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GPS-supported aerial triangulation - state of the art

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Abstract

Utilization of GPS-derived coordinates of the perspective centers in aerial triangulation is discussed. It is shown how to integrate these coordinates in the bundle block adjustment. Operational rules for treatment of practical problems are outlined in detail. A brief discussion of the expected accuracy level is also included.

1. Introduction

In photogrammetric work it usually is necessary to connect the models to a reference frame, traditionally a ground coordinate system (absolute orientation). This connection is often established by using control points, points with known coordinates in the reference frame. To get a reliable result of the absolute orientation, each model should contain at least five such points. The control points are normally determined in the reference frame by traditional geodetic methods. If the project involves several models, the required number of control points increases rapidly. Then it is more convenient to determine passpoints by an aerial triangulation and replace the control points with these.

When the absolute orientation of a model is finished, the images have been brought to their original positions and orientations, the situation of exposure is reconstructed. This reconstruction is done in two steps, interior and exterior orientation. The unknown parameters of the interior orientation are usually determined in a laboratory calibration of the camera. Exterior orientation has six unknown parameters. These are the image station coordinates in the ground coordinate system (X_0,Y_0,Z_0) and the three angles (φ,ω,κ) for the rotation of the image in the same reference frame. These six unknowns are often estimated in an aerial triangulation, either directly or later by using passpoints (tiepoints) from the same block adjustment. As described earlier, these passpoints are used when transforming a model to the ground coordinate system. Prior to this, the model is established by relative orientation of two images.

A photogrammetric block adjustment requires some ground control points, distributed in the block area according to certain rules. These are targeted points with known coordinates in the ground coordinate system. Targeting and surveying these points may require extensive, time and cost demanding field work.

If it were possible to measure all six parameters of the exterior orientation at the time of exposure, both fieldwork and block adjustment could be eliminated. It is readily seen that this means great savings in terms of time and money. This has been one of the biggest challenges for photogrammetry. Several methods have been suggested (ANDERSEN 1992 p. 4), but they have been either too expensive, incomplete or inaccurate.

GPS offers new possibilities to decide some of the exterior orientation parameters. Today it is possible to measure the exposure station coordinates (X_0,Y_0,Z_0) in an efficient and accurate manner with this technology. A weakness with the method is the inability to determine the angles (φ,ω,κ) with an acceptable accuracy. The aerial triangulation therefore, can not be eliminated. But, by knowing X_0,Y_0,Z_0 for all the images, it is possible to reduce the number of ground control points to a minimum (e.g. points in the block corners only). The GPS derived coordinates of the perspective centers can replace most of the ground control points in the block adjustment. An intuitive explanation is that the perspective centers can be regarded as ground control points, which have been moved up into the air.

