GEOMETRIC CORRECTION OF AIRBORNE WHISKBROOM SCANNER IMAGERY USING HYBRID AUXILIARY DATA

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ABSTRACT

This paper proposes the main aspects that must be considered for the development of a general concept for the geometric correction of airborne whiskbroom scanner imagery making use of hybrid auxiliary data. This may be the three-dimensional coordinates defining the sensor's position, the angles of the line-of-sight rays according to the axes of the three-dimensional reference system, a digital elevation model, the availability of orthoimages that can be used as a reference, interior orientation parameters and last but not least ground control information. All these information has to be treated in its specific accuracy context. The aim is to respond to the needs of a user who wants to get the best geometric correction results. The general concept for the geometric correction of whiskbroom scanner imagery regards all auxiliary information that can theoretically be available. This development is based on practical cases where airborne whiskbroom imagery has been captured. The concept tries to classify the reachable accuracy levels due to the given auxiliary data in a particular case.

1 INTRODUCTION

There is an increasing demand on hyperspectral data for geological applications and environmental monitoring (Mulders and Jordens, 1993). Most of the sensors capture the electromagnetic spectrum in bands from the visible light up to the far infrared. During the past years the number of bands was increased due to the technical progress, reaching up to 200 or more spectral channels (Kramer, 1996). It is essential that the data of each spectral band are captured to each other maintaining stable radiometric properties. In comparison with the pushbroom concept the radiometric calibration is easier with the whiskbroom concept. Besides the spectral sensitivity range of most pushbroom scanners is limited to 0,3-1,2 µm. To cover a strip along a straight flight track a rotating mirror or prism moves the instantaneous field of view (IFOV) cross to the flight track (Binnenkade, 1993). The capturing process can mathematically be described as a time variant function that defines the orientation of the line-of-sight rays due to a three-dimensional coordinate system at each moment of observation.

Hyperspectral sensors making use of the whiskbroom concept are operated both from spaceborne and airborne platforms. The latter are flexibler in operation and often adjustable to special needs (Nieuwenhuis, 1993). The treatment of the spaceborne imagery is relatively easy because of a stable flight path, attitude and smaller scales of the imagery. In this case geometric correction can be achieved by means of two-dimensional polynomial functions. However, in airborne applications the sensor movements are complexer due to irregular and high frequent aircraft motions. To overcome the related problems airborne sensors are mounted on stabilized platforms. But even such platforms cannot compensate all of the disturbances. Another effect results directly from the whiskbroom concept. Because the ray-of-sight rotates across the flight direction around the sensor's projection center each pixel is projected onto some part of a circle around the projection center (cylindrical projection). This effect is known as panoramic distortion. Additional distortions result from the topographic relief of the terrain. Therefore geometric correction requires a Digital Elevation Model (DEM). Thus, if hyperspectral data has to be transformed into a specific geographic reference system (which is normally the case in practical use) this can only be attained in comprehensive postprocessing operation.

This geometric correction problem has been subject to research for more than thirty years (Albertz, 1998). The problem is mathematically well described. The geometric correction of the image data can easily be achieved if the sensor position and attitude can be measured with high precision by using an inertial navigation system (INS) in combination with a global positioning system (GPS) receiver (Lithopoulos, 1999). However, reality is sometimes far away from this ideal situation, and many problems remain in practical applications. Even if high precision sensor position and attitude measurement means are available there are always noise effects which have to be modeled for error estimation and quality management. Often combined GPS/INS is not available because these systems are very expensive if they reach high precision. Therefore low-cost navigation systems or simple GPS receivers providing a positioning accuracy of 30 meters or more are widely used. Such data serve only for approximation. Sometimes they turn out to be useless to achieve the desired correction accuracy.

2 THE PROBLEM

No remote sensing acquisition system can render a true geometric reproduction of the earth's surface without corrections (Binnenkade, 1993). This is why methods for geometric processing of the data are needed. The discussed problem in this paper deals with the elimination of all disturbing effects from the image data. These effects are superimposed (see Fig. 1) and some of them are correlated (Rose, 1984). The main effects are briefly described in the following paragraphs.

