EXPERIMENTAL TESTS ON FAST AMBIGUITY SOLUTIONS FOR AIRBORNE KINEMATIC GPS POSITIONING

Prof. em. Friedrich Ackermann

Institute of Photogrammetry
University of Stuttgart
Keplerstr. 11, 70174 Stuttgart
Germany

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ABSTRACT

OEEPE has started experimental investigations into the accuracy and reliability of fast OTF ambiguity solutions, based on controlled test flights in Norway and Germany. The paper reports about first results of the testflight Vaihingen by the pilot centre Stuttgart. Ambiguity solutions were successfully obtained up to distances of 386 km to the GPS ground stations, although the restored trajectories after signal interruption show small discontinuities and biases. The comparison with check values at camera air stations (by aerial triangulation) showed no accuracy dependency on distance to ground station (with one exception in z), but confirmed sytematic errors. The results are preliminary, awaiting completion of the additional tests.

1. INTRODUCTION

1.1 Biased ambiguity solutions

High precision airborne kinematic GPS positioning by differential phase observations has been applied in photogrammetry for several years. A particularly successful field of application has been GPS camera positioning for aerial triangulation, by which ground control points could be greatly reduced.

The main problem has been, from the beginning, the question of obtaining continuous and absolute GPS flight trajectories. There has always been the risk of signal interruption during flying, especially during flight turns. Such interruptions had to be accepted as real, not being completely and safely avoidable. Software methods for re-establishing ambiguity solutions were not available, for a long time. The only accessible practical approach was, therefore, to re-solve for ambiguities, after interruption, on the basis of the less precise C/A code pseudo-range positioning. The resulting ambiguity solutions were biased, in this case, and there remained discontinuities in the GPS trajectories. And, the subsequent parts of a GPS trajectory showed systematic (drift) errors which, fortunately, remained approximately linear for some short time afterwards. Such potential (constant and linear) GPS drift errors could be described by linear correction terms which - in the case of aerial triangulation - were applied and solved for during the combined block adjustment. That approach represented a most successful engineering solution to the problem and has worked very well in practice. There was, however, one condition attached: In order to avoid singularities in the block solution some additional GPS controlled cross-strips had to be flown and used in the combined block adjustment. For general reasons the drift parameters were usually applied per strip. Also, it became customary, to rely on a few ground control points, for solving the datum problem. The method of linear GPS corrections implied that any additional constant or linear errors were compensated as well.

That method has worked very well. It is accurate, reliable, safe. Many aerial triangulation projects have been treated in this way, without any problems. It is a special advantage, too, of the method that the ground receiver station can be placed at great distance from the mission area, up to 500 km or more, which sometimes is highly essential. Also the conventional single frequency GPS receivers were applicable. Recent additional developments (2 GPS antennae on the aircraft, more than 1 ground receiver station) have made the system safer, but are not considered mandatory.

It can be summarized that the approximate resp. biased ambiguity solutions of the method are unable to provide absolute GPS positions nor continuous trajectories. The post-solution via combined block adjustment is restricted to GPS application for aerial triangulation, i.e. in combination with aerial photo coverage. Other sensors (e.g. laser scanner) rely, however, on absolute GPS positioning. Hence, that method could and can only be considered an intermediate solution, awaiting more sophisticated techniques for fast ambiguity solutions, also known as OTF (on the fly) methods.

1.2 Fast OTF ambiguity solutions

The recent development of GPS hardware and software has changed the situation. Fast OTF solutions have been developed, based on dual frequency receivers. They are to provide continuous GPS trajectories by correctly restoring the ambiguity solutions after signal interruption. Successful applications have been reported. The method has started to be applied in practice.

Only, the reliability of the method has remained unclear. Seemingly, the method does not always give successful solutions if the distance between roving and stationary GPS receivers is large. It is understood, more or less, to remain within a distances of 50 km, preferably 30 km, in order to be safe. Also, it is not really known on what effects the reliability might depend. Practical application can accomodate to such restrictions, in many cases. Nevertheless, larger ranges would be highly desirable.