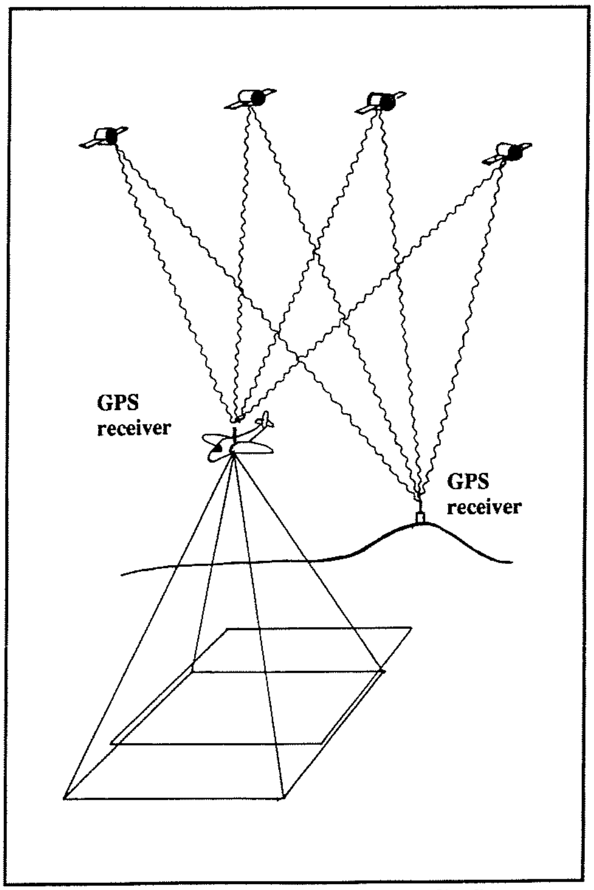


Figure 1 *Relative kinematic GPS*

As mentioned above, GPS is a method well-suited for deciding the coordinates of the perspective centers. For high precision applications, as block adjustment, relative techniques using the phase observable must be used. Two GPS-receivers are required. One of them is placed on a known site, and the other is carried in the aircraft during the photo mission. During the flight the two receivers observe carrier-phase data at the same rate. By postprocessing, using e.g. single or double differences, it is possible to obtain a few cm accuracy on the estimation of the exposure station coordinates (e.g. HOFFMAN-WELLENHOF/LICHTENEGGER/COLLINS 1992). However, several complicating factors must be considered before this accuracy level is obtained. It is necessary to correct for the spatial offset between the GPS-antenna and the entrance nodal point of the camera, and the time offset between the GPS-observations and each exposure. In addition, it is necessary to detect and correct the cycle slips in the phase observations, and the unknown ambiguities have to be determined. In addition, the result from the GPS-adjustment normally should be transformed from WGS84 to the local ground coordinate system.

The factors mentioned above will be discussed in the following sections. But first I will explain how to integrate GPS-derived exposure station coordinates with the bundle block adjustment.

2. Bundle block adjustment

Inputs to the bundle block adjustment are, traditionally, image coordinates and coordinates of ground control points, while the estimated parameters are six exterior orientation parameters for each image and X, Y and Z for all tiepoints (passpoints). It is also possible to include estimation of interior orientation in the same adjustment.

The mathematical model for bundle block adjustment is:

$$\begin{aligned} x_{ij} + v_x^{ij} &= x_0 - c\,\frac{r_{11}^j(X_i - X_0^j) + r_{12}^j(Y_i - Y_0^j) + r_{13}^j(Z_i - Z_0^j)}{r_{31}^j(X_i - X_0^j) + r_{32}^j(Y_i - Y_0^j) + r_{33}^j(Z_i - Z_0^j)} \\ y_{ij} + v_y^{ij} &= y_0 - c\,\frac{r_{21}^j(X_i - X_0^j) + r_{22}^j(Y_i - Y_0^j) + r_{23}^j(Z_i - Z_0^j)}{r_{31}^j(X_i - X_0^j) + r_{32}^j(Y_i - Y_0^j) + r_{33}^j(Z_i - Z_0^j)} \end{aligned} \qquad (1)$$

x_{ij}, y_{ij}	, Image coordinates of point P_i in image j.
v_x^{ij}, v_y^{ij}	, Residuals in x_{ij} and y_{ij}.
x_0, y_0	, Image coordinates of the principal point.
c	, Focal length.
X_i, Y_i, Z_i	, Ground coordinates of point P_i.
X_0^j, Y_0^j, Z_0^j	, Coordinates of perspective center PC_j in the ground coordinate system.
$r_{11}, \ldots, r_{33}$	, Elements in an orthogonal rotation matrix composed of non-linear functions of the three angles $\varphi_j, \omega_j, \kappa_j$.

In the block adjustment it is common to treat the coordinates of the ground control points as stocastical variables. Then a priori coordinates are treated as observations with proper weights.

For each ground control point, P_i, we apply these observation equations:

$$\begin{bmatrix} X_G \\ Y_G \\ Z_G \end{bmatrix}_i + \begin{bmatrix} v_X \\ v_Y \\ v_Z \end{bmatrix}_i = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_i \qquad (2)$$

X_G, Y_G, Z_G	, A priori coordinates of point P_i in the ground coordinate system, e.g. estimated in a network adjustment.
v_X, v_Y, v_Z	, Residuals in X_G, Y_G and Z_G.
X, Y, Z	, Estimated ground coordinates of point P_i in the block adjustment.

If GPS-derived coordinates of the perspective centers are available, further observation equations have to be included in the adjustment.

For each perspective center, PC_j, we apply these equations:

$$\begin{bmatrix} X_{0_{GPS}} \\ Y_{0_{GPS}} \\ Z_{0_{GPS}} \end{bmatrix}_j + \begin{bmatrix} v_X \\ v_Y \\ v_Z \end{bmatrix}_j = \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix}_j \qquad (3)$$

$X_{0_{GPS}}, Y_{0_{GPS}}, Z_{0_{GPS}}$, Coordinates of perspective center PC_j, estimated in a GPS-adjustment.
v_X, v_Y, v_Z , Residuals in $X_{0_{GPS}}$, $Y_{0_{GPS}}$ and $Z_{0_{GPS}}$.
X_0, Y_0, Z_0 , Coordinates of perspective center PC_j, estimated in the block adjustment.

In this sections the bundle block adjustment was discussed, but it is possible to integrate the GPS-derived exposure stations coordinates in the method with independent models as well.

3. Spatial offset

One complicating factor is that there is a spatial offset between the aircraft GPS-antenna and the perspective center. In relation to the ground coordinate system, this offset varies with the rotations between the camera and the aircraft, and between the aircraft and the ground. It is possible to correct for this offset in the block adjustment if the camera is fixed to the aircraft during the photo mission. The offset will then depend on the rotations of the camera in the ground coordinate system (φ, ω, κ) only. These rotations are estimated in the bundle block adjustment. Figure 2 illustrates the situation.