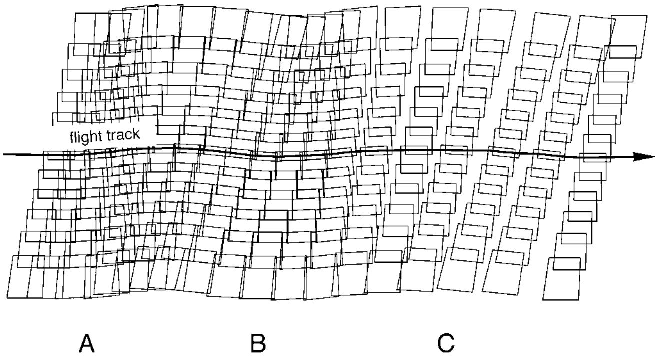

Figure 1. Schematic diagram of distortions

2.1 Panoramic Distortion

The cause of panoramic distortion is the cylindrical projection (see 1) across the flight track. For that reason the scale as well as the spatial resolution varies within one scanline. From the nadir (the place of maximal resolution) it decreases towards the sides. Furthermore the changes are different in x and y directions. A pixel is quadratic at the nadir and becomes a trapezoid at the sides. The panoramic distortion is sometimes also referred as tangential scale distortion (Buiten, 1993, Richards, 1986).

2.2 Underscan

The aim of hyperspectral scanning is to capture the terrain surface without any gap. The rotation velocity of the mirror (res. the scan rate) must be consistent with the velocity of the airplane along the flight track to meet this demand. It seems imaginable to pitch the scan rate constantly with the along track velocity during a flight mission. However the scan rate is constant in most practical applications. Therefore the pilot has to take care of keeping the along track velocity constant so that no gap could occur in the image data. If the gaps could not be avoided the resulting effect is referred to as an underscan (sometimes also referred as undersampling). In this case the information about the terrain is lost (see Fig. 1, section C).

2.3 Overscan

An overscan (res. oversampling) is the opposite of an underscan. It occurs if the along track velocity of the airplane is smaller than the allowed threshold. An overscan results in an increase of the along track scale of the image data. This is less dangerous than an underscan because no information is lost (see Fig. 1, section A). In the ideal case all nadir pixels are in touch (see Fig. 1, section B). But even then the margin pixels overlap especially if the airplane moves straight ahead and if the field of view is large.

2.4 "S-shape" distortion

This distortion results from the fact that the airplane moves ahead during the time one line is captured. This results in an S-shaped curvature (see Fig. 1). This effect is highly correlated with the yaw angle and the crab distortion. Each scan is mostly approximated to be a straight line because the rotation velocity of the mirror should be high compared with the along track velocity of the airplane. The "S-shape" distortion is sometimes also referred as sensor scan nonlinearities (Richards, 1986).

2.5 Crab distortion

The crab distortion results in a skewed image and occurs when extreme crosswind is encountered during data acquisition. In this case the axis of the airplane must be oriented slightly away from the flight axis to counteract the wind (Lillesand and Kiefer, 1994).

2.6 Roll distortion

The roll distortion yields to offsets across the flight track. The pixels are shifted, due to variations of the roll angle. The amount of one offset per pixel remains not constant even for a constant roll angle. It grows with an increasing scan angle of the line-of-sight (Albertz et al., 1995). An oscillating roll angle leads to a wavelike capturing of the terrain surface.

2.7 Pitch distortion

Movements in pitch can be serious if they lead to gaps in the image data. This can arise due to sudden forward or backward shocks of the sensor that cannot be compensated by a stabilized platform. Then there are some areas of the terrain that are depicted repeatedly whereas other parts remain unscanned.

2.8 Flying height distortion

The image data are affected by changes in scale if the flying height varies. This can result in underscans. Therefore variations of the flying height should be kept always within a certain tolerance because the scan rate and the along track velocity are balanced on the background of a chosen scale (res. spatial resolution) (Albertz et al., 1995).

2.9 Relief displacement

Elevation differences of the terrain result in displacements that increase with growing scan angle. The displacements occur in only a single direction (i.e. along the scan line, res. across the flight track). Its effect raises with increasing object height, with increasing distance from the nadir line, and with decreasing flying height (Avery and Berlin, 1992; Buiten, 1993).

2.10 Earth curvature

Scanning systems are not affected by earth curvature because of the low flying height of the aircraft (Richards, 1986).

3 AN APPROACH TO MEET THE USER'S NEEDS

The user needs the hyperspectral data as orthoimages, i.e. in the scale and the geometric properties of a map or another orthoimage. This should be achieved easily with high precision in a considerable period of time (Toutin, 1995).

