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THE NAVSTAR GLOBAL POSITIONING SYSTEM FOR AERIAL TRIANGULATION

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1. INTRODUCTION

The orientation of aerial photographs has always been the fundamental problem in aerial photogrammetry. In the last 60 years the orientation procedures in aerial photogrammetry were based solely on the indirect determination of the camera orientation elements by aerial triangulation using ground control points. There have always been many attempts to determine the exterior orientation or individual parameters of the exterior orientation directly during the photo flight mission, but none of these efforts were able to achieve a practical break-through. On the one hand these systems were not able to determine the orientation parameters with sufficient accuracy and on the other hand their practical use failed due to the high financial costs involved. Remarkable exceptions are in particular the statoscope and the APR (airborne profile recorder). The statoscope is able to yield the differences in altitude of the projection centres between individual exposure times with a high degree of accuracy (0.8 - 0.9 m), the APR additional terrain elevation data. In both cases the required vertical ground control can be considerably reduced, especially in combination with block adjustment (ref. 3, 8, 10).

The latest developments in inertial and satellite-based navigation systems will offer in the future new possibilities to determine the orientation parameters during the photo flights. The results obtained by analyses up to now show that the NAVSTAR GPS (Navigation System with Time and Ranging Global Positioning System) is the most promising for this purpose. In principle, the position of the GPS antenna is established by spherical intersection of distances measured simultaneously to at least four satellites (ref. 6). If GPS-observations are taken continuously during the photo flight, the determination of the camera positions at the moments of exposure is fundamentally possible.

From this the following possible applications in photogrammetry of the NAVSTAR GPS can be derived :

- GPS-based photo flight navigation according to a given flight plan including computer controlled camera release.
- Use of GPS-data recorded during the photo flight for computing the exterior orientation elements and introduction of these parameters into the bundle block adjustment as additional observations.
- If the accuracy of the orientation parameters determined from GPS-data is high enough, they can be applied for direct setting of the orientation parameters in analytical instruments for mapping or photomapping, without going through aerial triangulation first.

It is of prime interest to consider first the application of the exterior orientation elements computed from GPS-measurements as additional observations in aerial triangulation. The high effectiveness of directly measured orientation parameters as additional observations in the combined bundle block adjustment is a very well known fact, as earlier studies with statoscope and APR data have shown (ref. 3, 8, 10). Therefore , the integration of the GPS into aerial triangulation will be methodically developed and will be tested by experimental flights, within the framework of the Interdisciplinary Research Group " Precise Navigation " (Sonderforschungsbereich " Hochgenaue Navigation " SFB 228, Deutsche Forschungsgemeinschaft DFG) at the University of Stuttgart.

In the first chapter a review of preliminary investigations will demonstrate with which precision the orientation parameters must be obtained by GPS to be of interest for aerial triangulation. The main point of interest of this paper will be the description of an evaluation model of GPS-data. For this reason the GPS observation types, their accuracy potential and the most important systematic effects will be briefly described. Results of the first analyses obtained with this model are presented and their importance for aerial triangulation is discussed.

2. ACCURACY REQUIRED FROM THE GPS

The preliminary investigations for the inclusion of the NAVSTAR GPS into aerial triangulation concentrated on the theoretical accuracy behaviour of the block triangulation, if the exterior orientation elements are introduced into the bundle block adjustment as additional observations.

The aim of these studies, carried out by computer simulations, was on the one hand to investigate the effect of observed orientation elements on the point accuracy and ground control in photogrammetric blocks. On the other hand the question should be answered with which precision the parameters of the exterior orientation have to be determined in order to be of interest or of use for aerial triangulation.

In particular, simulations with several accuracy levels of the orientation parameters and different cases of ground control were carried out. In addition it was distinguished whether all six exterior orientation parameters, only the postion data , or only the attitude data are available as observations. The photo scale 1 : 60 000 was used for all computations. The simulations completed so far are based on greatly simplified assumptions (no systematic errors, no correlations between the observations), and give as a result a comprehensive overview of the accuracy of the combined block adjustment in dependence upon the assumed precision of the observed orientation elements.

The most important result of the simulations in respect of the utilization of the GPS for the determination of the exterior orientation is the great effect of the camera position data on to the block accuracy. If one introduces only the coordinates of the projection centres with an accuracy of ± 10 m as additional observations into the combined bundle block adjustment, one achieves after the block adjustment with four X,Y,Z ground control points in the block corners, a position accuracy of 2 m and an altitude accuracy of 3 m, using a photo scale of 1 : 60 000. Hereby all the demands on a small scale mapping are fulfilled. Without observed camera coordinates the same accuracy could only be obtained with bridging distances of not more than eight baselengths (ref. 18, 19).

The determination of the camera attitudes would only be of interest for aerial triangulation, if the precision of the observations reaches the order of 1 mgon. Only with this level of precision can the attitudes replace the position data, or alternatively in combination with them, give rise to an additional improvement of the block accuracy.

In general it can be maintained, that orientation elements as additional observations in the combined block adjustment can always fully replace terrestrial ground control with regard to the accuracy of the block triangulation. Ground control points are merely required for the datum transfer, i.e. in order to establish the relation to the geodetic coordinate system.

Summarizing, one can say based on the simulation studies, that for aerial triangulation the determination of the camera positions will be sufficient for the present and that it will be most advantageous with respect to the thereby possible great reduction of ground control. For small scale mapping an accuracy of ± 10 m for the camera positions is required. In table 1 (taken from ACKERMANN 1986 ref. 16) the degrees of precision are presented , which are required from GPS in order to satisfy the specifications of aerial triangulation for medium and large scale mapping and photomapping.