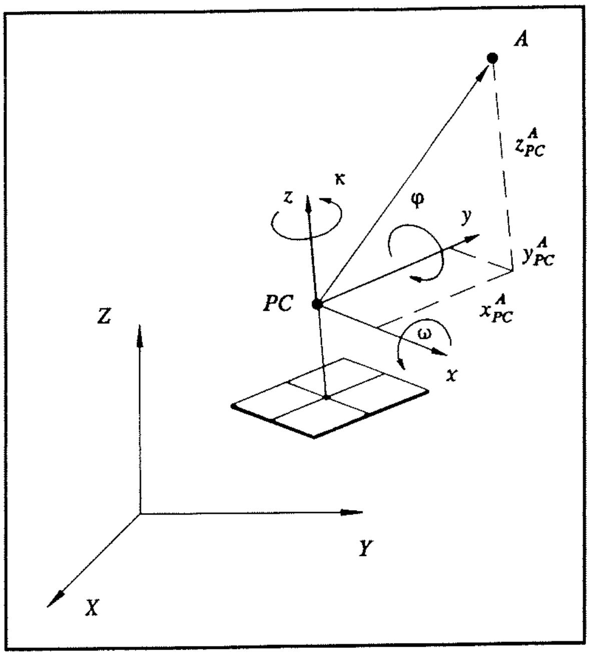


Figure 2 *Spatial offset (A = antenna, PC = perspective center)*

Correction for the spatial offset in the block adjustment (by using (φ, ω, κ) requires that the eccentricity vector is known in the image coordinate system. There are several different methods available for the determination of this vector. One method is based on terrestrial photogrammetry (SCHWIERTZ/DORRER 1991). Accuracies better than ± 1 cm is achievable with this method. Another possibility is to use normal survey techniques, e.g. theodolite and tape. This method is based on intersections from sites surrounding the aircraft (see figure 3). Horizontal directions, zenith distances and distances are measured from each site. The vector from the principal point to the antenna phase center is estimated in a network adjustment where the fiducial marks define the image coordinate system. Simple algebra brings us from this vector to the sought vector from the nodal entrance point to the antenna.

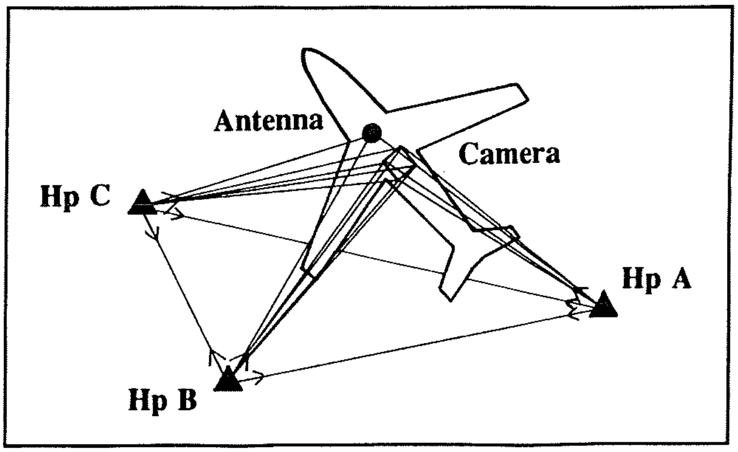


Figure 3 *Determination of the spatial offset*

In the project "USE OF GPS IN AERIAL PHOTOGRAMMETRY", which is carried out at the Department of Surveying, the eccentricity vector was estimated with the theodolite method. The estimated standard deviation was 1 mm in x- and y-, and 2 mm in z coordinates. In our case the GPS-antenna was mounted on the fuselage, almost directly above the camera. Another antenna was mounted on top of the aircraft tail-fin. The vector to this tail-fin antenna was measured with an accuracy of 14 mm in x- and y-, and 2 mm in z coordinates.

The offset of the GPS-antenna position is handled in the block adjustment by modifying equations (3). In these observation equations the antenna coordinates are treated as observations instead of the exposure station coordinates. The new observation equations are:

$$\begin{bmatrix} X_{A_{GPS}} \\ Y_{A_{GPS}} \\ Z_{A_{GPS}} \end{bmatrix}_j + \begin{bmatrix} v_X \\ v_Y \\ v_Z \end{bmatrix}_j = \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix}_j + R(\varphi,\omega,\kappa)_j \cdot \begin{bmatrix} x_{PC}^A \\ y_{PC}^A \\ z_{PC}^A \end{bmatrix} \tag{4}$$

$X_{A_{GPS}},Y_{A_{GPS}},Z_{A_{GPS}}$	, GPS-antenna coordinates of image j.
v_X,v_Y,v_Z	, Residuals for $X_{A_{GPS}}$, $Y_{A_{GPS}}$ and $Z_{A_{GPS}}$.
X_0,Y_0,Z_0	, Coordinates of perspective center PC_j.
$R(\varphi,\omega,\kappa)_j$	, Orthogonal rotation matrix composed of non-linear functions of the three angles $\varphi_j,\omega_j,\kappa_j$.
$x_{PC}^A,y_{PC}^A,z_{PC}^A$	, GPS-antenna coordinates in the image coordinate system.

