# EXPERIMENTAL GPS-SUPPORTED AERIAL TRIANGULATION

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ABSTRACT
The paper discusses first results of a research project aimed at GPS-supported aerotriangulation without ground control. By concentrating on differential kinematic GPS positioning techniques for flying aircraft, a survey of problems currently encountered in photogrammetric applications is given. During flight tests in the summer of 1987 an area targetted with some 700 control points was photographed in 1:6000 with an RMK 15/23 aerial camera modified for capturing the center point of the exposure time signal together with onboard GPS carrier phase measurements. Due to overall unfavorable conditions a considerable amount of GPS data was "bad". Hence, direct comparison of the camera positions obtained from block triangulation with computed GPS antenna positions showed discrepancies not reflecting the expected high accuracy. The experiments are to be continued.

## INTRODUCTION

In recent years continuing interest in the application of the NAVSTAR Global Positioning System (GPS) to photogrammetric point positioning has been observed. The methods of static relative (differential) GPS positioning have reached an accuracy level of $10^{-7}...10^{-6}$, i.e. 1...10 cm over a range of 100 km, and are thus becoming indispensable tools for the determination of photogrammetric control. Establishing ground control for aerial blocks, however, is time consumung and expensive. Therefore, with increasing demands on both accuracy and cost effectiveness of photogrammetric restitution techniques, investigations into the utilization of navigational data for aerial triangulation have been started on by several researchers in order to reduce the necessary ground control (*Ackermann,* 1984). With the needs of other technical disciplines for very precise (relative) positioning of moving vehicles, and with the promising results obtained sofar by various organizations (see e.g. *Hein et al,* 1988), utilization of GPS in a kinematic mode for the direct measurement of the camera positions for aerial triangulation has become feasible.

By means of extensive computer simulations, *Frieß* (1987) showed that of the six exterior orientation parameters of a photograph the three coordinates of its perspective center play a dominating role. I.e., the impact of known orientation angles on aerial triangulation is by far less relevant than the influence of the camera position. Equivalent influence on the photogrammetric model provided, orientation angles would have to be measured to an accuracy of a few seconds of arc. This is not possible with present day technology. Hence, as intriguing as the direct measurement of the complete orientation of all photographs of a block might be (*Hartl et al,* 1986), if already positions alone are capable of revolutionizing aerial triangulation, then efforts should be directed towards a synthesis of photogrammetry and GPS technology.

The following paragraphs assume the reader to be familiar with the basic principles of GPS as well as photogrammetry. The paper concentrates solely on differential kinematic GPS positioning of flying aircraft and the applicability of this method to aerial block triangulation.

## A SURVEY OF CURRENT PROBLEM POINTS

GPS Signal Detection Requirements. High precision applications of relative kinematic GPS positioning presumes two receivers - one stationary, the other on the moving vehicle - to continuously track *carrier phase* from at least four satellites. If relative 3D-coordinates on the sub-decimeter accuracy level are to be gained, *dual frequency* receivers seem to be absolutely necessary (*Hein et al.*, 1988). There are indications that *multichannel* type receivers are less apt to loss of lock inflight than *multiplexing* type equipment. Possible causes for the loss of lock include a weak signal, i.e. low signal-to-noise ratio, or multipath from reflections off some part of the aircraft (*Krabill*, et al., 1987). Inflight, this deficiency leads inevitably to ambiguity problems that hardly can be resolved. Only if the phase of both L1 and L2 from each satellite can be tracked (as with the TI4100 receivers), intermediate brief losses of lock by one channel may be bridged with relatively high confidence. However, there is always the possibility of cycle slips.

From an operational point of view in a kinematic environment, the *tracking bandwidth* must be optimized for minimal phase lock losses and maximum signal-to-noise ratio. This imposes certain restrictions on the permissable magnitude and direction of aircraft accelerations. An important role plays the type of the GPS antenna* and its place of installation on the airplane. Probably the best position is atop the tail (*Lucas*, et al., 1987) or on the top of the fuselage.

Currently the most serious problem is posed by the limited *satellite coverage* due to the preliminary status of GPS. This, e.g., entails that permanent observation of the same four satellites must be retained during a mission. Since "good" geometric configurations between the antenna and the four satellites necessitate a minimum elevation angle of 20° and a Geometric Dilution of Precision (GDOP) of 6 or less, a window with these characteristics is presently limited to about one hour per day. The window moves anticlockwise with a speed of about 4 minutes per day.