1.3 Experimental tests by OEEPE

In that problem situation the European Organisation for experimental photogrammetric research (OEEPE) decided to take up experimental investigations about the performance of fast OTF ambiguity solutions with the prime objective to look into the operational reliability of the method as function of the base length, i.e. of the distance between stationary receiver(s) and mission area. A working group was established under the chairmanship of Prof. O. Anderson (Agricultural University, Ås, Norway) and the author. Two pilot centres in Ås (Department of Mapping Science, Agricultural University) and Stuttgart (Institute of Photogrammetry, University of Stuttgart) were charged with the execution of the investigations. The experimental tests make use of two photogrammetric testfields:

(1) Testfield Fredrikstad near Ås, extension 4.5 km x 6.0 km, 52 known signalized points.
(2) Testfield Vaihingen/Enz near Stuttgart, extension 4.7 km x 7.3 km, 40 known signalized points.

The set up of the tests was simple, in principle. Flight lines with continuous GPS recordings (C/A code and L1/L2 phase observations) were to go repeatedly over a testfield. When flying over the testfield the air survey camera would take photographs, whilst outside the testfield only the GPS recordings would continue. The crew was not to take the risk of signal interruptions into special consideration, i.e. fly normally, or even go intentionally into steep turns, in order to provoke signal loss of lock, for the purpose of the investigation. The flight duration, i.e. the total trajectory, should cover at least 1.5 hours. During the flight simultaneous GPS data recordings were to be taken at several ground receiver stations, at different distances from the mission area. It was expected to get several testflights, possibly with different airplanes and different GPS receivers.

For the GPS data processing, including OTF ambiguity solutions, in first instance commonly available software in form of different software packages was to be applied, as different programs may have different performance.

The first part of the investigations was designed to evaluate and compare the restored GPS flight trajectories resp. the OTF ambiguity solutions in relation to the different ground receiver stations. In the second part the GPS results would then be evaluated in absolute terms, by comparing the GPS positions at the camera air stations with the actual perspective photo centres, as derived by conventional aerial triangulation of the images taken over the test areas. Thus, the controlled parts can only refer to sub-intervals of the continuous GPS trajectories.

There are four completed flight missions of summer and fall 1995 which are used for the present investigations (some additional data sets may be considered at a later date):

(1) mission of 26 July by Hansa Luftbild GmbH, Trimble 4000 SSE receiver, testfield Vaihingen, 6 GPS ground stations, distance up to 386 km, photo-scale 1 : 13000,
(2) mission of 9 October by Schweizerisches Bundesamt für Landestopographie, Trimble 4000 SSE receiver, testfield Vaihingen, 7 GPS ground stations, distance up to 386 km, photo-scale 1 : 15000,
(3) mission of 11 October by Norsk Luftfoto og Fjernmaling A/S, Ashtech Z 12 receiver, testfield Fredrikstad, 9 (+11) GPS ground stations, distance up to 110 km (2200 km), photo-scale 1 : 5000,
(4) mission of 13 October by Fotonor A/S, Trimble 4000 SSE receiver, testfield Fredrikstad, 9 (+11) GPS ground stations, distance up to 110 km (2200 km), photo-scale 1 : 5000.

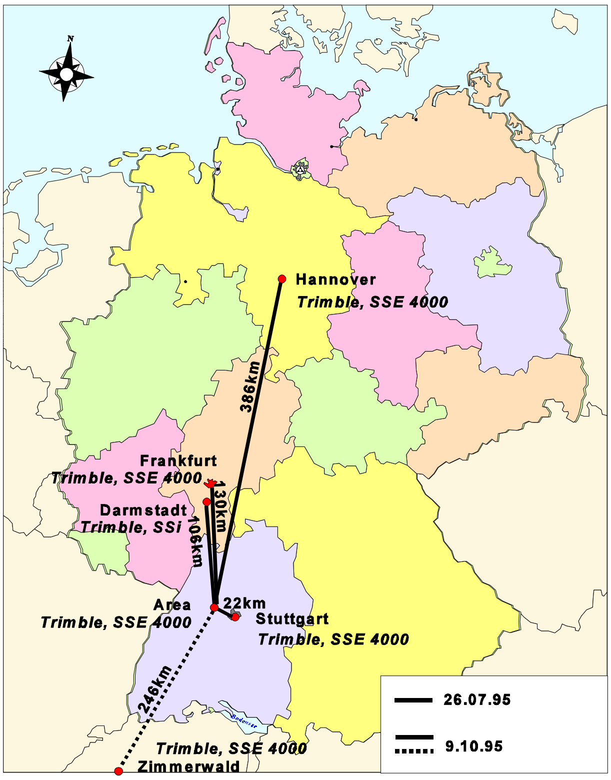

Figure 1: Location of testfield Vaihingen with GPS ground stations

The locations of the GPS ground receiver stations of missions (1) and (2) are sketched in Fig. 1.