Table 1 : Required precision of the camera positions for combined block adjustment

(photo) map scale	photo scale	required accuracy of AT $\mu_{x,y}$	μ_z	contour interval	required precision of the camera positions $\sigma_{x,y}$	σ_z 3)
1 : 100 000	1 : 100 000	5.0 m	4.0 m	20 m	30.0 m	16.0 m
1 : 50 000	1 : 70 000	2.5 m	2.0 m	10 m	15.0 m	8.0 m
1 : 25 000	1 : 50 000	1.2 m	1.2 m	5 m	5.0 m	4.0 m
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1 : 10 000	1 : 30 000	0.5 m	0.4 m	2 m	1.6 m	0.7 m
1 : 5 000	1 : 15 000	0.25 m	0.2 m	1 m	0.8 m	0.35 m
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1 : 1 000	1 : 8 000	5 cm	10 cm	0.5 m	0.4 m 1)	0.15 m
numerical point determination	1 : 4 000	1-2 cm	6 cm		0.15 m 2)	0.15 m

Assumption : σ_o = 15 µm, 1) σ_o = 6 µm, 2) σ_o = 3 µm, 3) σ_{oz} = 15 µm

The requirements of aerial triangulation with regard to the precision of the camera postions are met by NAVSTAR GPS in all cases of applications in small and medium scale mapping (ref. 20).

Investigations by MADER et. al. (ref. 21, 22), where accuracies in the order of decimeters were obtained, show that GPS can also be used for large scale operations. The aim of the future to derive from navigation systems directly applicable parameters for the orientation of aerial photographs is therefore more realistic than was ever thought up to now.

3. INCLUSION OF THE NAVSTAR GPS INTO THE AERIAL TRIANGULATION

3.1 SOLUTION STRATEGY

After it has now been shown in chapter 2 that the NAVSTAR GPS is most suitable for the determination of the camera positions of a photo flight, a possibility of its inclusion in aerial triangulation will be described in the following. Proceeding from the basic concept of the evaluation process of an aerial triangulation with GPS the problems of the realisation, which have to be solved, will be pointed out.

The individual steps of an aerial triangulation with the inclusion of the NAVSTAR GPS are :

1. Performing and recording of GPS-observations during the photo flight mission with one GPS receiver with an observation rate as high as possible.

2. Computation of the coordinates X(t), Y(t), Z(t) of the GPS antenna phase centre at the exposure times and the variance-, covariance matrices pertaining to them in any desired coordinate system.

3. Introduction of the coordinates of the antenna phase centre into the combined bundle block adjustment as additional observations.

The concept of an aerial triangulation with the integration of the GPS can indeed be easily structured, but due to several conditions some difficulties will occur during the realisation of the particular parts.

1. The registration of the GPS-observations takes place independent in time of the camera release. In order to guarantee during the evaluation the interpolation of the position coordinates onto the exposure times, the moments of exposure have also to be recorded on the receiver time scale.

2. The GPS-measurements recorded during the photo flight mission have to be suitably prepared in order to be able to subsequently estimate the coordinates of the antenna phase centre. Coordinates computed from GPS-observations are, however, obtained first of all in the geocentric coordinate system WGS 84. The reference systems normally used in aerial triangulation are, however, the state coordinate systems which refer to local ellipsoids. Therefore, several transformations are necessary, whereby among other things effects such as precession, nutation and polar motion have to be taken into consideration. Worthy of particular emphasis is the fact that the altitudes determined by GPS refer to an ellipsoid and, thereby, deviate by the geoid undulations from the altitudes normally used in surveying, where the geoid is the reference surface.

3. The coordinates determined with GPS refer to the antenna phase centre and not as desired to the projection centre of the camera. This fact has to be taken into account in the use of the phase centre coordinates in the combined bundle block adjustment.

The recording of the moments of exposure on the receiver time scale is a pure hardware-problem. The camera has to transmit an impulse at the moment of greatest lens aperture which causes the registration of the internal time in the receiver. For the planned test flights appropriately modified cameras are already available.

The computation of the coordinates from GPS-observations and their consideration in the combined block adjustment is on the other hand purely a software-problem. Only after the development of corresponding computer programs, will one have the possibility to experimentally analyse the error characteristics of the GPS-measurements and of the coordinates computed therefrom, which is of extreme importance for the further application of the coordinates as additional observations in the bundle block adjustment.

The mathematical model necessary for this will be described in the following sections. For easier understanding the observation types of GPS, their accuracy potential and the most important systematic effects will first of all be briefly presented.

3.2 MATHEMATICAL MODEL FOR THE PROCESSING OF GPS-MEASUREMENTS

GPS-satellites are active satellites continuously transmitting two different L-band signals L1 and L2 which are complex in structure (ref. 7). The two carrier frequencies of the signals are 1575.42 MHz and 1227.42 MHz for L1 and L2, respectively. Three different codes are modulated on these carrier frequencies : two pseudo-random sequences, which are used for pseudorange measurement, and a data code, which contains various information such as satellite orbit parameters, satellite clock parameters, satellite status etc. (ref. 5).

With regard to the pseudo-random sequences a difference is made between the P-code (Precise Positioning Service) and the C/A-code (Standard Positioning Service). The P-code is modulated on the carrier with a frequency of 10.23 MHz, which corresponds to a wavelength of approx. 30 m, the C/A-code with a frequency of 1.023 MHz, i.e. with a wavelength of approx. 300 m.