Offset between antenna and camera. While the GPS antenna is mounted on top of the aircraft, the aerial camera always is situated at the bottom. This spatial eccentricity is accompanied by a temporal offset of the instants of time of the camera exposures from the GPS receiver/recorder clock time tags. As the aircraft moves considerably within one sampling interval - e.g. a speed of 180 km/h yields 50 m at 1 Hz sampling frequency - , precise synchronisation between camera exposures and GPS time is essential. This entails that the photogrammetric camera must be equipped with a shutter-synchronized electronic signal providing an accuracy of better than 1 ms. Unfortunately, not all commercially available cameras do have this feature.

The relevancy of the spatial antenna-camera offset follows from uncontrolled attitude changes of the aircraft inflight. Assuming a rigid aircraft body, the components, $e_\nu$ , of the eccentricity vector **e** (Figure 1) from camera projection center **C** to antenna phase center **A** are constant with respect to a camera-fixed coordinate system as long as the camera is fixed to its carrier. Such a solution (*Mader* et al.,1986; *Lucas* et al.,1987) permits the offset vector **e** to be utilized as additional parameter within the bundle block adjustment. However, this approach is unsatisfactory as both crab and slope angle of the camera may have to be adjusted to changing flight conditions. For a truly operational solution such changes must be accounted for and recorded by means of a simple yet precise inflight procedure.

With known offset components $e_\nu$ in the camera system, the object coordinates of the antenna phase center and the projection center are related to each other by

$$A_\mu - C_\mu = r_{\mu\nu} e_\nu \quad , \qquad (1)$$

where $r_{\mu\nu}$ represents the rotation matrix between both systems. This condition may either be incorporated in an extended bundle block adjustment or used only for deriving $A_\mu$ from $C_\mu$ after a conventional adjustment.

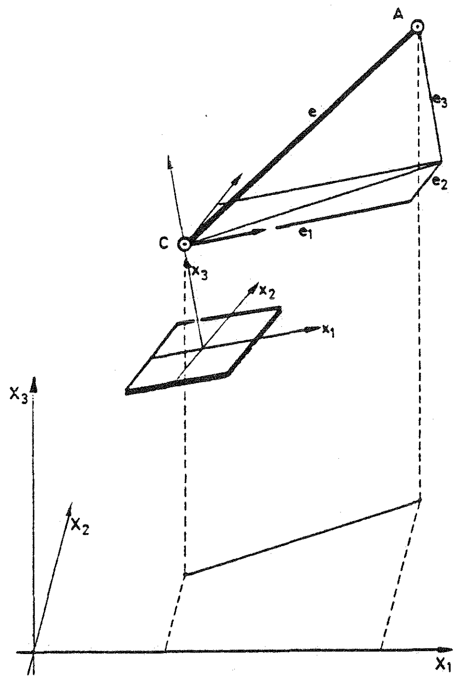

Figure 1. Eccentricity between Camera (C) and Antenna (A) in Camera Based System

Being identical to the entrance pupil of the camera lens, the perspective center C of the camera is separated from the image plane by a distance k that has nothing to do with the calibrated focal length c. For a Zeiss RMK, e.g., c=153 mm, but k=237 mm. This difference cannot be neglected if the full accuracy potential of GPS is to be exploited.

Interpolation. The GPS aircraft trajectory is represented by a set of discrete positions of the antenna at intervals of time determined by the utilized GPS sampling frequency. On these time marks the receiver software provides WGS 84 geocentric coordinates with an accuracy dependent on the distance to the ground receiver station. For distances up to 1ØØ km achievable accuracies lie in the sub-decimeter range (*Hein*, et al., 1988).

Into this set of coordinates the antenna phase centers must be interpolated according to the times of exposure. Obviously, the trajectory between consecutively computed antenna positions is more likely to be perturbed by uncontrollable aircraft movements the larger the sampling time intervals have been chosen. *Lucas* et al. (1987) used third-order interpolation polynomials to four consecutive time values spanned by 1 second intervals of a TI41ØØ receiver; *Frieß* (1988) was able to apply linear interpolation to the Ø.6 second intervals of a Sercel NR52 receiver.