One disadvantage of this concept is that the camera has to be fixed to the aircraft. Consequently the crab-settings have to be kept constant during the flight. This limitation is not necessary if the crab-settings can be recorded, either manually or automatically. In the future this registration might be done by a stabilization camera mount.

If the GPS-antenna is mounted directly above the camera, the crab angle will hardly affect the eccentricity vector (ACKERMAN 1992). Tilt corrections of the camera will still change the offset vector. The effect of the tilt corrections is small with this antenna position, but not neglectable for large image scales.

4. Time offset

During flight, relative kinematic GPS-positioning gives the GPS-antenna position in a sequence defined by the measuring rate of the GPS-receivers, e.g. once per second. The camera positions are sought at moment of exposure, or to be more precise, at the mid-time of exposure. If the camera runs independently of the GPS-receiver, an offset from the sought position occurs. The situation is illustrated in figure 4.

The problem can be solved in three possible ways:

- The measurement in the GPS-receiver is released by a mid-exposure pulse from the camera.
- The mid-time of exposure is recorded, and the sought position is estimated trough interpolation between the GPS-positions.
- The shutter of the camera is released by a pulse from the GPS-receiver. The time offset is then eliminated or at least minimized.

The first method is not realistic, because there does not exist any GPS-receiver capable of performing measurements at specific epochs. It would also be difficult to obtain simultaneous observations from the two GPS-receivers. This is a requirement when the postprocessing software is based on single or double differences.

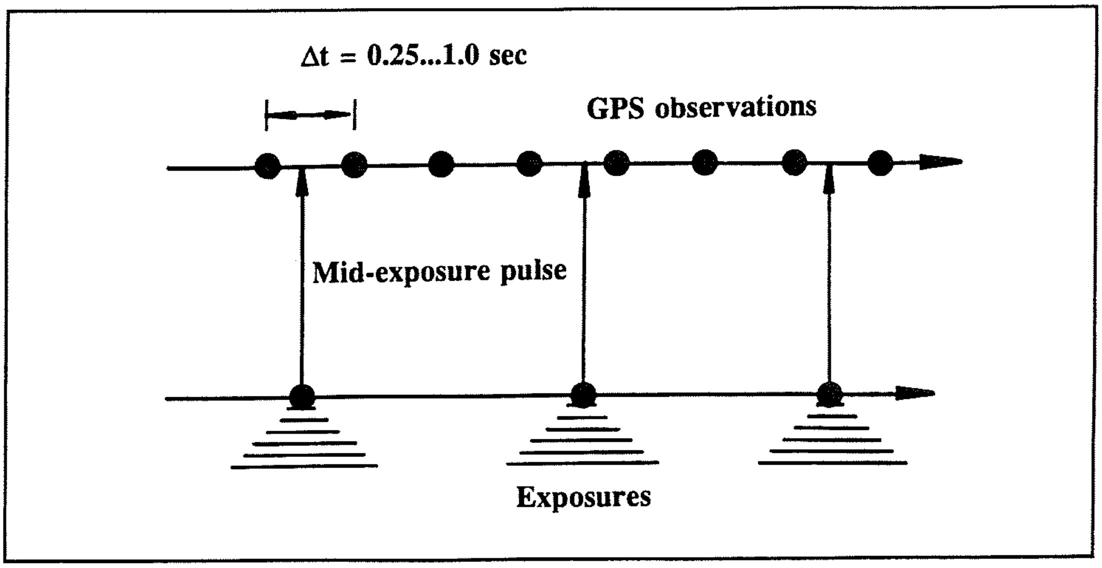
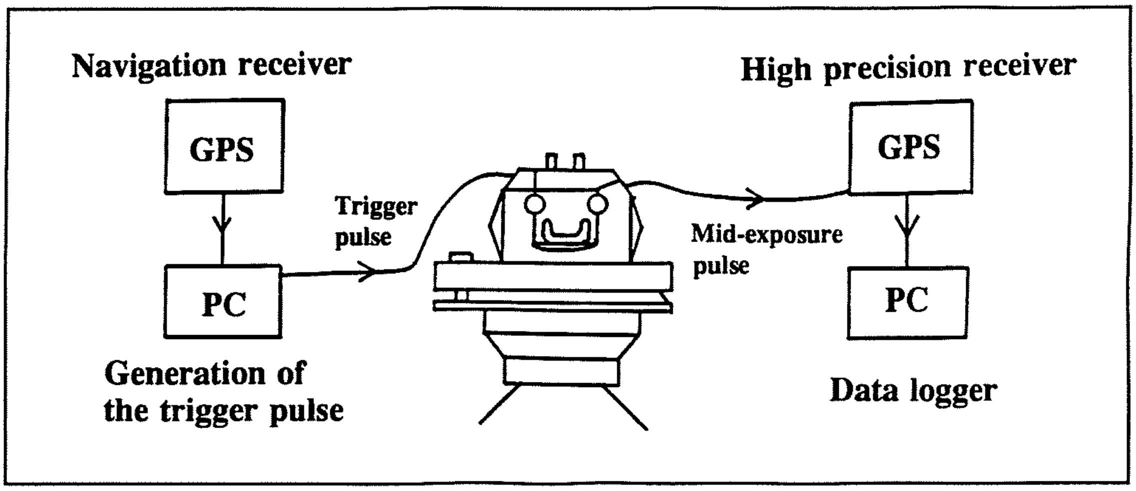