Therefore reliable software which allows for high quality radiometric and geometric correction must be readily available. The radiometric correction however will not be discussed in this paper but should be considered as an integral part of hyperspectral data preprocessing. To get precise results in geometric correction based on a holistical concept one agrees today that this can be done only by using a parametric model (Pope and Scarpace, 2000; Schläpfer et al. 1998; Jacobs, 1988). Nevertheless the non-parametric models do not seem to lose in value (Ji and Jensen, 2000; DeJong et al., 1999; McGwire, 1998). But these approaches can only achieve good results under special conditions (e.g. flat terrain, good flight conditions, etc). Another reason may be the fact that non-parametric methods are available in most remote sensing software systems whereas the access to software based on parametric modeling is still limited.

4 INITIAL DATA

The initial starting point when someone gets a raw hyperspectral data set differs from each project to another. For this reason all possible initial auxiliary informations that might come with the hyperspectral data are investigated in the following. Figure 2 gives an overview.

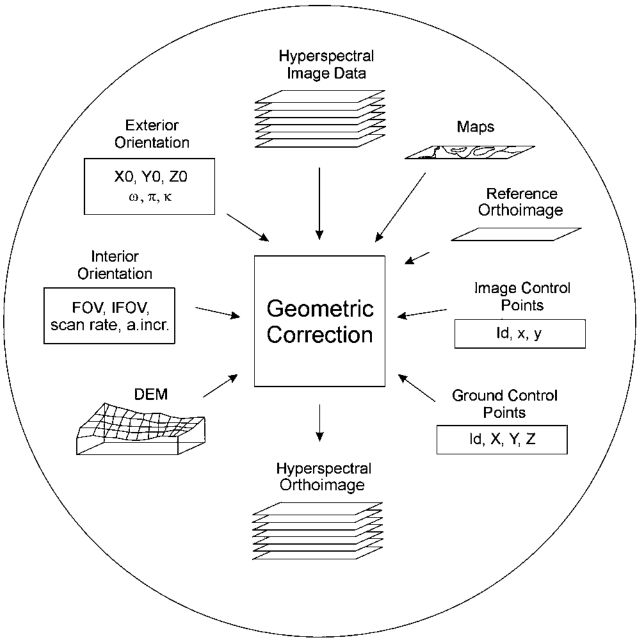

Figure 2. Different types of initial Data

4.1 Hyperspectral Image Data

The hyperspectral image data are of course the essential data in the following context. They need to be corrected. The import of the hyperspectral data is mostly the starting point of the postprocessing pipeline. Today the data come on tape or CD-ROM. The common formats are BSQ (band sequential) or BIL (band interleaved). Often auxiliary data such as position and attitude measurements are stored together with the image data. This is the reason why it is difficult to define standards for the storage of hyperspectral data because the kind of data often varies from one sensor to another. Therefore a specific import routine is needed for an individual scanner type. In principle the individual format has to be well described to be able to adapt an import routine to the geometric correction software.

4.2 Interior Orientation

The interior orientation consists of values and (if possible) residuals of angular increments, number of pixels per line, number of channels, field of view (FOV), instantaneous field of view (IFOV), scan rate and rotation direction of the rotating mirror or prism concerning the flight direction (clockwise or anti-clockwise). These data should be constant during one mission and supplied together with a mission protocol.

4.3 Exterior Orientation

The exterior orientation defines the position and attitude of the sensor at each instant of time. There are six exterior orientation parameters: three coordinates that define the position and three angles that define the direction of the line-of-sight rays. The knowledge about the exterior orientation parameters is essential to solve the geometric correction problem because they define the geometric linkage between the raw image data and the reference system to which they have to be transformed.

4.4 Maps

Maps contain important geometric reference information but it has to be guaranteed that the map scale is large enough to satisfy the needs. Normally maps are used to derive coordinates for ground control points. In this case it must be possible to identify these points in both, the image data and the map. Sometimes maps are used to derive a digital terrain model from contour lines. Maps provide also shape information (e.g. linear features) that can be used as constraints in the geometric correction algorithm. An important information is the georeference (scale, reference frame, datum) of the map. It is possible that the reference frame of the map does not correspond to the reference system needed for the geometric correction of the hyperspectral data. In this case an appropriate transformation has to be applied to the coordinates before they can be used.

4.5 Reference Orthoimage

Today orthoimages are available in many areas of our globe. Their potential is quite similar to those of maps. In combination with a digital terrain model they serve for the derivation of ground control points. Like maps the scale (res. the spatial resolution) must be large enough to satisfy the needs of precision. In comparison with the maps the orthoimages contain image information instead of vector information. This makes it possible to apply matching algorithms for automated control point derivation. For accuracy estimation it is important to know how the orthoimages were compiled. Normally it is necessary that the rectification be done differentially whereas rectification based on projective transformation can mostly not supply acceptable results (especially in rugged terrain).