Inflight data problems, e.g. loss of lock or cycle slips, however, cannot be excluded from the very beginning, particularly for the TI41ØØ receiver. *Krabill* et al. (1987) explicitly report on these difficulties and conclude about their impact on the reliability of the results. Both *Mader* et al.(1986) and *Lucas* et al.(1987) only mention similar problems without further analyses. It must be emphasized, though, that any disruption of the sampling time intervals will seriously decrease the degree of smoothness of the trajectory. On the one hand this stems from the theory of interpolation and approximation of observational data, on the other hand, however, inherently from kinematic GPS positioning, since missing samples are due to satellite signal perturbations presumably caused by abrupt changes of both attitude and speed of the aircraft.

In this case neither polynomial nor spline nor any other filtering (e.g. Kalman filter) or smoothing interpolation algorithm can approximate the antenna positions with sufficient accuracy. Only additional onboard hardware such as the inertial navigation system (INS) with continuously measuring aircraft acceleration, pitch and roll, would be capable of reconstructing the actual trajectory within longer sampling gaps. No such applications to aerial photogrammetry, however, are known to be carried out sofar.

Interior Orientation. In conventional techniques of aerial photogrammetry with nearly vertical camera axes and predominantly flat terrain, systematic disturbances of the inner orientation of a camera can mainly be absorbed by parameters of exterior orientation without seriously affecting the reconstructed photogrammetric model. To a certain extend this is also true for atmospheric refraction and image deformation.

In GPS-supported aerial triangulation, exterior orientation cannot absorb these effects due to now known antenna positions. Being rigidly attached to the eccentricity vector **e**, camera **C** with its bundle of rays is literally hanging on antenna **A** (Figure 1), constrained on the surface of a sphere around **A**. Any systematic contamination of the bundle disturbs the geometric consistency between antenna-camera, model and object. This may particularly be aggravating if the antenna positions are to be processed in a combined GPS-photogrammetric adjustment.

Several solutions can be envisaged:

- testfield calibration under actual flight conditions (*Kupfer* ,1986)
- self calibration explicitly utilizing interior orientation parameters
- selective determination of interior orientation with the help of GPS determined ground control
- determination of interior orientation parameters together with exterior orientation.

Functional and Stochastic Model. The main goal of GPS-supported aerotriangulation being reduction of geodetic control, the functional model ought to be devised towards a solution for which ground control is completely obsolete. The necessary control will be fully provided by airborne GPS data - eventually supported by INS data - gathered during the photo flight. Since the perspective centers have to be considered individually via the spatial offset, the mathematical approach must be based on bundles rather than independent models. If the antenna positions are considered as high precision airborne control, the collinearity condition used in "conventional" aerotriangulation, viz.

$$\frac{x_\alpha - c_\alpha}{-c_3} = \frac{(X_\mu - C_\mu)\, r_{\mu\alpha}}{(X_\mu - C_\mu)\, r_{\mu 3}}, \qquad \alpha = 1,2; \quad \mu,\nu = 1,2,3 \qquad (2)$$

- with $X_\mu$ representing a tie point, $x_\alpha$ the corresponding image point, $c_\nu$ the perspective center in image space - can be extended to incorporating the antenna phase center, $A_\mu$, from Equ. (1). This yields the form

$$\frac{x_\alpha - c_\alpha}{-c_3} = \frac{(X_\mu - A_\mu)\, r_{\mu\alpha} + e_\alpha}{(X_\mu - A_\mu)\, r_{\mu 3} + e_3} \qquad (3)$$

In principle, Equ.(3) may be interpreted as observation equation with (random) observables $x_\alpha$, (dependent) unknowns $r_{\mu\nu}$ , and all other quantities as constants. From the stochastic point of view a more realistic approach is obtained if $A_\mu$ and $e_\nu$ were considered random variates with proper covariance matrices. In order to compensate for systematic errors, the image space coordinates of the perspective center may be introduced as additional block-, strip- or even photo-invariant parameters, particularly in the case of available GPS ground control. Compensation of other systematic perturbations may be carried out analog to conventional block adjustment.

Geodetic Datum. While the positions provided by GPS correspond to the geocentric coordinate system WGS 84, the coordinates utilized in aerial triangulation are based on state plane systems referred to local spheroids (ellipsoids of revolution). Moreover, the (orthometric) heights are referred to the geoid, thus differeing from their corresponding geometrical, i.e. ellipsoid-referred heights by the geoidal height. The World Geodetic System WGS 84 is a nearly conventional terrestrial system (*Decker*, 1986) which is anchored in the center of mass of the earth and earth-fixed. It plays the key role for any transition between GPS-satellite based and earth based observations.