Figure 4 *Time offset*

The second method demands that each exposure is recorded in the time-frame of the GPS-receiver. Modern cameras are designed to emit a very accurate pulse at the mid-point of exposure. In the Wild RC20 camera this emitted pulse has a maximal deviation of ± 52 µs from the exact mid-point of exposure. In a ground speed of 100 m/s this will result in an neglectable 5 mm forward motion. The emitted pulse is sent to the GPS-receiver and recorded in the time-frame of the receiver. In this way it is guaranteed that the time-tags of exposure and the GPS-observations are referred to the same time frame. This time tagging of the mid-exposure pulse is only possible if the GPS-receiver has a photogrammetry option. In the project "USE OF GPS IN AERIAL PHOTOGRAMMETRY" one Ashtech M XII-P receiver equipped with this photogrammetry option was used, courtesy by the Finnish Geodetic Institute.

The sought antenna positions can be found easily by interpolating the closest GPS-positions. Several interpolation formulas have been suggested, e.g. ordinary linear interpolation (ACKERMAN 1992) or Lagrange interpolation of third order (FRIEß 1991). The maximal data rate for the newest GPS-receivers is twice a second. Assuming an aircraft ground speed of 100 m/s, this means that the camera moves 50 m between two GPS-registrations. It is readily seen that the interpolated position may deviate several cm from the true position because of the this wide interpolation interval. It is possible to improve the result if the camera is triggered close to a GPS-registration.

Several GPS-receivers can emit a pulse, which can be used to trigger a camera. A limitation is that the pulse is emitted at a constant rate. In aerial photogrammetry, constant overlap is usually required within the strips. This is only achievable if it is possible to vary the time interval between two subsequent exposures. The need for variation of the interval is caused by variations in the ground speed of the aircraft and the terrain heights.



Figur 5 *Recommended instrumentation*

If the camera is connected to a navigation system based on GPS (e.g. code measurements), it is also possible to assure proper overlap between the images. The navigation system will combine the camera position with other information (flight plan, elevation model, etc.) and decide when to trigger the camera. The trigger-pulse is emitted simultaneously with the closest GPS-registration. The camera performs the exposure and emits the mid-exposure pulse to the GPS-receiver for recording. This is necessary because the unsynchronized clocks in the two GPS-receivers and the delay in the camera shutter still makes interpolation necessary. But the small deviation between a GPS-registration and the time of exposure will cause only neglectable errors in the interpolated position.

For use in the navigation system, an inexpensive GPS-receiver will be sufficient. But for the actual positioning of the camera, a precise geodetic dual frequency receiver should be used. Observations are carried out almost simultaneously (within a few milliseconds) in the two receivers, as both are synchronized to GPS-time (through the satellite clocks).

5. Problems in relative kinematic positioning

Before positioning by use of carrier phase observations is possible, the initially unknown integer number of cycles from the receiver to the satellites (ambiguities) must be determined (e.g. HOFFMAN-WELLENHOF/LICHTENEGGER/COLLINS 1992). In relative kinematic GPS-positioning several methods are available for this ambiguity resolution.

The following methods are suitable when the antenna is fixed on an aircraft:

- Static initialization by a known vector, prior to the aircraft leaving the airport.
- Static determination of the vector from the reference station to the aircraft antenna.
- Determination of the ambiguities while the aircraft is moving ("on the fly ambiguity resolution").

In the first method, the aircraft must be placed on a site with known coordinates. Since the vector from the reference receiver to the aircraft is known, only a few observations are necessary to solve for the ambiguities. The accuracy of this fixed baseline must be better than 6-7 cm to obtain a reliable result.

