Exterior Orientation Parameters

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The georeference of any photogrammetric product is based on the reconstruction of the geometric relations of imaging in a chosen object coordinate system. For the handling of aerial photos traditionally the bundle of rays from the image points over the projection center to the ground points is modelled by means of the camera calibration information and the exterior orientation determined by means of control points. Today the time consuming ground survey of control points can be reduced by block adjustment or even more by combined block adjustment with projection center coordinates from relative kinematic GPS-positioning. It is also possible to avoid control points like the measurement of image coordinates of tie points by direct sensor orientation with a combination of GPS and an inertial measurement unit (IMU).

1. Interior Orientation

The interior orientation is required for the reconstruction of the bundle of rays – the location of the projection center has to be known in relation to the image points together with the geometric influence of the lens system. The calibration certificates of the camera manufacturers are including the location of the principal point, the focal length and the radial symmetric lens distortion. This is sufficient for the traditional handling of single models because the remaining differences against the mathematical model of perspective geometry are small. The mathematical model of perspective geometry is expressed by the colinearity equation – image point, projection center and ground point are located on a straight line and the photo is exactly plane. Even if the radial symmetric lens distortion, earth curvature and refraction correction are respected, this is only an approximation. The tangential distortion, caused by not centric location of the lenses in relation to the optical axis of the lens system is not investigated by the manufacturers and the image is not located in a strict plane surface. In addition the focal length may be influenced by the air temperature, the air in front of the camera may cause a deformation of the bundle of rays and the photos may be deformed by the developing process. The caused small deviations against the mathematical model may sum up in the case of a block adjustment with only a reduced number of control points, resulting in a deformation of the block. Especially the height is sensitive for such effects. In a bundle block adjustment with self calibration by additional parameters the difference between the mathematical model and the real image geometry can be determined as so called "systematic image errors". But the systematic errors are changing from photo flight to photo flight and even from film cartridge to film cartridge, so they have to be determined for every individual block. Small changes of the focal length and the location of the principal point are compensated by the exterior orientation – this is not possible for the direct sensor orientation, so together with the boresight misalignment also the inner orientation has to be determined.

Photo coordinates cannot be measured directly, with analytical plotters plate coordinates are available and digital plotters are delivering the pixel addresses of the scanned photos. The photo coordinates are computed by a transformation of the measured to the calibrated positions of the fiducial marks. The film shrinkage, different in both directions and also angular affinity are requiring an affine transformation. A higher degree of transformation is not necessary and is even decreasing the accuracy. Digital cameras equipped with an area CCD do not have fiducial marks, image coordinates can be computed by a multiplication of the pixel addresses with the pixel size and a shift to the principal point. The multiplication with the pixel size should also respect the definition of the system of axis – pixel addresses do have usually the origin in the upper left corner and the row is counting downwards, photo coordinates do have the y-coordinates from the principal point counting upwards. Area CCD's do have usually a very stable geometry, not requiring self calibration parameters for the image plane.

2. Exterior Orientation

2.1 Reference System

The exterior orientation describes the location and orientation of the bundle of rays in the object coordinate system with the 6 parameters: projection center coordinates (X0, Y0, Z0) and the rotations around the 3 axis (omega, phi and kappa). The definition of the rotations has to be respected, most often the successive rotations with the sequence omega, phi, kappa or phi, omega, kappa are used. A transformation from one rotation system to the other can be made – the angular values are different, but the numerical values of the corresponding rotation matrix are identical. As object coordinate system usually the national net coordinate system is used, even if it is not corresponding to the mathematical model. The national net coordinates are following the curved earth, so it is not orthogonal. The difference between the curved reference system and the mathematical model can be respected with a change of the image coordinates by the earth curvature correction. This is sufficient for small and medium blocks, for large blocks and the direct sensor orientation second order effects are causing a loss of accuracy and the handling in an orthogonal coordinate system like a tangential system to the earth ellipsoid should be preferred. The net projection has a scale which is different from location to location. Such scale differences are compensated by the exterior orientation for the horizontal coordinates; for the vertical component it is causing an affine deformation, which should be respected for the combined adjustment and the direct sensor orientation.

The national coordinate systems are mixed systems – the horizontal coordinates are defined by the map projection, the height is related to the geoid. Geoid undulations can be neglected for usual block adjustments, but it has to be respected for the height determined by GPS which is related to the WGS84-ellipsoid.

2.2 Classic Model Orientation

The classic model orientation will been done in 2 steps with the relative and absolute orientation. The 2 x 6 = 12 orientation unknowns for a model of 2 images are separated to 5 unknowns for the relative orientation and 7 unknowns for the similarity transformation of the model to the ground coordinates. By the relative orientation one image is oriented to the other enabling an intersection of corresponding rays. After relative orientation a stereoscopic view to the model is possible. Based on the orientation elements of the relative orientation, model coordinates can be computed by intersection. The absolute orientation of the model is a three-dimensional similarity transformation of the model to control points. For the 7 unknowns (3 shifts, 3 rotations, scale), at least 3 vertical and 2 horizontal control points are required. The model orientation is an optimal fit of the images to the ground coordinates in the model area, it is also compensating several remained errors described before. As disadvantage we do have the high number of required ground control points and also problems of the geometric fit of neighboured models. Both problems can be reduced by a block adjustment.

2.3 Block Adjustment

The orientations of all images of a whole block can be determined together with the ground coordinates by a bundle block adjustment. The block adjustment by independent models, based on a simultaneous three-dimensional transformation (or iterative horizontal and vertical transformation) of the models together and to control points is not any more the state of the art because with the same effort it is not resulting in the same accuracy like the bundle block adjustment. The bundle block adjustment is using with the image coordinates the original observations for the adjustment. The mathematical model is based on the colinearity equation improved by additional unknowns for modelling the "systematic image errors". Of course statistical tests should be used to exclude additional parameters which are not significant.