Local reference ellipsoids are founded upon classical land survey networks supplemented by astronomical fixes in order to establish local approximations to the geoid. Hence, geodetic datum systems, defined each by the axes of a corresponding reference ellipsoid, can principally be related to WGS 84 by shift, rotation and scale. For practical reasons local Cartesian systems should be chosen, particularly in photogrammetric applications.

Joining the actual GPS coordinate system with a terrestrial coordinate system is one of the major, yet unsolved tasks in GPS supported aerial photogrammetry. Although high fidelity of both ground and airborne control - each referred to its own system - may be ensured , the mutual geometric connection in between cannot be guaranteed with sufficient accuracy by photogrammetry alone. The reasons are manifold: systematic perturbations of the photogrammetric bundles of rays, insufficient knowledge of ellipsoid transfer, systematic drifts in the GPS system. At least for the present time, these impediments seem to exclude a rigorous aerotriangulation without any ground control. Thus, a combined GPS-photogrammetric bundle block adjustment must make provision for the necessary datum transfer and this can only be achieved if a few control points are anchored in both systems.

The difficulties are obviously more pronounced for vertical than for horizontal coordinates. As elevations are generally related to the (local) geoid, any anomalies of the geoid with respect to the reference ellipsoid have to be taken into account. While this may not be of much concern in regions with adequate vertical control and negligible geoid varations, it does impose serious problems elsewhere.

## FLIGHT EXPERIMENTS

In the spring of 1987 a series of photogrammetric GPS flight tests were planned over several areas with abundant control previously signalized by Bayerisches Landesvermessungsamt München (BLVM). The corresponding research project is conducted jointly with the Institute of Astronomical and Physical Geodesy (IAPG) of UniBwM. Both preparation and conductance of the flight tests involved a cooperative effort between IAPG/IPK and Wehrtechnische

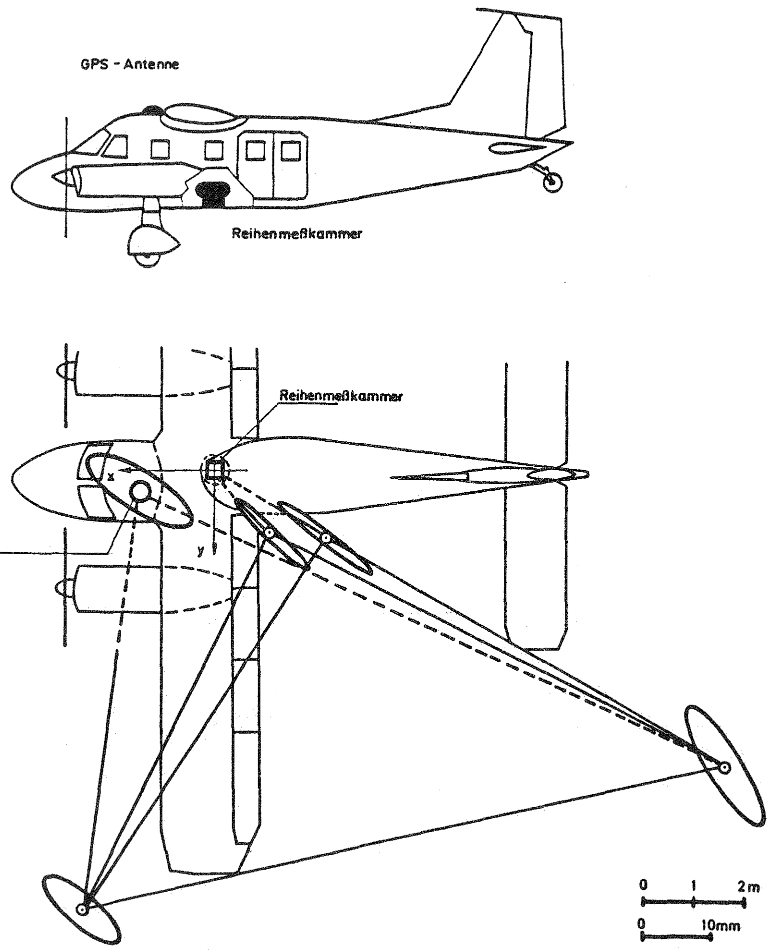


Figure 2. Antenna and Camera Installation in the Aircraft Dornier Do 28 and In-Hangar Eccentricity Calibration Network

Dienststelle für Luftfahrzeuge (WTD) of the Bundeswehr, Manching. WTD provided a *Dornier Do 28* aircraft and the associated personnel for the installation of the equipment and the actual flights while IAPG provided two geodetic quality GPS receivers (model TI4100, made by Texas Instruments). A dual-frequency GPS flight antenna DM C146-2-1 from Dorne & Margolin Inc., N.Y. was mounted atop the fuselage between cockpit and wings (Figure 2). A photogrammetric camera RMK 15/23 with electronic signal for the shutter release was made available by Zeiss, Oberkochen.