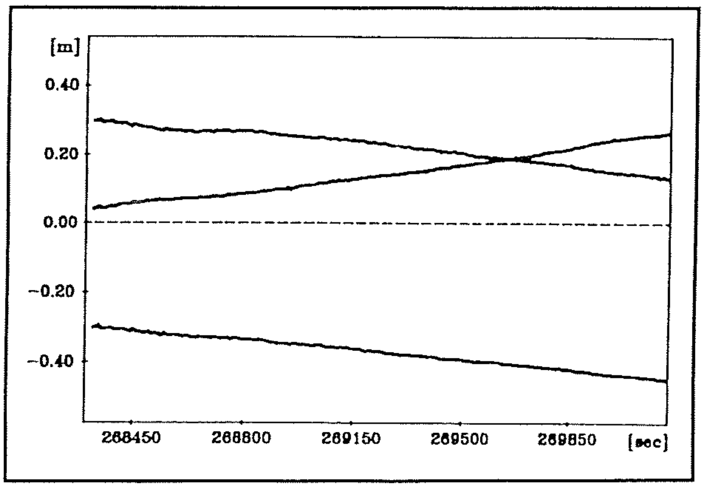
The second method is based on a traditional static solution of the unknown vector from the reference station to the aircraft. The observation time-span will vary from five minutes to two hours, depending on the length of the vector, receiver type, available software, satellite geometry and ionospheric disturbances.

There are several weaknesses with both the above methods. They are time demanding and cumbersome, and they require that GPS-registration begins at the airport. If the photo-area is far from the airport, this is unpractical because of the huge amount of GPS-data being collected (approximately 7 megabyte per hour). These methods are also vulnerable to cycle slips or loss of lock. There exists several methods for cycle slip correction (e.g. ØVSTEDAL 1992), but their functionality is limited.

Many of the described problems could be avoided if it were possible to perform the ambiguity resolution while moving. Much attention has been paid to this subject for years, and several algorithms have been proposed (ØVSTEDAL 1992). Some of these algorithms require additional information from P-code observations. A common limitation for most of the algorithms is that 10-15 minutes of continuous phase measurements is necessary to achieve a solution.

There is always a risk that the initial ambiguity resolution might be wrong, or that cycle slips will occur, which are impossible to correct (e.g. receiving signals from < 4 remaining satellites). In kinematic applications it is sometimes difficult to detect errors in the estimated ambiguities. But the navigated position will, of course, be falsified if the ambiguities are incorrect determined.

Figure 6 illustrates how the estimated coordinates are falsified due to incorrect constrained ambiguities (SCHADE 1992). The solution deviates from the true value. This deviation is not constant, but changes over a period of time. The drift is explained by the false conditions introduced in the GPS-adjustment by the incorrect ambiguities. During a limited time interval, like 10-15 minutes, this drift error is approximately linear (FRIEß 1991). These systematic errors can be modelled by six parameters, one constant and one time-dependent shift per coordinate. Since the GPS-positions are treated as observations in the block adjustment, it is possible to estimate these six drift parameters.



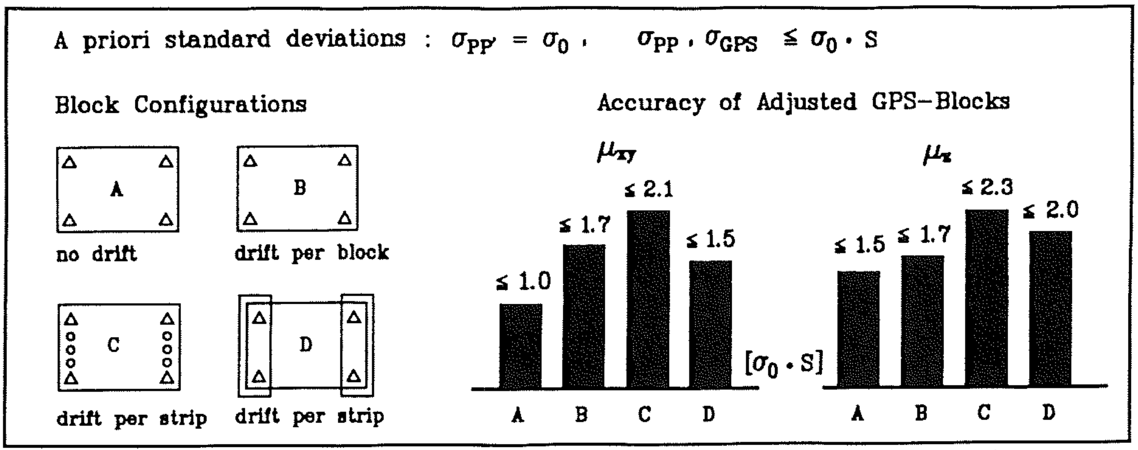
Figur 6 *Systematic error effects due to incorrect ambiguities* (SCHADE 1992)