If one takes for the code or alternatively for the pseudorange measurement derived therefrom a resolution of 1/50 of the wavelength as a basis (ref. 12), there then results a distance resolution of 0.6 m for the P-code and one of 6 m for the C/A-code.

In addition to the possibility of using both the codes as measurement values, one can also make use of the carrier itself i.e. of the phase of the carrier as a measurement value. The wavelengths, which correspond to each of the carrier frequencies, are approximately 19 cm and 24 cm, respectively. If a resolution of 3° - 5° (ref. 12) is assumed for the phase measurement, then the corresponding resolution of distance is approx. 2 mm or 2.5 mm.

When positioning with GPS there are thus fundamentally two observation types at one's disposal, the code-dependent pseudorange observation and the code-independent carrier phase measurement. One can choose between these two observation types all depending on the degree of precision required.

With the pseudorange observation the spatial distance between receiver and satellite is in principle obtained by measuring the signal transit time. The signal transmission time is modulated on the satellite signal, the reception time of the signal is registered in the receiver. The difference between the signal reception time and the signal transmission time multiplied by the propagation velocity of the signal would give the spatial distance between satellite and receiver, in the case of the receiver clock and satellite clock being synchronised. Since this is not the fact, the so-called pseudorange is obtained, which is falsified proportional to the synchronization error.

The phase measurement is carried out on the signal carrier and is, therefore, independent of the C/A- or alternatively the P-code. In principle, the phase of the incoming satellite signal is compared with the phase of a reference signal generated in the receiver. One obtains the slant distance between satellite and receiver from the phase shift plus an initially unknown number of complete wavelengths.

Pseudorange- and phase observation can in principle be compared with the observation methods used in electronic distance measurement (EDM), whereby distances are likewise determined by means of transit-time- or phase measurements.

Both these observation types are subject to certain systematic influences. Since the camera positions in aerial triangulation are not required in real-time, one has the possibility of evaluating all GPS-observations of a photo flight simultaneously, i.e. one thus has the required redundancy in order to model systematic effects by choosing suitable parameters. The decisive systematic effects will, therefore, be briefly described in the following. They can be divided into three groups : into satellite-dependent, signal-propagation-dependent and receiver-dependent effects.

The uncertainties in the transmitted satellite ephemeris and the satellite clock errors can be mentioned as satellite-dependent effects.

Normally the positions of the satellites are calculated from the orbit parameters (ephemeris), which the satellites themselves transmit. The accuracy of the orbits calculated from the ephemeris varies between 20 m - 50 m (ref. 17). An improvement of the satellite orbits cannot be avoided, if one wishes to have the full advantage of the accuracy, with which the observations can be carried out. The evaluation model for GPS-observations has to thus allow for a suitable modelling of the satellite orbits.

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When performing and evaluating GPS observations time is the factor of greatest importance. On the one hand it is used as a measurement value for pseudorange observations, and on the other hand it is required for the calculation of the satellite positions. With GPS one distinguishes between three time systems : the system- or GPS-time, the satellite-time and the receiver-time. Neither the satellite-time nor the receiver-time are synchronous with the GPS-time. The differences are described as satellite-time-offsets or receiver-time-offset, or in general terminology as satellite clock- or receiver clock errors.

The satellite-clock-offsets are not constant due to particular drifts of the satellite frequency standards and also because of general and specific relativistic effects. The parametrisation of the satellite clock errors has to take both causes of drift into consideration.

Since the signal propagation does not take place in the vacuum, one has to consider the influences of ionospheric and tropospheric refraction. The ionospheric propagation delay can be eliminated by a linear combination of observations on both frequencies (L1 and L2), because it is among other things inversely proportional to the square of the transmitted frequency. If one only has observations of one frequency, the influence of the ionosphere has to be modelled (ref. 7, 11, 13). For the modelling of the influence of the tropospheric refraction most models make use of the temperature, air pressure and the partial water vapor pressure as observed at the earth's surface. There are several troposphere models at one's disposal : the modified and the simplified Hopfield Model (ref. 1, 11), the Saastamoinen Model (ref. 2, 13), the Rahnemoon Model (ref. 23) etc..

The receiver clock error, analogous to the satellite clock errors, is also not constant in time, as a result of fluctuations of the receiver frequency standard. It causes the greatest receiver dependent systematic influence on the observation and has, therefore, to be taken into consideration in the evaluation model.

After having briefly stated the most important systematic influences, one can proceed to the development of a model for evaluating GPS observations for aerial triangulation. As previously mentioned a real-time solution is not of interest here. For this reason all the GPS observations of one photo flight can be simultaneously evaluated. The evaluation model for aerial triangulation hereby differs from the one used in navigation. In navigation the position coordinates are required in real-time, and thereby in order to calculate them, only the observations of one observation epoch and the preceeding observations are at one's disposal. There also exists, however, a great difference to those evaluation methods found in geodesy. When applying GPS for the point determination in geodetic networks the receiver is stationary, the duration of the observation is thus of no considerable importance. Observations for the determination of the coordinates of one point can normally be carried out over a longer period of time.