The camera was time-tagged with the "one-pulse-per-second" (1 pps) cycle of the TI4100 via a frequency generator (precision 0.25 ms) built inhouse. The offset between the 1 pps and GPS time was recorded from the J2 port of the TI4100 via an RS-232C interface while the offset between the shutter release pulse and the 1 pps was measured on the frequency generator via a HP-IB interface. Both interfaces were software controlled by a HP-IL recording loop run on a simple HP 71B pocket computer (Figure 3).

Due to bad weather and the failure of GPS satellite PRN9 just prior to the test flights, only one flight experiment was applicable to photogrammetry. Figure 4 shows the path of this flight, conducted on August 17, 1987, over test area "München-Freimann" in the north of the city of Munich. One GPS receiver was installed in the aircraft, the other was deployed near the runway on Neubiberg airport. It was considered imperative that both receivers track the same four satellites continuously from some 15 minutes prior to departure from the parked position of the aircraft until again some 15 minutes after it returned to the same point.

The static collection of data during parking was necessary in order to perform independent ambiguity estimates in case the airborne receiver might lose lock on takeoff or landing. It also provided initial positions of the antenna on the airplane relative to the ground receiver located about 1 km away. During the parking periods the position of the antenna was projected down onto the parkway by means of two theodolites and clearly marked. The two theodolite stations were tied to the state plane system via sightings to known survey points including the ground receiver. This assured that all these points could be determined in both the GPS and the state system.

The offset between antenna and perspective center of the camera was determined in an aircraft-fixed reference system by means of extensive in-hangar calibration measurements. The geometrical configuration is shown in the lower part of Figure 2. The components of the eccentricity vector e = 1.152 0.147 1.712 m were calculated to 1 cm within the image space system. For reasons of ease, the camera inclination was rigidly fixed to the fuselage. The crab angle, however, was deliberately released from such a restraint and the camera operator instructed to read any change from the coarse angular scale on the camera mount.

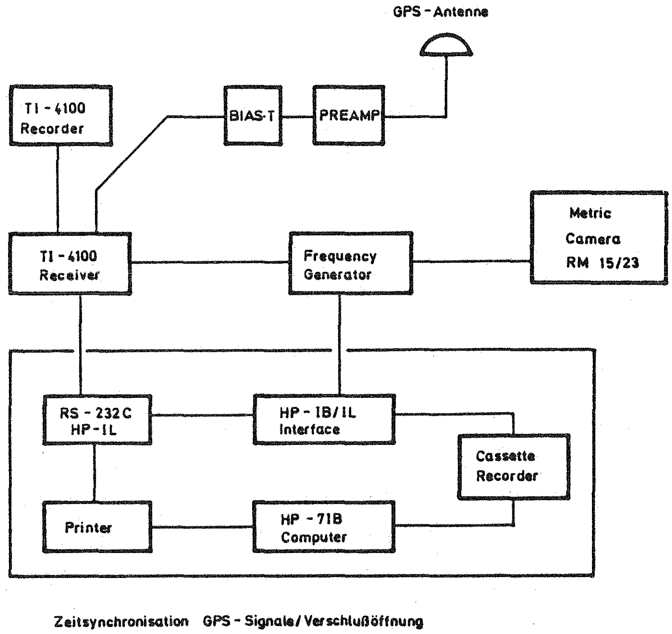


Figure 3. Block Diagram of Time Synchronization Camera Shutter and GPS Receiver Signals

The failure of one satellite caused a severe deterioration of the GDOP for the four remaining active satellites , thus limiting the airborne observation window to about 30 minutes - just enough for the photo flight. Flown in 1:6000 at a height of 900 m above ground and with 80% overlap and 30% sidelap, the 4.3 km by 1.4 km test area was covered by two strips of 17 photos each. In fact, photographs were taken all along the flight path in order to eventually provide some aid in resolving unexpected cycle slips.