1.4 Test flight Vaihingen by Hansa Luftbild

The photogrammetric and the GPS data processing of the various data sets has started, at both pilot centres Ås and Stuttgart. The investigations being in execution it is too early to submit a final report. In this paper the preliminary results of the mission (1) of 26 July 1995 by Hansa Luftbild of the Vaihingen test area are presented, as processed with the standard Trimble software package GPSurvey 2.0 (by M. Cramer and M. Englich of the Stuttgart pilot centre).

Fig. 2 and 3 display the flight lines and the photo strips of that mission which extended over 2 h 12 min (1 h 21 min in the test area). The test block has multiple photo coverage, consisting of 2 photo-blocks of 3 strips each (flown in both directions) and 1 photo-block of 5 cross-strips, each of the 3 photo-blocks having

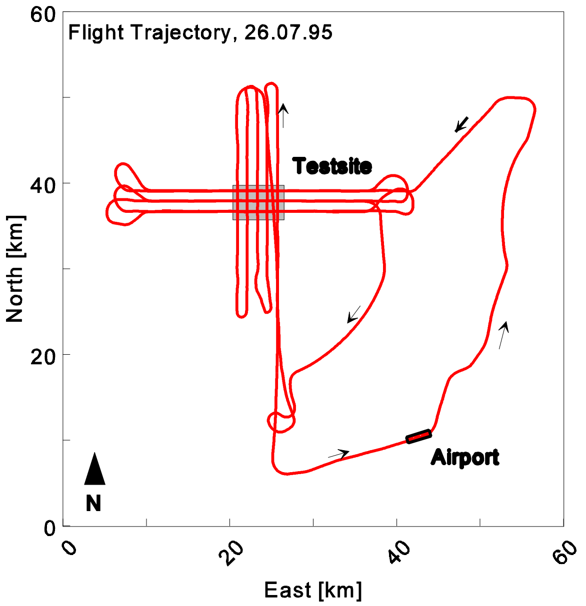

Figure 2: Testfield Vaihingen, total flight trajectory

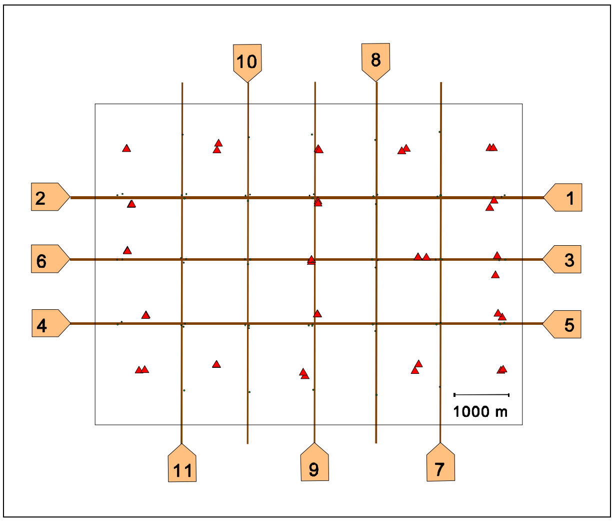

Figure 3: Testfield Vaihingen, photo strips and ground control points

60 % side overlap. The wide-angle aerial photographs were taken with a Zeiss RMK TOP camera at 2000 m flying height (photo scale 1 : 13000). The airplane (Cessna 404) had 3 GPS antennae mounted, of which 2 were connected to Trimble 4000 SSE receivers. There were 5 GPS ground receiver stations operating during the flight mission, namely stations A (in the test area), S (at Stuttgart University), D (TH Darmstadt), F (IfAG Frankfurt), H (Hannover). The distances to the testfield are, respectively, 0, 22, 106, 130, and 386 km. Station D recorded with a Trimble SSI, all other stations with Trimble 4000 SSE receivers, the last station (H) being a permanent station. Altogether, there are 5 independent GPS data sets for either antenna on the airplane.