The following observation equations for pseudorange- and phase observations are taken as a basis for the calculation of the coordinates of the antenna phase centre in aerial triangulation :

$$\begin{aligned} P_r^{Si} &= R_r^{Si} + c\,\delta T_{Si} - c\,\delta T_r + (\delta R_r^{Si})_{ion} + \varepsilon_P \\ \lambda D_r^{Si} &= -R_r^{Si} + c\,\delta T_{Si} - c\,\delta T_r + (\delta R_r^{Si})_{ion} + \lambda N_r^{Si}(t_1) + \varepsilon_D \end{aligned} \qquad (1)$$

whereby :

$$R_r^{Si} = \sqrt{(X_{Si} - X_r)^2 + (Y_{Si} - Y_r)^2 + (Z_{Si} - Z_r)^2}$$

P_r^{Si}	, Pseudorange observation from receiver r to satellite S_i
D_r^{Si}	, Phase observation from receiver r to satellit S_i
X_r, Y_r, Z_r	, coordinates of the antenna phase centre of receiver r
X_{Si}, Y_{Si}, Z_{Si}	, coordinates of satellite S_i
δT_{Si}	, clock error of satellite S_i
δT_r	, clock error of receiver r
$N_r^{Si}(t_1)$	, unknown number of wavelengths λ
$(\delta R_r^{Si})_{ion}$	, correction due to ionospheric refraction

c , speed of light

ε_p , pseudorange observation error

ε_D , phase observation error

Because of the drift characteristic of the frequency standards used, polynoms are well suited for the modelling of the clock errors of the satellites and of the receiver (ref. 5, 9). All secular relativistic effects are also absorbed by using polynoms of the second order for the satellite clock errors (ref. 5). This gives :

$$\begin{aligned} \delta T_{Si} &= B_0 + B_1(t_i - t_o) + B_2(t_i - t_o)^2 + \ldots \\ \delta T_r &= A_0 + A_1(t_i - t_o) + A_2(t_i - t_o)^2 + \ldots \end{aligned} \qquad (2)$$

whereby : t_o = reference time
t_i = observation time

If possible the observations are corrected according to the influence of the tropospheric refraction before the actual calculation of the coordinates takes place. For this reason the correction term for the tropospheric refraction does not appear in the observation equations. If the GPS observations were performed on both frequencies, the effect of the ionosphere can also be eliminated beforehand and does not have to be allowed for in the adjustment. If, however, the GPS observations were performed on only one frequency, the influence of the ionospheric refraction will then be modelled by (ref. 7) :

$$(\delta R_r^{Si})_{ion} = cI_1/f^2 + cI_2/f^3 + cI_3/f^4 + \ldots \qquad (3)$$

whereby : c = speed of light
f = signal frequency

According to the laws of Kepler, which describe the two-body problem, a satellite moves on a ellipse orbit, whereby a focus of the ellipse coincides with the centre of the earth's gravity field. The coordinates of satellite S_i can be calculated from the Keplerian elements

a , semi-major axis
e , orbit eccentricity
i , inclination angle
Ω , right ascension of ascending node
ω , argument of perigee
T_o, time of perigee passage

as follows :

$$\begin{bmatrix} X_{Si} \\ Y_{Si} \\ Z_{Si} \end{bmatrix} = a \cdot R_3(-\Omega + \Theta) \cdot R_1(-i) \cdot R_3(-\omega) \cdot \begin{bmatrix} \cos E - e \\ \sqrt{1-e^2}\,\sin E \\ 0 \end{bmatrix} \qquad (4)$$

whereby : Θ = Greenwich apparent sidereal time
E = eccentric anomaly

The Keplerian elements are included as unknown values in the evaluation process, whereby the possiblity is given of improving the satellite orbits.

To summarize, the pseudorange- and phase observations can be represented as functions of the sought coordinates of the antenna phase centre and of particular model parameters.

$$\begin{aligned} P_r^{Si} &= P(\,X_r,Y_r,Z_r,\ A_o,A_1,A_2,\ B_o,B_1,B_2,\ I_o,I_1,I_2,\ a_i,e_i,i_i,\Omega_i,\omega_i,To_i) \\ D_r^{Si} &= D(\,X_r,Y_r,Z_r,\ A_o,A_1,A_2,\ B_o,B_1,B_2,\ I_o,I_1,I_2,\ N_r^{Si},\ a_i,e_i,i_i,\Omega_i,\omega_i,To_i) \end{aligned} \qquad (5)$$

In this model the following values appear as unknowns :

1. The sought unknown coordinates of the antenna phase centre X_r, Y_r, Z_r
2. The orbit parameters :
   - a_i, e_i, i_i, Ω_i, ω_i, To_i ... orbit parameters for satellite S_i
3. The parameters for the modelling of the systematic effects :
   - A_o, A_1, A_2, ... receiver clock parameters
   - B_o, B_1, B_2, ... satellite clock parameters
   - I_o, I_1, I_2, ... ionosphere parameters
   - $N_r^{Si}(t_1)$.................. ambiquity parameters

After an appropriate linearization of the observation equations the unknown values are estimated according to the method of least-squares.

If four satellites at a time are observed simultaneously, one obtains for a photo flight of, for example, one hour and using a GPS receiver with an observation rate of one second :

n_i = 3600 observation epochs
n_S = 4 observed satellites

$n_B = n_i * n_S = 14\,400$ pseudeorange- or phase observations

$u_{rc} = 3 * n_i = 10\,800$ unknown receiver coordinates
$u_{rcl} = 3$ unknown receiver clock parameters
$u_{scl} = 3 * n_S = 12$ unknown satellite clock parameters
$u_{ip} = 3$ unknown ionosphere parameters
$u_{op} = 6 * n_S = 24$ unknown orbit parameters

$u_u = u_{rc} + u_{rcl} + u_{scl} + u_{ip} + u_{op} = 10842$ unknowns

In order to compensate for systematic effects numerous parameters were introduced in the described observation model. The question as to whether all parameters can be determined is, at least for the time being, an open one. Since many of these parameters have the same effect on the observations, and are thereby correlated among one another, the normal equation system is weakly conditioned or perhaps not solvable because of singularity. For this reason the parameters are not treated as free unknowns in the adjustment, but are introduced as fictitious observations in order to achieve numerical stability.