Cycle slips does often occur when the aircraft is turning, but within each strip this problem is less. It is therefore suitable to introduce one set of drift parameters per strip. The first time this concept was implemented in a block adjustment, was in the Norwegian GAFF-project (ANDERSEN 1989). The drift parameters are included in the block adjustment by further extension of equations (4). We get these new observation equations for the antenna coordinates:

$$\begin{bmatrix} X_{A_{GPS}} \\ Y_{A_{GPS}} \\ Z_{A_{GPS}} \end{bmatrix}_j + \begin{bmatrix} v_X \\ v_Y \\ v_Z \end{bmatrix}_j = \begin{bmatrix} X_0 \\ Y_0 \\ Z_0 \end{bmatrix}_j + R(\varphi,\omega,\kappa)_j \cdot \begin{bmatrix} x_{PC}^A \\ y_{PC}^A \\ z_{PC}^A \end{bmatrix} + \begin{bmatrix} a_X \\ a_Y \\ a_Z \end{bmatrix}_k + dt \cdot \begin{bmatrix} b_X \\ b_Y \\ b_Z \end{bmatrix}_k \qquad (5)$$

$X_{A_{GPS}}, Y_{A_{GPS}}, Z_{A_{GPS}}$	, GPS-antenna coordinates of image *j* in the ground coordinate system.
v_X, v_Y, v_Z	, Residuals in $X_{A_{GPS}}$, $Y_{A_{GPS}}$ and $Z_{A_{GPS}}$.
X_0, Y_0, Z_0	, Coordinates of perspective center PC_j in the ground coordinate system.
$R(\varphi,\omega,\kappa)_j$	, Orthogonal rotation matrix composed of non-linear functions of the three angles $\varphi_j, \omega_j, \kappa_j$.
$x_{PC}^A, y_{PC}^A, z_{PC}^A$	, GPS-antenna coordinates in the image coordinate system.
a_X, a_Y, a_Z	, Time independent translations of strip *k*.
b_X, b_Y, b_Z	, Time dependent translations of strip *k*.
dt	, Elapsed time since start of strip *k*.

The estimation of the drift parameters in the block adjustment will weaken the geometry of the block. To avoid singularity problems, it is necessary to have some ground control points (e.g. points in the block corners). New block configurations may be necessary, e.g. block configuration C or D in figure 7. Simulation studies have shown that block configuration D will be the most accurate, when six drift parameters per strip is allowed (ACKERMAN 1992). Ground control points in the corners of the block, besides one cross strip at each block-end, will be necessary. These cross strips may be substituted by two chains of height control points, but with some loss of accuracy in the tiepoints. If it is possible to correct all cycle slips between strips, six drift parameters for the whole block will satisfy. In that case, cross strips are not needed.



Figur 7 *Theoretical accuracy og GPS supported blocks (results of simulations)* (Frieß 1992)

Figure 7 (Frieß 1991) shows some results from the above mentioned simulation. The simulation was performed with a block of 6 strips each containing 21 images, and the image scale was 1:30000. The accuracy of image coordinates, including the image coordinates of ground control points (PP'), was assumed to be σ_0. For both ground control points (PP) and GPS-derived antenna positions, the accuracy was assumed to be $\sigma_0 \cdot S$ (S = image scale). The accuracy of tiepoints (μ_{XY} and μ_Z), estimated in the combined block adjustment, is given in units of $\sigma_0 \cdot S$. Empirical results from a test flight in Northern-Germany in autumn 1990, confirmed the results from the simulations (Frieß 1991). The achieved accuracies, calculated from true errors in independent checkpoints, were 6.3 cm in X- and Y-, and 8.5 cm in Z coordinates. At image scale 1:8000, this corresponds to 1.3 and 1.7 $\sigma_0 \cdot S$.

In the simulation study, $\sigma_{GPS} \leq \sigma_0 \cdot S$ was assumed. This accuracy is too optimistic for large image scales. An image scale of 1:5000 and σ_0= 5.0 µm leads to σ_{GPS}= 2.5 cm. It is more realistic to assume σ_{GPS}= 5.0 - 10.0 cm (2 - 4 $\sigma_0 \cdot S$). These new assumptions lead to slightly worse results in the block adjustment, but not as bad as the magnification-factor of σ_{GPS}. In Ackerman (1992) it is indicated that even if σ_{GPS}= 10 $\sigma_0 \cdot S$, accuracies like μ_{XY}= 3.5 $\sigma_0 \cdot S$ and μ_Z= 5 $\sigma_0 \cdot S$ can be expected.