DATA REDUCTION AND ANALYSIS OF RESULTS

A detailed analysis for the GPS data is given in *Hein et al*, (1988).Table 1, taken from there, summarizes the observation statistics for the airborne receiver. The extremely large number of cycle slips in the observations of the two low elevation satellites 3 and 11 must be attributed to antenna shadow casting from the wings due to aircraft pitch and roll. In addition, the flight antenna revealed a significantly lower signal-to-noise ratio in L2 frequency than the standard TI4100 antenna. These two anomalies are the reason for the relatively large amount of "bad data" which, by definition, were considered not usable for a derivation of adequate positions.

IAPG performed the reduction of the GPS data by means of an algorithm containing cycle slip fixing and Kalman filtering implemented in a special software package DYNAMITE (*Hein et al*, 1988). Due to the unfavorable situation described above, a considerable percentage of losses of lock and/or cycle slips had occurred during the flight. Since data with a signal-to-noise ratio below 40 db have to be rejected for high precision kinematic positioning, ambiguities could only be resolved for GDOP threshold values below 6. Therefore, reliable GPS positions of the antenna phase center could only be computed for the easterly strip (Figure 5) over a period of 66 s of time. Almost half of the 66 recordings failed, however,

Table 1. Observation statistics for the airborne receiver in flight. Flight test "München-Freimann"

| Date: 17-Ø8-1987 | | Satellites 3 | 11 | 12 | 13 |
|---|---|---|---|---|---|
| Elevation range | | 11°-36° | 39°-21° | 71°-74° | 48°-66° |
| Average SNR(db) | L1 | 4Ø.3 | 42.6 | 42.3 | 43.4 |
| | L2 | 35.8 | 36.8 | 39.7 | 39.4 |
| "Bad data"(%) | L1 | 38.4 | 24.4 | 4.1 | 1.7 |
| | L2 | 38.4 | 24.4 | 4.1 | 1.7 |
| Number cycle slips | | 39 | 58 | 16 | 7 |

thus seriously impeding the interpolation of the antenna stations. Figure 4 exhibits the altitude vs. time profile of this portion of the flight path after a coordinate transformation from WGS 84 to a local Cartesian system based on the International Ellipsoid, situated as close to the system used for photogrammetric data reduction as possible.