The described adjustment model has already been transformed into a computer program with which first analyses of GPS observations have been carried out. A result of these investigations is discussed in the next chapter.

3.3 FIRST ANALYSES OF GPS OBSERVATIONS

In order to guarantee a proper control of the results GPS pseudorange observations of a known fixed station were used to test the model. The observations were kindly made available to us by the National Geodetic Survey (NGS).

The set of test data comprised of 889 observation epochs (approx. 15 minutes observation time). Pseudoranges (with P-code) were observed on both frequencies (L1 and L2) to four satellites (satellite nos : 6, 9, 11, 13) with an observation rate of one second. The influence of the ionospheric refraction was, therefore, able to be eliminated before the adjustment. The corrected pseudorange observations were introduced into the adjustment with a standard deviation of σ_{pr} = 2.0 m (ref. 4). Although the observations were carried out stationarily, they were treated in the adjustment process as observations of a mobile receiver, i.e. the coordinates of 889 points were estimated.

The obtainable accuracy for the adjusted coordinates of the antenna phase centre is dependent upon the choice of the parameters to be determined. The effect of individual parameters and combinations of parameters on the result (coordinates) was investigated by means of numerous test runs. A good absolute accuracy was only then obtained when the satellite orbits were assumed to not be fixed, i.e. when individual orbit parameters were estimated in the adjustment process.

The representation of the results of all the investigations is not possible within the framework of this paper. The result of greatest interest for the aerial triangulation is presented in table 2 and in the figures 1 - 6. It shows that the developed model is very well suited for the evaluation of GPS observations in aerial triangulation. In this example the receiver clock parameters A_o and A_1 were treated in the adjustment as known values. The orbit parameters to be estimated were empirically chosen in such a way that they were only weakly correlated ($r < 0.5$).

Table 2 :

absolute accuracy	inner precision	
r.m.s.$\hat{X}$ = ± 2.82 m	$\overline{\Delta X}$ = 0.00 m	r.m.s.ΔX = ± 2.81 m
r.m.s.$\hat{Y}$ = ± 2.97 m	$\overline{\Delta Y}$ = 0.00 m	r.m.s.ΔY = ± 2.07 m
r.m.s.$\hat{Z}$ = ± 2.53 m	$\overline{\Delta Z}$ = 0.00 m	r.m.s.ΔZ = ± 1.94 m

The values for the absolute accuracy correspond to the root mean square values of the differences between reference coordinates and adjusted coordinates. The reference coordinates of the station were supplied by the NGS.

Since one is dealing with the adjustment of stationary observations, no differences in the coordinates between each of the consecutive observation epochs should occur, assuming an error-free evaluation model. The differences calculated from the adjusted coordinates (ΔX, ΔY, ΔZ) between the individual observation epochs can thus, on the one hand, be used for assessing the modelling of the systematic effects, and on the other hand they reflect the observation accuracy. The root mean square values of these differences are denoted here as the inner precision.

In the given example (table 2) the mean values of the coordinate differences between each of the consecutive observation epochs ($\overline{\Delta X}$, $\overline{\Delta Y}$, $\overline{\Delta Z}$) are zero, i.e. all linear systematic effects were modelled by means of the chosen parameters (fig. 4 - 6). The inner precision, i.e. the accuracy of the coordinate differences, is good, it corresponds approximately to the a priori precision of the pseudorange observations.

The obtained absolute accuracy (fig. 1 - 3) of approximately ± 3 m is excellent for this type of observation and it might well be regarded as the lower limit for the positioning accuracy with pseudorange observations (P-code), since the precision of the pseudorange observation, i.e. the distance between satellite and receiver antenna, can only be assumed as approx. ± 2 m (ref. 4).

In order to demonstrate the importance of this result for aerial triangulation one can refer back to the simulations. In the case of the coordinates of the projection centre being able to be introduced with an accuracy of ± 3 m as additional observations into the combined bundle block adjustment, one would achieve after the block adjustment a position accuracy of ± 1 m and an altitude accuracy of ± 2m in the block, when using a photo scale of 1 : 60 000, a σ_o = 15 µm, a block size of 10 x 41 photographs and with four X,Y,Z ground control points in the block corners.

The result underlines the suitability of the NAVSTAR GPS for determining the exterior orientation in aerial triangulation and thereby gives encouragement to perform further investigations. For applications in the field of small-scale mapping, the pseudorange observations are by all means suited for the determination of the camera coordinates. The highly precise phase measurement will, on the other hand, make the application of GPS possible for large scale mapping, too.