4.6 Control Points

A control point consist of an identifier, two sets of coordinates and (if possible) residuals. Related to the image space a control point has two plane coordinates in x’ and y’. Related to the spatial reference system the same point is defined with three coordinates X, Y and Z. It is necessary to calculate geometric corrections in this reference system X, Y, Z. It is sometimes useful for point identification to have control point sketches which show the location of the points. As mentioned above control points can be derived from maps and orthoimages but also from field surveys. The latter is of course the most expensive way to get coordinates. But it is sometimes the only possibility to achieve high accuracy. This is especially the case in remote areas where if at all only small scale maps or orthoimages are available.

4.7 Digital Elevation Model

A digital elevation model (DEM) describes the shape of the terrain in its three dimensions. The two main data structures of a DEM are regular grids and triangulated irregular networks (TINs) (Hutchinson and Gallant, 1999). TINs are advantageous regarding effective data storage whereas regular grids are preferred if grid interpolation is needed. This is especially the case in the following context. The spatial resolution of the grid should not be higher than ten times the spatial resolution of the image data. The DEM must be based on the same reference system in which the geometric correction is performed. If this is not the case an appropriate transformation has to be applied before other processing steps. The DEM is needed to correct the relief displacement (see 2.9).

5 THE CONCEPT OF A GENERAL APPROACH

A general concept for geometric correction must be oriented towards a holistic philosophy that takes into account all available auxiliary information. The aim is to get an optimal solution even if the initial information is sketchy. Generally a geometric correction algorithm is divided into three main processing steps. That is first the preparation, second the establishment of a three dimensional coordinate frame based on the reference system and third the re-sampling of the hyperspectral image data. Sometimes purists prefer to do without the resampling because they want to keep the radiometric information unchanged. But in this case the results that are gathered from the hyperspectral image data have to be transformed instead. Therefore a third processing step is always needed.

5.1 Preparation

The preparation step is necessary to prepare all initial data in order to make it compatible with the geometric correction software. It sometimes appears that the initial data are affected by blunders. In general every initial data set can be involved here. An effect that occurs quite often is the occurrence of registration gaps during the image data capturing. This arises especially when attitude and position data are stored together with the image data. In such a case some lines may appear as "black" lines without any information. To fill the gaps one practical method is to take the image information from neighboring pixels. Another problem arises if flight position and attitude data are disturbed. In this case the data have to be filtered to separate the noise from the signal. Sometimes the position and attitude values have to be derived from related measurements that are stored as housekeeping data together with the image information.

5.2 Georeferencing

During the second step the coordinates for each pixel of the hyperspectral data set are determined. To do this a three-dimensional coordinate frame is established and filled during the subsequent processing. This can be done in different ways. The appropriate algorithm depends on the availability and the accuracy of the available auxiliary information (see 4). These yields different accuracy levels that will be described later on (see Fig. 3). The best case would be if the position and the attitude of the flight path were directly measured with high precision during the mission. Then "direct georeferencing" can be performed. The worst case is if there are neither attitude data, nor positions data and even no DEM. To get a solution that may be better than nothing it would be the only way to apply a non-parametric interpolation method (res. "rubber sheeting"). Combinations between different proposed solutions seem to be useful. Some proposed solutions are discussed in section 6.

5.3 Resampling

During the resampling step the image data are transformed to the regular grid of the reference frame. A desired spatial resolution and a method for interpolation have to be selected. Some well known interpolation methods are "nearest neighbor" (the pixel value of the nearest original pixel is taken), "bilinear interpolation" (the pixel value is derived from the adjacent original pixels using a first order interpolation), and "cubic convolution" (the pixel value is derived from the adjacent original pixels using a third order interpolation). Other methods are possible such as "interpolation using weighted means" (were the interpolation is done due to the distances of the adjacent pixels). Because hyperspectral image data are designated for classification purposes based on the inherent hyperspectral information it is sometimes not desired as mentioned above to change the original pixel values during the resampling. In this case the classification is run on the original hyperspectral data and the classification results are resampled afterwards instead of the hyperspectral data.

5.4 Accuracy Levels

The aim is to define accuracy levels in which the geometric correction results can be classified. Such a classification is useful for everybody who wants to estimate the expected correction accuracy that may be reachable in an individual case. However, it is impossible to postulate a scheme that is universally valid because of the variety of conceivable initial situations. But the presented scheme may play the role of a guideline or scale.