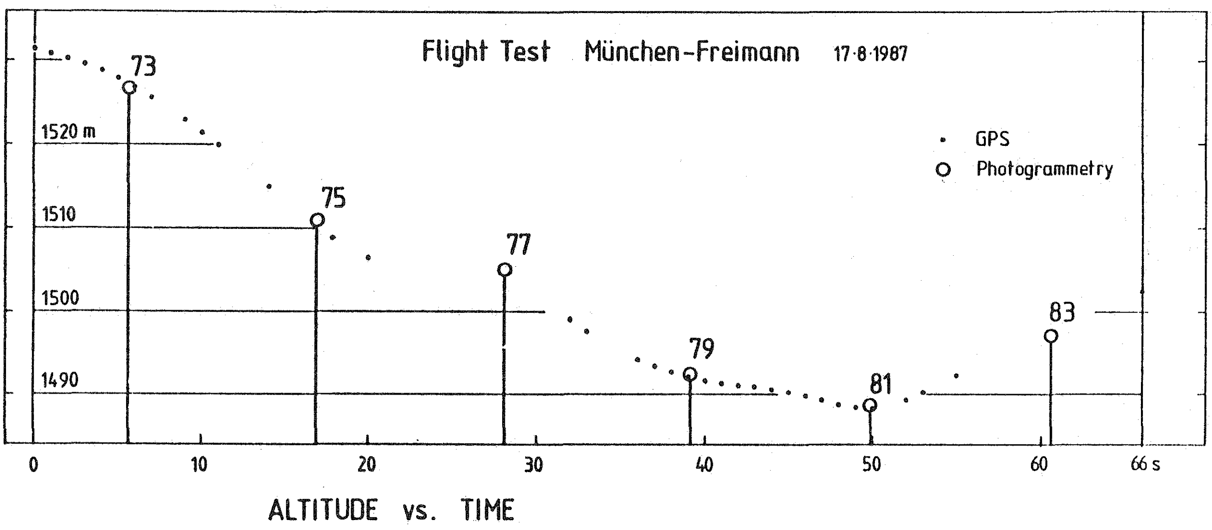


Figure 4. Altitude vs. Time Profile of Flight Path

From the 17 pictures of the easterly photostrip only every second photo was chosen for mensuration. The object coordinates (standard deviation 1-2 cm) of some 5ØØ signalized ground points had been made available to us by BLVM. As painted circles on the pavement, the targets originated from a previous cadastral photoflight for the City of Munich and were still visible. The mensuration of the 8 photographs was performed pairwise on IPK's Planicomp C1ØØ and image coordinates for each picture were assembled with a special routine (accuracy 5 µm). After image data cleaning and transformation of the ground data to a local Cartesian photogrammetric system, the photostrip was adjusted by means of a modified MOR bundle block program (*Wester-Ebbinghaus,* 1985).

With the exception of photo 87, the coordinates of the perspective centers of photographs 73 through 85 were determined with standard deviations within the ranges 0.023...0.056, 0.019...0.072, 0.008...0.043 m in x, y, z, respectively. Photo 87 showed much larger error values due to inhomogenious distribution of control and it was not used furtheron. The achieved accuracy can be considered adequate for a comparison with the positions resulting from GPS.

With the rotation matrix **R** being known from the bundle adjustment, the photogrammetric coordinates of the perspective centers could now be transferred to the associated antenna phase centers with the help of Equ.(1). For the 6 photographs falling within the 66 second segment, the corresponding GPS coordinates were interpolated by local third order polynomials. As seen from Figure 5, only stations 73, 79 and 81 can be considered reliable enough; the other stations, viz. 75, 77 and 83 lie on portions of the flight path where the interpolation interval is between 4 and 12 s as compared to the sampling rate of 1 s.

Despite the precise recording of the camera exposures into GPS time scale, the analog watch imaged on each photograph was found to be very valuable for an exact correlation between photo numbers and corresponding records. As it turned out, the frequency counter sporadically dropped one full cycle for unexplained reasons. Within the actual photostrip, though, these synchronization problems could be resolved.

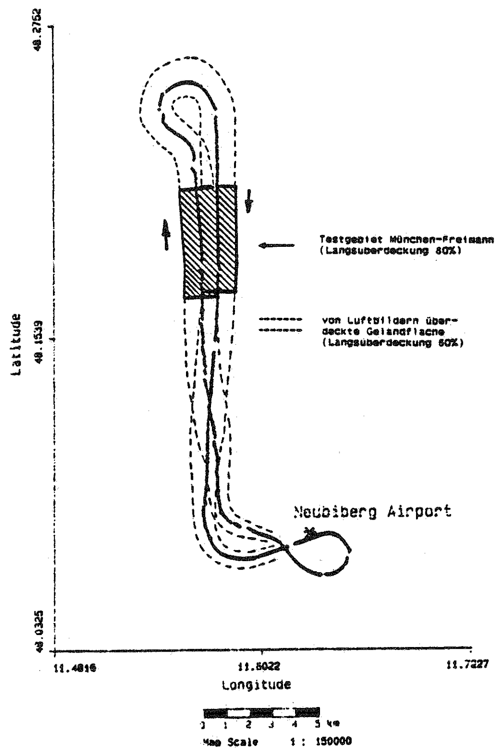


Figure 5. Flight Path of GPS-Supported Phototriangulation. Date: 17-8-1987

Table 2. Absolute coordinate differences of antenna phase centers as determined from phototriangulation and differential kinematic GPS positioning. Values refer to local Cartesian systems.

| Station | X (Easting) | Y (Northing) | Z (Elevation) |
|---|---|---|---|
| 73 | 29.512 m | 310.326 m | -25.174 m |
| 75 | 23.477 | 312.228 | -24.017 |
| 77 | 20.150 | 331.705 | -23.099 |
| 79 | 16.880 | 303.783 | -25.675 |
| 81 | 12.833 | 299.465 | -26.355 |
| 83 | 10.913 | 297.067 | -27.546 |

The differences between the coordinates determined by photogrammetry and by means of GPS are shown in Table 2. Obviously, the relatively large values must be attributed predominantly to datum differences. In view of the bad data material *per se* no efforts were made to solve this problem by pure geodetic reasoning via ellipsoidal transfers. Instead, the local GPS system was simply shifted ("offset") and rotated ("slope" or "drift") into the local photogrammetric system, where the transformation parameters were only determined from the three reliable stations 73, 79 and 81. Such a pragmatic approach is entirely legitimate as long as its limits are realized, apart from the fact that it was applied also by *Lucas et al* (1987) and *Frieß* (1988). Table 3 exhibits the residual differences between both systems.