Fig. 1 : Absolute accuracy in X

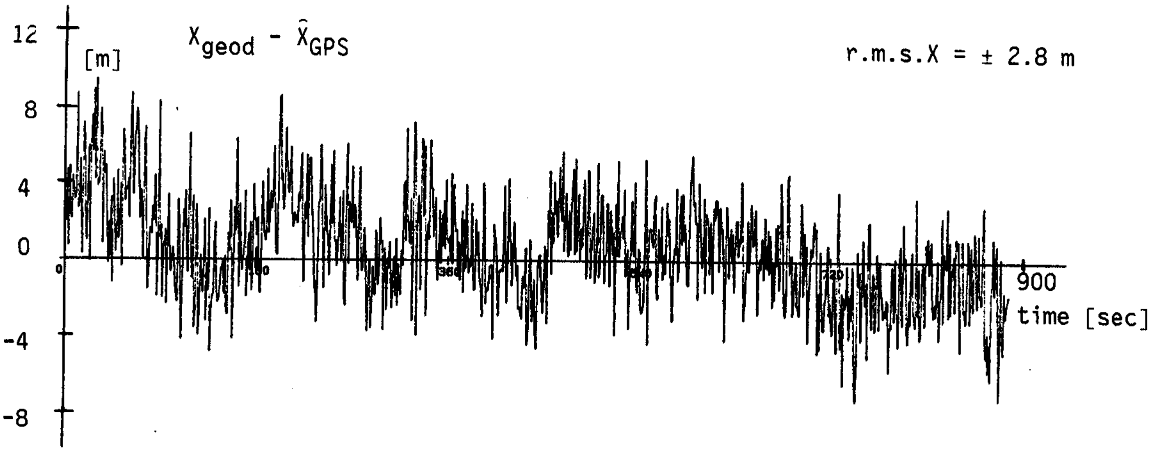


Fig. 2 : Absolute accuracy in Y

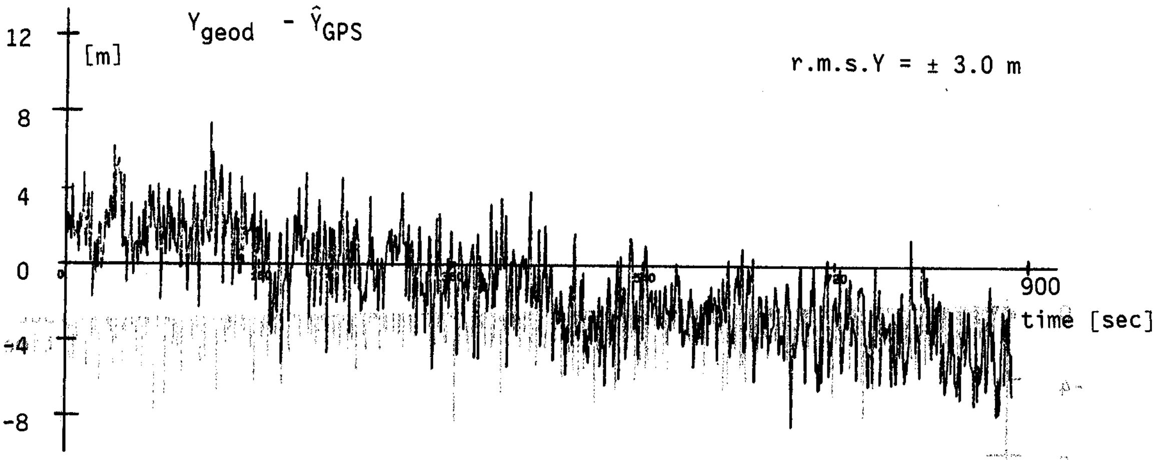
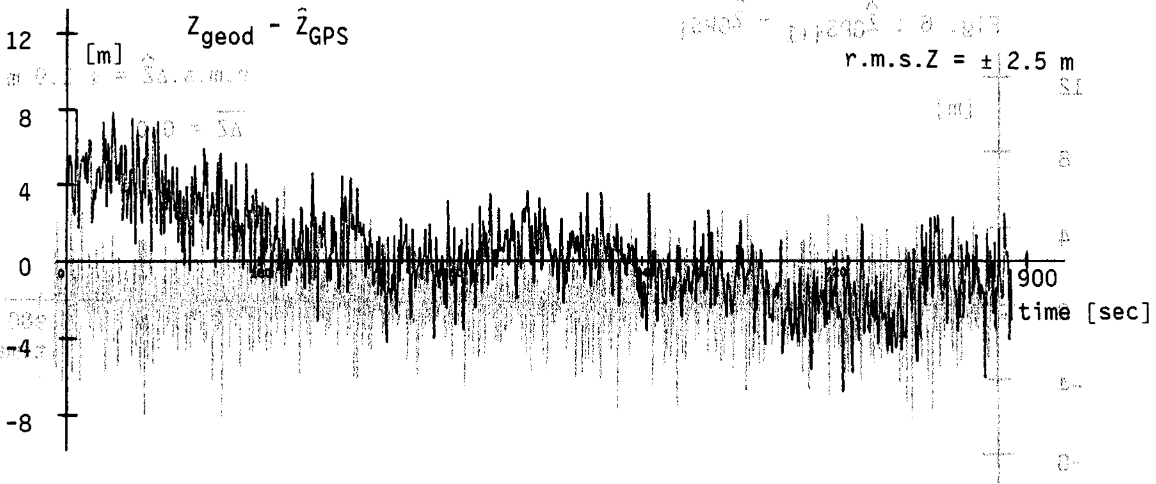


