of model orientations from direct georeferencing can in fact be used for stereo plotting, this is not always the case. For both data sets there is a substantial number of models with y-parallaxes larger than 10 µm. In addition, the percentage of stereo models with y-parallaxes larger than 20 µm is rather high for the IGI data set. In order to further investigate this issue plots were created for all participants showing a distribution of the RMS y-parallaxes in the XY plane. As a representative example the plots for one participant (DI-IAR)are presented in figures 13 for Applanix and in figure 14 for IGI.

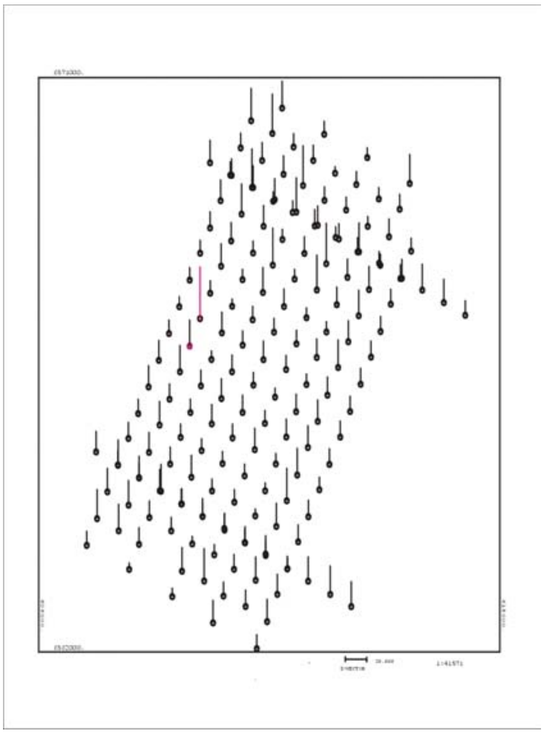

Figure 13: Remaining RMS y-parallaxes in individual stereo models, Fotonor/Applanix flight, participant DIIAR (red vectors show large parallaxes)

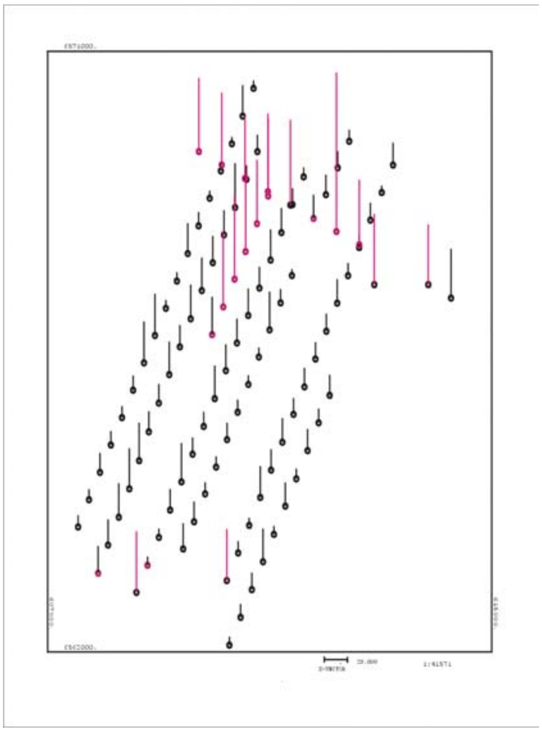

Figure 14: Remaining RMS y-parallaxes in individual stereo models, FW/IGI flight, participant DIIAR (red vectors show large parallaxes)

It can be seen that while for the Applanix data the RMS y-parallaxes are more or less similar across the whole block, for IGI two strips, namely the cross strip and a short strip in the middle of the block show distinctly larger y-parallaxes (see also Forlani, Pinto 2001 for a discussion of this effect).
At first sight this effect is surprising. The photogrammetric data give no evidence that an error in the image coordinates of the tie points can explain it. A possible explanation can be given when referring again to figure 7 and the GPS conditions during the FW/IGI test flight. As is evident from the flight management recordings the two strips in question are the two last strips flown during the complete mission, at a considerable time interval to the other strips of the block. The images in the middle of the block could not be captured before due to clouds, and the cross strip was planned to be the last strip anyway. As was mentioned before, about the second half of the block was captured under unfavourable GPS constellations. The two strips discussed here where flown shortly after the PDOP had returned to a value of about 1.7, however, the time interval between the last good satellite constellation and the acquisition time of the two strips may have been too long to again reach an adequate positioning accuracy.
In order to test this hypothesis these two strips were discarded from the analysis procedure, and the whole process was repeated for some participants. The results are presented in table 7.

Participant	**IGI** 88 models, without the two problematic strips						
	σ_o [μm]	RMS differences to GCP			$\sigma_{o,rel}$ [μm]	% of models with RMS y-parallaxes	
		X [cm]	Y [cm]	Z [cm]		> 10 μm	> 20 μm
IGI	30.1	15.9	14.6	21.7	29.4	86	49
GIP	16.0	6.9	7.9	10.2	18.0	70	26
DIIAR	16.4	7.4	10.6	11.6	17.2	68	22

Table 7: Comparison of IGI results with and without the two questionable strips

When comparing these values to the corresponding entries in table 4 and 6 an improvement can be seen. As was to be expected this improvement mainly concerns the results in image space, since the object space coordinates are of course not only influenced by the models of the two discarded strips. Nevertheless a small improvement is also visible in the RMS differences to the GCP.

5.4 General discussion of the 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 seems to allow for the generation of orthophotos and other applications with less stringent accuracy requirements. However, stereo plotting is not always possible due to the sometimes large RMS y-parallaxes of individual models. It should also be kept in mind, that also the reliability of the results remains a weak point of direct georeferencing 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 necessarily 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 nearly 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 and are processed simultaneously (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 possibly the difference in the GPS conditions during the test flights. Also the use of dry-tuned gyros in the (today outdated) IGI system may play a role, Applanix had already used a fibre optics gyro in the test. A conclusive explanation for the differences, however, can not be given based on the test data. 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 object space 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. 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. A theoretical analysis should be carried out in order to quantify the errors introduced by the approximations inherently contained in the UTM system. 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, Wegmann 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 least for high accuracy work.

6 CONCLUSIONS

In the first phase of the OEEPE test on integrated sensor orientation an accuracy potential of direct geo-referencing for 1:5.000 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 is a serious alternative to classical and GPS-assisted 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 always possible with such data due to the sometimes 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 confidential, 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 particularly important 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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