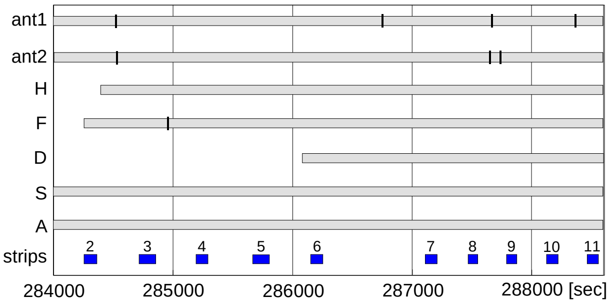

Figure 4: Overview of GPS data recordings

2. GPS DATA PROCESSING

2.1 Overview

Fig. 4 gives an overview over the various GPS data recordings of the mission. Not all 5 GPS ground stations covered the flight completely, for logistic reasons, but the coverage is sufficient for the investigation. The marks in Fig. 4 indicate the major signal interruptions (3-10 sec) which happened during flight turns. In addition there were a number of cycle slips (not shown) which the OTF ambiguity solutions had to handle, too.

2.2 Trajectory computations

The recorded GPS data sets - after conversion - are being processed at present, with 3 different software programs. Here, the results referring to the Trimble software package GPSurvey 2.0 are presented and discussed. The prime problem was to bridge the signal interruptions and the gaps by OTF ambiguity solutions. It is a first, most remarkable result that the software succeeded to bridge all signal interruptions and to provide coherent GPS trajectories for all GPS data sets, i.e. for both antennae and all 5 ground receiver stations.

The GPS recordings at the ground stations were relatively coherent, with 3-6 satellite constellation changes per recording (5-9 satellites tracked), with PDOP values between 1.5 and 4.3. The airborne GPS recordings showed, however, a much more irregular behaviour, with frequent constellation changes between less than 4 and 9 satellites, especially during the flight turns. The PDOP values varied between 1.5 and 3.3, except for much higher peaks in the flight turns. During the double difference trajectory computations the situation worsened, as in some parts (turns) the number of common satellites went down, preventing GPS positioning at all for short intervals.

The computations were carried out in the GPS (WGS 84) coordinate system, to be transformed later into the Gauss-Krüger national coordinate system for easier interpretation.

2.3 Internal consistency

In order to investigate the internal consistency and the mutual compatibility the restored trajectories were compared to each other, by computing the differences against the trajectory from station A (in the testfield). Some results (for antenna 1, which had a poorer performance than antenna 2) are shown in Fig. 5 a-c.

The graphs show that the differences between trajectories from stations S, D, and H against A are close to zero. Obviously, the ambiguity solutions are consistent over short and medium distances. Only for the large distance (H-A) small constant differences (up to a few dm) between recovered intervals start to creep in.The results with antenna 2 show similar behaviour. It means that the restored trajectories start to show small biases, after signal interruptions and constellation changes, if the distances get larger.

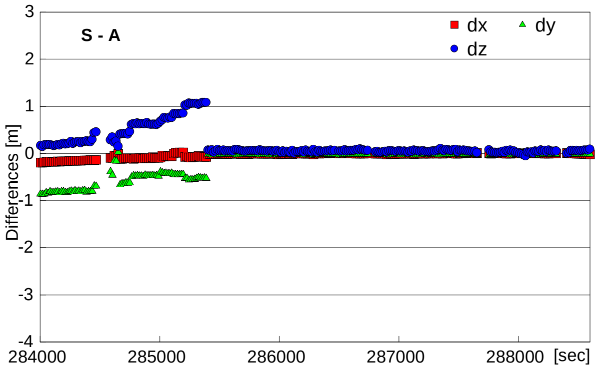

Figure 5 a: Trajectory differences Stuttgart - Area

(Antenna 1, Gauss-Krüger coordinates)