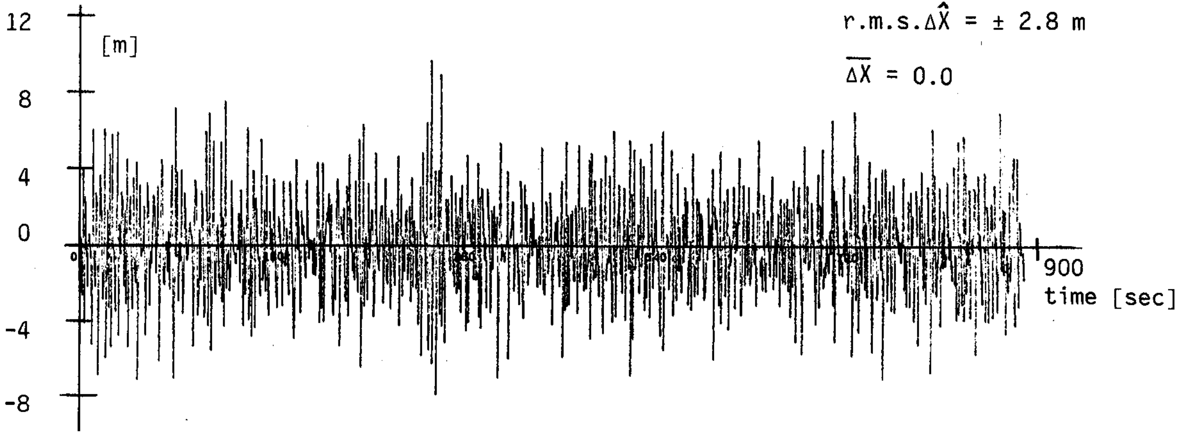
Fig. 3 : Absolute accuracy in Z



X_{geod}, Y_{geod}, Z_{geod} = reference values

Fig. 4 - Fig. 6 : Differences between consecutive points

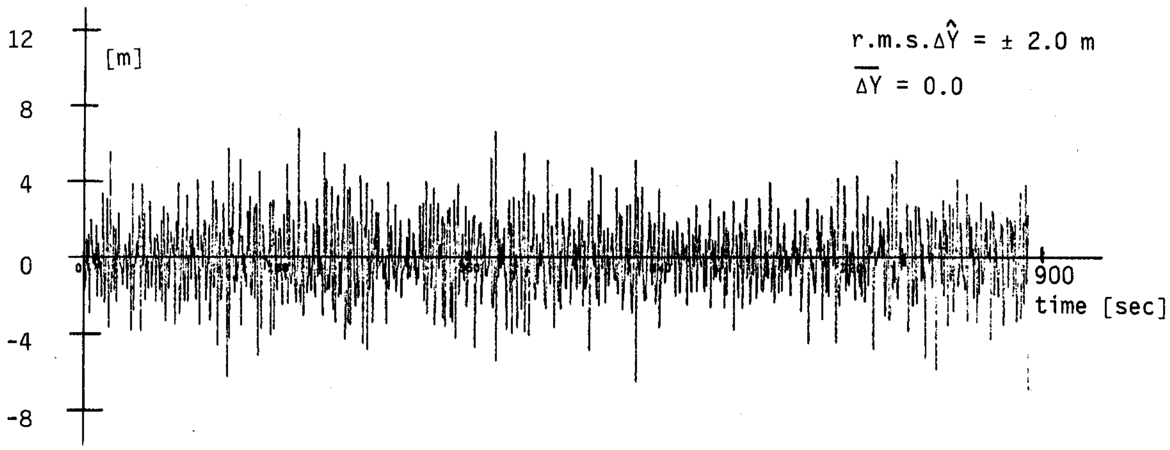
Fig. 4 : $\hat{X}_{GPS_{i+1}} - \hat{X}_{GPS_i}$



r.m.s.$\Delta\hat{X}$ = ± 2.8 m

$\overline{\Delta X}$ = 0.0

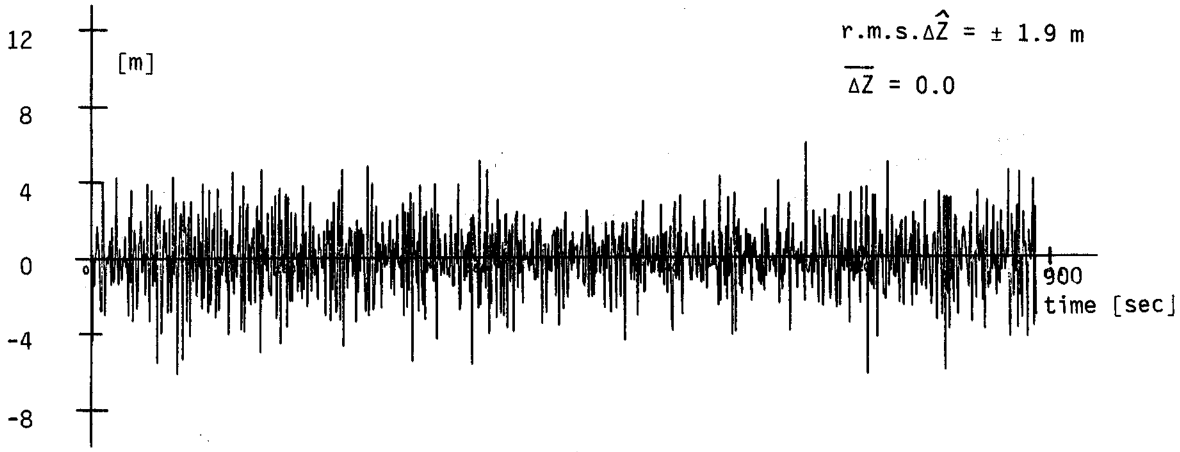
Fig. 5 : $\hat{Y}_{GPS_{i+1}} - \hat{Y}_{GPS_i}$



r.m.s.$\Delta\hat{Y}$ = ± 2.0 m

$\overline{\Delta Y}$ = 0.0

Fig. 6 : $\hat{Z}_{GPS_{i+1}} - \hat{Z}_{GPS_i}$



r.m.s.$\Delta\hat{Z}$ = ± 1.9 m

$\overline{\Delta Z}$ = 0.0

4. OUTLOOK

During preliminary investigations the accuracy demands on the camera positions determined with GPS, which have to be met in order to enable their application as additional observations in the bundle block adjustment, were ascertained, the suitability of the GPS for this application established and an appropriate evaluation model for GPS observations developed. The theoretical investigations can thus for the time being be regarded as concluded. The experimental analysis of GPS pseudorange- and phase observations is now in the foreground for the further development. For this purpose several controlled photo flights with varying tasks are planned with GPS data registration and in part these have already been carried out.