The standard block configuration is including strips of images with approximately 60% overlap in the flight direction and 20% - 30% overlap of the neighboured flight strips. For the three-dimensional determination any ground point is required at least in 2 images. This could be done also with 50% endlap, but for the navigation tolerance and also for the block geometry 60% are needed. Without points located in the threefold overlap and also measured in 3 images within a flight strips, the block is not stable in the Z-direction. Neighboured flight strips have to be connected with common tie points. For such a block geometry horizontal control points are required only at the periphery of the block with a distance of approximately 4 – 6 base length (base length = distance of 2 neighboured projection centers in the flight direction). Vertical control points are required also inside the block. Lines of vertical control points perpendicular to the flight direction, with a distance of the lines of approximately 4 base length and within the lines with a vertical control point in approximately every overlap of the flight lines and at the periphery are required. The amount of vertical control points only can be reduced with crossing flight strips. If they are available, the distance of the control points in the lines can be extended to 4 base length.

With such a configuration as rule of thumb the same ground accuracy like in a direct oriented model can be reached, that means the standard deviation of the ground points are SX ~ SY ~ scale number x accuracy in the image and SZ ~ SX x flying height / base.

The image orientations determined by bundle orientation should be used directly – or transformed to the required definition – for the orientation of the models which have to be used for the data acquisition in a GIS or for other details. This includes the advantage of an optimal fit of the neighboured models and avoids additional effort for the model orientation.

2.3 Combined Block Adjustment with Projection Center Coordinates

Even if the number of control points needed for a block adjustment is quite smaller like for the direct orientation of every model, the ground survey of the control points is still time consuming and in some special cases with limited access to the area it may be also difficult. The use of projection centers determined by relative kinematic GPS-positioning can reduce this problem. By GPS the position of the antenna on top of the aircraft will be determined, which is not identical to the projection center. So the lever arm from the antenna to the entrance node of the camera has to be determined and respected.

By theory a block of images including at least 2 flight strips can be handled also without ground control points, but the kinematic GPS-positioning includes the problem of the ambiguity solution. The phase of the GPS-signal can be measured, but the number of full waves has to be estimated. A distance error of one or even more wavelength to the satellite causes a position error which in first order is constant, in the second order linear time depending. By this reason constant or sometimes, especially in the case of a poor PDOP linear time depending position errors cannot be avoided. During the turn around from one flight line to the next, the contact to some satellites can be lost and the ambiguity has to be estimated again. By this reason systematic GPS-position errors have to be expected which are different from flight strip to flight strip,. Such position errors have to be determined by the combined block adjustment with projection center coordinates. For every flight strip shifts in X, Y and Z have to be introduced as unknowns. With the current number and distribution of GPS-satellites not so often linear time depending errors are available, but corresponding unknowns should be included together with statistical tests for the exclusion of not required unknowns. Such unknowns can only be determined by means of control points. If no crossing flight lines are available, at the begin and end of every flight line at least a vertical control point is required and full control points at every corner of the block. If crossing flight lines at the end of the flight lines are available, it is sufficient to have only control points at the corners of the block. Long flight lines at the block periphery should be stabilised with full control points every 20 base length to avoid a rotation of the flight lines around the line of projection centers.

2.4 Direct Sensor Orientation

With the progress of the inertial measurement units also a direct determination of the image orientation is possible without use of control points and photo coordinates. An IMU is a combination of gyros and accelerometers. As gyros today the fiber optic gyros are preferred. The double integration of the acceleration together with the directions from the gyros leads to coordinate differences, that means from a known start point to absolute positions. But the IMU has only a good short time accuracy, it is affected by strong drifts; as stand alone system it is not sufficient, it has to be combined with the good absolute accuracy of relative kinematic GPS. By iterative Kalman filtering both positioning systems are combined, this has also advantages for the GPS-positions because it is not any more degraded by a loss of reference during the turn around, the short time accuracy of IMU is avoiding this. The attitude information can be available with a frequency of up to 200 Hz, so even under turbulent conditions the direct sensor orientation can be used.

The IMU, fixed to the camera body, is generating roll, pitch and yaw of the IMU axis, but camera orientations are required. So the attitude relation between the IMU and the camera has to be determined by a so called boresight calibration. Usually a small test field with control points is used for the traditional determination of the exterior camera orientation and the IMU-orientation information is compared with this. Of course the different attitude definition has to be respected.

In principal the object determination based on direct sensor orientation is an extrapolation from the projection centers to the ground coordinates - this is opposite to the other methods of photogrammetric orientation where we do have an interpolation within the frame of control points. By this reason for a precise point determination by means of direct sensor orientation all possible sources of errors have to be taken into account. This includes also the inner orientation, especially the focal length which may not be identical to the calibration under laboratory conditions. The influence of a shift of the projection center in Z-direction cannot be separated from the change of the focal length if the reference flight will be made only in one flying height, so for a full system calibration a flight in two different height levels over the test field is necessary, resulting in the attitude relation between IMU and camera, shifts of the projection centers in X, Y and Z and also the determination of the actual focal length and location of the principal point. It is also possible to include systematic image errors.

Based on such a boresight misalignment together with the improved camera calibration a standard deviation of the ground coordinates in the range of +/-0.1m - +/-0.2m can be reached with large scale images. No problems are existing with the orthophoto generation in any scale based on direct sensor orientation, but there are still some problems with the y-parallaxes in models orientated by such information. A combined adjustment of the image orientation together with image coordinates of tie points, but without control points, is solving this problem.