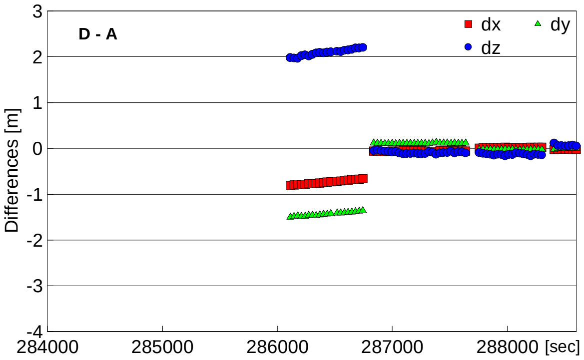

Figure 5 b: Trajectory differences Darmstadt - Area

(Antenna 1, Gauss-Krüger coordinates)

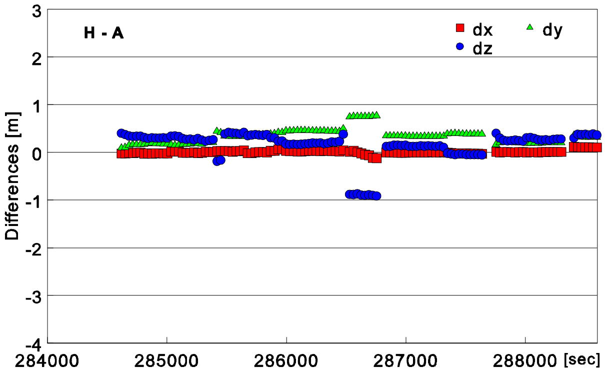

Figure 5 c: Trajectory differences Hannover - Area

(Antenna 1, Gauss-Krüger coordinates)

The graphs of Fig. 5 a-c show, however, some other effects. Certain parts of the trajectory comparisons show stretches with large off-sets, amounting to 50 cm and more. The comparison with the flight plan shows that such cases happened during flight turns and trajectory intervals which are too short to give a proper ambiguity solution (required are continuous flight intervals of about 5 min duration). With one exception those jumps did not propagate into the photo strips. The one exception concerns the beginning of the recording at Darmstadt station. There was a disturbance at antenna 1 which gave erroneous results, whilst antenna 2 still provided proper results.

It can be concluded that successful ambiguity solutions are likely to provide consistent and accurate GPS trajectories. But there are exceptions, the conditions for which must be flagged out by the software, being dependent on the details of the satellite geometry.

The internal evaluation of the restored GPS trajectories is here not pushed any further, at this time. It remains to be seen whether the results of different software packages and of the other test flights show the same effects.

3. ABSOLUTE CHECKS

3.1 Camera air stations for comparison

The results of Chapter 2 referred to GPS data directly, no other information having been brought in. Now, we make use of the aerial photographs taken during the flights over the test area. By photogrammetric aerial triangulation the coordinates of the camera air stations are obtained. They serve as check points for the GPS station coordinates, after offset-reduction to the GPS antennae.

The photogrammetric block, consisting of 67 aerial photographs of scale 1 : 13000, had multiple overlaps (see Fig. 3). The analytical aerial triangulation, based on 40 GPS determined ground control points, included selfcalibration with 12 parameters. The theoretical accuracy of the resulting coordinates of the perspective photo- centres is about 12 cm horizontally and 8 cm vertically. It should be kept in mind, however, that systematic errors are to be expected in the same order of magnitude, at least. The block-adjustment referred directly to the national Gauss-Krüger coordinate system.

The coordinate differences between the photogrammetrically determined camera air stations and their GPS equivalents were calculated for each of the 67 camera air stations. The further comparisons were all based on the arithmetic means of the differences per strip, composed of 7 resp. 5 air stations, the accuracy of the individual GPS positions being not the goal of the investigation. The photogrammetric error part in the mean differences therefore is expected to be in the order of 5 cm for the random components. The systematic photogrammetric errors, however, may still be in the order of 10 to 20 cm. This is to be kept in mind, as we deal here with differences of absolute errors.