1. Photo flight over a test area in the Netherlands. Rijkswaterstaat, Meetkundige Dienst Delft is in charge of the planning, preparation and the realization of the project. The flight takes place with one stationary and one GPS aircraft receiver produced by the Sercel company (France). Pseudoranges and phase observations are recorded. Aerial photographs on the scale of 1 : 4000 are taken. The photo flight comprises of 12 strips, which cover an area of 4 km x 4 km. There is a considerable number of ground control and check points signalled in the area, which have been measured with high precision using both conventional geodetic methods and also GPS.

2. Photo flights over the test areas Mindelheim and Münster. The flights will be carried out by the DFVLR using the GPS receiver developed at the Institute of Navigation at the University of Stuttgart within the framework of the Interdisciplinary Research Group " Precise Navigation ". Pseudorange observations will be recorded.
The flight over the test area Mindelheim will take place in the aerial photo scale of 1 : 20 000 with double coverage (8 strips W.E., 10 strips N.S.). The test area was arranged by the University of the Federal Armed Forces Munich and in cooperation with the Bayrisches Landesvermessungsamt. The test area with a dimension of 25 km x 33 km contains a considerable number of signalled ground control- and check points.
The flight over the area of Münster in Nordrhein-Westfalen is comprised of 5 parallel strips each measuring 50 km in length with 60 % forward and side overlapping. The planned photo scale is 1 : 22 000. The coordinates of the ground control- and check points will be taken from the ground control field for orthophotos established in Nordrhein-Westfalen. The accuracy of these ground control points is in the order of 20 cm.

The flight in the Netherlands was already carried out in June of this year, the flight over the test areas of Mindelheim and Münster are scheduled for July of this year.

The subsequent investigations contain the analysis of the recorded GPS observations with respect to the accuracy and systematic effects. The testing of the accuracy hereby takes place using aerial triangulation. The project in the Netherlands aspires to a high degree of accuracy (1 dm) and is primarily used for the analysis of the GPS phase measurement. The flights over Mindelheim and Münster are to point out the potential of pseudorange observations. An accuracy of a few meters is expected.

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ABSTRACT

The orientation of aerial photographs was based up to now on the indirect determination of the exterior orientation elements using ground control. The satellite-based NAVSTAR GPS (Navigation System with Time and Ranging Global Positioning System) offers in the future the possibility of determining parameters of the exterior orientation, which can be introduced into the combined bundle block adjustment as additional observations, whereby an extreme reduction of the necessary ground control points will be possible.

In a review of performed simulations the effect of observed orientation parameters on point accuracy and ground control in photogrammetric blocks is shown on the one hand, and on the other hand, the accuracy requirements are summarized, which the camera positions determined with GPS have to fulfil to enable their application as additional observations in the combined bundle block adjustment for small- through to large-scale mapping. A draft for the inclusion of GPS in aerial triangulation is briefly described, as well as the problems arising thereby.

The main point of interest of this paper is formed by the presentation of the GPS observation types, of their accuracy potential, the systematic effects and the evaluation model for GPS observations developed therefrom. A result of first analyses of GPS pseudorange observations carried out with this model is presented and its importance for aerial triangulation is discussed.

DAS NAVSTAR GLOBAL POSITIONING SYSTEM FÜR DIE AEROTRIANGULATION

ZUSAMMENFASSUNG

Die Orientierung von Luftbildern beruhte bisher auf der indirekten Bestimmung der äußeren Orientierungselemente mit Hilfe von Paßpunkten. Das satellitengestützte NAVSTAR GPS (Navigation System with Time and Ranging Global Positioning System) bietet in Zukunft die Möglichkeit, Parameter der äußeren Orientierung zu bestimmen, die als zusätzliche Beobachtungen in die gemeinsame Bündelblockausgleichung eingeführt werden können, wodurch eine extreme Reduzierung der Paßpunkte ermöglicht wird.

In einem Rückblick auf durchgeführte Simulationen wird zum einen die Wirkung beobachteter Orientierungsparameter auf Punktgenauigkeit und Paßpunktanordnung in photogrammetrischen Blöcken gezeigt, zum anderen werden die Genauigkeitsanforderungen an die mit GPS bestimmten Kamerapositionen für ihre Verwendung als zusätzliche Beobachtungen in der gemeinsamen Bündelblockausgleichung bei klein- bis großmaßstäbigen Aufgabenstellungen zusammengefaßt. Ein Konzept zur Einbeziehung des GPS in die Aerotriangulation, sowie die dabei auftretenden Probleme werden in groben Zügen beschrieben.

Schwerpunkt des Berichtes bildet die Darstellung der Beobachtungstypen des GPS, deren Genauigkeitspotential, die systematischen Einflüsse und das daraus entwickelte Auswertemodell von GPS-Beobachtungen für die Aerotriangulation. Ein Ergebnis erster Analysen von GPS-Pseudorangebeobachtungen mit diesem Modell wird dargestellt und dessen Bedeutung für die Aerotriangulation diskutiert.

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