Table 3. Residual Coordinate Differences

| Station | X (Easting) | Y (Northing) | Z(Elevation) |
|---|---|---|---|
| 73 | -Ø.ØØ2 m | -Ø.25Ø m | -Ø.Ø58 m |
| 75* | -1.8Ø5 | 4.271 | 1.367 |
| 77* | -Ø.9Ø7 | 26.366 | 2.553 |
| 79 | Ø.ØØ7 | 1.Ø34 | Ø.242 |
| 81 | -Ø.ØØ5 | -Ø.784 | -Ø.183 |
| 83* | 2.Ø94 | -Ø.692 | -1.119 |

For the three "good" points, RMSE values of Ø.ØØ5, Ø.763, Ø.178 m are obtained, although on a rather low signficance level. While the X-residuals across flight are astonishingly small, the along flight Y-residuals reach rather large values that might be suspect of either abrupt and erratic velocity changes of the aircraft or unexplained time synchronization failures. The Z-residuals may very well reflect the accuracy potential of kinematic GPS positioning under particularly unfavorable conditions.

The results obtained do not confirm the high accuracy level of GPS in the order of a few cm as to be expected from recently achieved kinematic measurements on land (*Hein et al,* 1988). In order to demonstrate this a few more flight tests are required.

## CONCLUSIONS AND CRITICAL REMARKS

The GPS flight tests have demonstrated that, under overall poor conditions, the accuracy level to be expected from theory could not yet be reached. Better conditions provided, sub-decimeter accuracy will certainly be achieved in the near future. The experiments have also shown that a GPS phase tracking receiver in an aircraft must assure that it maintains lock during takeoff and landing, and during normal flight on at least four satellites, preferrably for both frequencies L1 and L2. In addition, problems such as low signal-to-noise ratio of the satellite signals, possible synchronization failures of the camera exposure signal with respect to GPS time scale, and inadequate procedures for ambiguity estimation, have to be properly tackled and solved prior to further flight experiments. Nevertheless, there is still a long way to go until a fully operational solution for the purpose of aerotriangulation will be found.

In our opinion, the promising results published by *Lucas et al* (1987) have to be considered from an *ideal case* point of view, and it must be warned of its generalization. Actually, he as well as *Frieß* (1988) have proven no more than the high accuracy potential inherent in differential kinematic GPS positioning when applied to aerial photogrammetry, at the same time demonstrating the necessity for further research.

From a methodical point of view, generally three cases for a utilization of kinematic GPS data in photogrammetry should be distinguished:

1. Data for aircraft navigation in real time. For this, only methods such as "Differential Position Corrections" and "Phase-Smoothed Pseudo-Range" (*Hein et al,* 1988) are suitable.
2. Biased raw GPS data for the camera-antenna positions. Originating from simple functional models and computational procedures, these data can be used on segments of the flight path - e.g. along strips - and will be adjusted together with photogrammetric data. I.e., the bias parameters (in its simplest form offset and drift) are considered unknowns of the adjustment. In his analysis of a flight test in the Netherlands, *Frieß* (1988) uses segments of some 60 s within each strip of a block. Obviously obtained under favorable conditions, these results may indicate a GPS accuracy potential in the range of 3-5 cm.
3. Supply of final relative antenna positions of high precision. Together with their covariance matrices, these 3D-positions could be processed directly without any intermediate reductions. To our knowledge, neither realistic accuracy statements or estimates are available, nor has a truly operational combined block adjustment been performed. It is essential for this method that deterministic effects be removed by properly modelling their physical and geodetic nature.

ACKNOWLEDGEMENTS

Research leading to this paper has been funded by the German Research Foundation (DFG); its continuing support is gratefully acknowledged. Thanks are given also to BWB in Koblenz and WTD Manching for providing a Do 28 aircraft for the flight tests as well as the personnel required for the installation of the equipment and the actual flying. The flight qualified antenna was given to us on loan from the U.S. National Geodetic Survey, Rockville, Md., the prototype aerial camera with electronic shutter signal from Carl Zeiss, Oberkochen. Prof. Lange and his Institute for Basic Electrical and Mechanical Engineering of UniBwM constructed the camera-GPS receiver frequency generator.

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