3.2. Comparison

The mean differences per strip between photogrammetric and GPS positioning of the camera air stations (reduced to the respective GPS antenna positions) are collected in Table 1. The figures all

Strip	Station d[km]	A 0	S 22	D 106	F 130	H 386	□□h
← 1	X	-20	-21	-	-	-	-20.5
	Y	1	-3				1.0
	Z	-41	-37				-39.0
→ 2	X	18	20	-	19	-	19.0
	Y	-24	-16		-2		-14.0
	Z	-39	-33		-44		-38.7
← 3	X	-2	-3	-	0	-1	-1.5
	Y	9	12		34	37	23.0
	Z	-45	-38		-52	-31	-41.5
→ 4	X	19	19	-	22	18	19.5
	Y	-15	-17		22	2	-2.0
	Z	-44	-42		-82	-15	-45.8
← 5	X	-1	-2	-	-2	3	-0.5
	Y	18	16		34	58	31.5
	Z	-47	-41		-62	-18	-42.0
→ 6	X	14	14	14	13	14	13.8
	Y	-22	-24	-25	-6	21	-11.2
	Z	-45	-41	-49	-57	-19	-42.2
↑ 7	X	27	26	22	25	23	24.6
	Y	6	3	17	17	28	14.2
	Z	-44	-38	-56	-58	19	-35.4
↓ 8	X	-12	-12	-18	-12	-17	-14.2
	Y	-8	-9	4	1	21	1.8
	Z	-42	-35	-51	-43	8	-32.6
↑ 9	X	19	20	21	21	20	20.2
	Y	5	3	2	11	26	9.4
	Z	-45	-43	-58	-46	-20	-42.4
↓ 10	X	-7	-7	-5	-8	-7	-6.8
	Y	-18	-22	-21	-11	2	-14.0
	Z	-53	-48	-67	-55	-26	-49.8
↑ 11	X	14	13	12	17	20	15.2
	Y	2	0	2	8	34	9.2
	Z	-54	-48	-48	-17	11	-31.2
□□h	X	6.0	5.9	8.3	9.8	8.2	7.5
	Y	-4.5	-5.1	-4.8	11.6	26.1	4.6
	Z	-45.0	-40.0	-54.6	-52.9	-11.7	-40.4

Table 1: Coordinate differences between photogrammetrically and GPS-determined camera air stations (arithmetic means of strips, antenna 2, Gauss-Krüger, in [cm])

	A	S	D	F	H	□□h
L	10.3	10.5	8.7	10.2	10.6	10.2
C	15.3	14.5	17.2	13.7	17.7	15.5
V	-45	-40	-54.6	-52.9	-11.7	-40.4 (-48.1)

Table 2: Overall mean differences in L, C, V at air stations for each GPS ground station (antenna 2, in [cm])

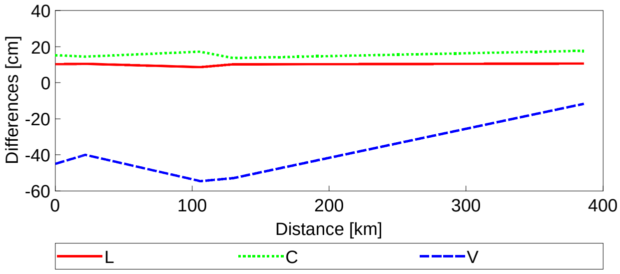

Figure 6: Overall mean differences in L, C, V at air stations as function of distance to GPS ground station (antenna 2)

concern GPS antenna 1 and refer to the national Gauss-Krüger coordinate system: y = R = E; x = H = N; z = h. The table also summarizes the overall arithmetic means for all strips (mean values taken over all ground stations) and the arithmetic means for all ground stations (mean values taken over all strips).

It is somewhat difficult to directly assess and interpret the detailed contents of Table 1 as the coordinate differences refer to different flight directions. It is obvious, however, that there are clear systematic error effects which alternate with the flight direction, whilst error effects related to the GPS ground stations seem not to be predominant. Also, a constant difference in z of considerable magnitude (40 cm) is evident. In order to separate potential error effects, for further evaluation, the values of Table 1 have been re-classified with regard to a reference system fixed to the airplane: L (in flight direction), C (perpendicular to the flight direction, + to the right), V (vertical = z).