In Burman (1992), corresponding simulations were carried out, but with other restrictions. One of the simulations was carried out with image scale 1:5000. Block configuration D in figure 7 was used, but with two ground control points in each corner. This will only slightly improve the geometry, but is a safety measure against gross errors in the ground control points. The a priori standard deviations were: σ_0= 5.0µm, σ_X= σ_Y= σ_Z= 1 cm for ground control points and σ_X= σ_Y= σ_Z= 10 cm for the GPS-positions. Three different block sizes were used (4·13, 6·13 and 6·25 images). The obtained results were 6.5 - 7.5 cm for μ_{XY} and 8.5 - 10.4 cm for μ_Z. This corresponds to μ_{XY}= 2.6 -3.0 $\sigma_0 \cdot S$ and μ_Z= 3.4 -4.2 $\sigma_0 \cdot S$. These results are 1.7 - 2.1 times worse than the results in figure 7.

Inclusion of drift parameters in the block adjustment makes the photo mission much easier. Cycle slips between the strips will no longer cause problems. This means that the pilot does not have to take precautions when turning. Nor is it necessary to determine the unknown cycle ambiguities before leaving the airport. An approximate solution before the first exposure is sufficient. These approximate ambiguities can be calculated from GPS-code observations (Frieß 1990).

6. Datum problems

The GPS-adjustment refers to the global datum WGS84, while the ground coordinate system most often is referred to a national datum, e.g. NGO48 in Norway. The ellipsoids, to which the two datums are related, are most likely different in shape and size. The spatial orientation of the ellipsoids is often well-defined, but even here there might be small differences. A complicating factor is that the network of the local area often has scale and rotation errors, when compared to the national datum. The local network might also be inhomogeneous.

On one hand, the height reference is usually referred to the geoid. On the other hand, the spatial coordinate differences between the reference receiver and the roving receiver are on the other hand, related to the WGS84 ellipsoid. Usually the geoid and the ellipsoid form an angle at the reference site (deflection of the vertical).

As mentioned above, the results from the GPS-positioning are the WGS84 coordinates of the antenna, while the mapping most often is done in the national reference system. It is therefore necessary to transform the antenna coordinates to the mapping system. When having common terrain points with known coordinates in both systems, a possible approach is to use a transformation. Common points in the block-corners is ideal. If the deflection of the vertical is constant within the block-area, the above mentioned problems, except local discrepancies, will be taken care of by a Helmert transformation (seven parameters).

If an a priori transformation of the antenna coordinates is impossible, then it is necessary to include this transformation in the block adjustment. One could think of a further extension of equations (5) by seven more elements, but this would lead to singular or at least near singular normal equations. This is caused by strong correlations between the drift parameters and the transformation parameters (FRIEß 1991).

By estimating one set of drift parameters per strip, the transformation of antenna coordinates will be taken care of by the drift parameters. If only one set of drift parameters is estimated for the whole block, only parts of the transformation are taken care off by the block adjustment.

Some of the above mentioned problems would be eliminated if the ground coordinate system was referred to WGS84. Nevertheless, problems related to the geoid and the discrepancies in the network, would remain.

7. Conclusions

The NAVSTAR Global Positioning System is not yet fully operational, and until recently relative kinematic positioning has been limited to short periods of the day. The method requires at least four available satellites and good geometry, but at least six satellites should be present due to the risk of cycle slips. Even if relative kinematic positioning has been possible in short periods, it has been difficult to carry out the photo mission in these short periods. These problems will be reduced when new satellites are launched.

By choosing block configurations that can handle cycle slips between the photo-strips (see figure 7), it is possible to perform GPS-supported aerial triangulation with a minimum of ground control points. If the accuracy of the remaining ground control points is good, it is possible to achieve sufficient accuracy for all common image scales.

Software presently exists for both the kinematic GPS-processing and the GPS-supported block adjustment. Software for kinematic GPS-processing has existed for years, and improved versions are constantly being developed. Regarding block adjustment, software packages now include GPS-derived camera positions, and some of them also allow for inclusion of drift parameters.

From the above description one can conclude that GPS-supported aerial triangulation is possible under certain conditions. Several problems, however, remain unsolved, and further research is necessary. It is necessary to investigate how critical the quality of the remaining ground control points is for the block adjustment result. Another question not yet answered, is how far the reference station can be from the photo-area. Present practice is to place the reference receiver within the photo area, which is a an inconvenient restriction. Concerning the GPS-positioning, more robust methods for ambiguity resolution and cycle slip corrections should be developed.

8. Acknowledgement

The Finnish Geodetic Institute most kindly lent us two Ashtech XII P-code receivers last spring. The receivers were freely placed at our disposal, for two weeks during a test flight in the project "USE OF GPS IN AERIAL PHOTOGRAMMETRY". Their cooperation is highly acknowledged.

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