Now, the results look considerably more consistent. Especially the mean differences in L and C (in flight direction and perpendicular to it), taken of all photo-strips per ground station, show practically no dependency on the distance to the ground stations at all. Those mean differences are listed in Table 2 and plotted in Fig. 6. It can be seen that the coordinate differences between photogrammetrically and GPS-determined air stations have in first instance constant shifts

(magnitude in flight direction 10.2 cm, across flight direction 15.5 cm, vertical -40.4 cm). The variations of the blocks against the constant shifts are remarkably small, remaining within a band of +0.4 cm to -1.5 cm in L direction, resp. of +2.2 cm to -1.8 cm in C direction. As far as the mean vertical differences are concerned the most likely interpretation assumes a constant shift of -48.1 cm for the GPS ground stations A - F (up to 130 km distance). The block variations against the constant shift then remain within a band of +8.1 cm and -6.5 cm, whilst the results of station H would then jump out by 37.4 cm. It is assumed, in this case, that the outlier at station H may be caused by ionospheric error effects, which can be expected in that order of magnitude over a distance of nearly 400 km.

The overall results thus are highly consistent, showing no distance effect, except for the z errors from the long baseline to station H. The question remains, however, what are the causes for the constant error magnitudes. As the constant errors are clearly related to the flight directions it can be stated that they must be caused by effects related to the sensor system of the airplane. This is in first instance the camera system with possibly small additional influences from the GPS antenna- and time- offsets. Constant photogrammetric errors at the camera air stations of 10 - 20 cm (at h = 2000 m) are quite likely to happen. It should be realized that we are concerned here with absolute errors which normally in photogrammetry are not visible (at the air stations) or are compensated by degrees of freedom. Whether, however, constant vertical errors of more than 40 cm can be attributed to the photogrammetric part remains doubtful, although there is no easy other explanation at hand.

The assessment of the mean coordinate differences per strip (taken over all stations) between GPS positions and photogrammetric check values (like in Table 1) is here not carried any further. The variations against the constant shifts are now considerably smaller than in Table 1. They amount to magnitudes between +10 cm and

-12 cm in L, resp. between +16 cm and -16 cm in C and still show some alternating effects, the causes of which must be in the GPS system. It could be effects of satellite constellations or related to the airborne GPS antenna. The z results are the same as of Table 1. They are particularly consistent, the mean differences per strip varying within +9 cm and -9 cm. The analyses will be continued as soon as the other test flights will have been processed.

4. PRELIMINARY CONCLUSIONS

The results obtained so far can be summarized in a few statements:

- The software succeeded to provide OTF ambiguity solutions in all cases, from all ground stations.
- The restored trajectories still have some gaps, and they show some large systematic errors in parts of poor satellite constellations, especially in flight turns. Nevertheless, the trajectory parts of the photo-strips have been properly restored based on the antenna 2 recordings.
- A warning has to be stated, that successful OTF ambiguity solutions still have to be checked on sufficient satellite geometry, before accepting the restored trajectory.
- The direct comparison of photogrammetric camera air stations and their GPS positions showed considerable constant and other systematic errors which are related to the flight directions. The further analysis confirmed that a large part of the systematic errors relates to the aircraft sensor system. It means that with regard to absolute GPS positioning systematic discrepancies originating in the camera system have to be expected. Not really explained is a constant error in z of about 40 cm magnitude.
- The check results show no dependency on the distance to the GPS ground receiver stations.

It may be tentatively concluded, on the basis of the preliminary results of this investigation, that the restoration of GPS trajectories by OTF ambiguity solutions works generally very well, even for large distances to the GPS ground receiver stations. But constant or systematic errors can occur, especially in comparison with the photogrammetric camera / image system. Precise calibration of the multi-sensor system becomes more mandatory the more the GPS positioning is used in absolute terms. It seems advisable, whenever possible, to leave some degrees of freedom open in the combined system to be determined externally, by ground control for instance.

It is recalled that this paper only refers to preliminary results of the first test flight Vaihingen. The investigations of the OEEPE Working Group are continued. It remains to be seen whether the further tests will confirm the preliminary results, before final conclusions can be drawn. Further reports are to published in due time.