In case 1 there are only the hyperspectral image data available but no other auxiliary information. It is obvious that in such a case geometric correction of the hyperspectral data is impossible. Even for the application of a “rubber-sheeting” method (see 6.1) ground control points are needed.

In case 2 ground control information can be derived in form of plane coordinates based on the map’s reference system. If no other information are supplied the non-parametric method (res. “rubber sheeting” or polynomial approach) is the only possible way to get a corrected image. However, the reachable accuracy depends very much on the shape of terrain because the relief displacement (see 2.9) is not corrected. Besides this method is a local approach which means that the correction accuracy may vary significantly within the corrected image. This case is better than nothing but mostly does not meet the desired results.

In case 3 there is a reference orthoimage instead of a map. This case is very similar to case 2 because the orthoimage provides plane ground control too. But it contains also image information that may be used for image-to-image matching (see 6.2). The second makes possible to reconstruct the flight path using a parametric approach. However, the interior orientation parameters are unknown and have to be estimated. This influences the correction accuracy directly.

Case	Hyperspectral Image Data	Interior Orientation	Exterior Orientation	DEM	Maps	Reference Orthoimage	recommended method for geometric correction	expected accuracy
1	X	-	-	-	-	-	correction impossible	-
2	X	-	-	-	X	-	non-parametric method	2 - 30 Pixel
3	X	-	-	-	-	X	non-parametric or parametric method	1 - 30 Pixel
4	X	X	LA	X	X	-	parametric method	1 - 20 Pixel
5	X	X	LA	X	-	X	parametric method	< 1 - 10 Pixel
6	X	X	HA	X	-	-	parametric method	< 1 Pixel

(LA = low accuracy, HA = high accuracy)

Figure 3. Combinations of initial data and accuracy levels

In case 4 image data, the interior and exterior orientation, a DEM and a map are available. The exterior orientation parameters are provided with low accuracy. Sometimes position and attitude is measured by the GPS/INS of the aircraft’s autopilot system only. Normally these systems are neither geometrically connected to the hyperspectral sensor nor are they able to provide high accurate measurements. But nevertheless the data of such systems are kept as housekeeping data together with the image data. In this case position and attitude cannot be used for direct georeferencing but they can serve as starting values that have to be improved by the subsequent algorithm (see 6.3). If the initial accuracy of the other initial data is sufficient and if the conditions of the site and the mission were good an accuracy up to one pixel can be reached.

Case 5 is similar to case 4. Instead of a map there is a reference orthoimage provided here. As mentioned above the orthoimage offers the opportunity for automated image-to-image matching (see 6.2). If the spatial resolution of the reference orthoimage is the same or higher than the spatial resolution of the hyperspectral data and if there is sufficient texture in both image data sets then an accuracy better than one pixel seems to be reachable.

Case 6 can be denominated as the optimal case. Here the position and attitude data are provided with high precision that means a sophisticated combined GPS/INS measurement unit was mounted directly on the sensor and used during the mission. With this technique position accuracy in the range of ten centimeters and velocity determination at the level of a few cm/s is possible. The attitude parameters can be derived with an absolute accuracy in the range of 0,01° (Cramer, 1999, Hutton et al, 1998). Assuming these optimal conditions direct georeferencing can be applied and subpixel accuracy can be reached.

6 PROPOSED SOLUTIONS

There a several approaches that were proposed during the last years to solve the problem of geometric correction of hyperspectral image data. Regarding these solutions it becomes apparent that each method starts from a specific initial situation where the kind of initial data is well defined. The proposed solutions are normally classified to be non-parametric, parametric or mixed approaches.

6.1 Non-parametric approaches

Non-parametric approaches use polynomial functions or triangulation based methods to correct the disturbances of the image data but do not take into account any sensor position or attitude data. These methods require an adequate number of ground control points. Globally applied polynomial functions normally do not meet the requirements because of the local character of the image distortions. Hence a “Continuous Piecewise Method” is proposed by Ji and Jensen (2000). Another approach is the “Facet Method” described by Buiten (1993). This method is also referred to as “Rubber Sheeting”. Here a triangulation is performed over all control points. Then a polynomial interpolation is performed inside each triangle. This method is suitable to correct geometrically the local deformations in the image. But problems occur outside the mesh with extrapolation.

6.2 Parametric approaches

Within a parametric approach all parameters of the time-variant image capturing process can be modeled rigorously. Normally this is done within an adjustment procedure, which allows the modeling of error propagation. With a parametric approach it is possible to model the inherent disturbing effects individually because of the fact that even correlation between observations can be modeled if they are known. However, these methods need adequate initial auxiliary information like position and attitude data, a DEM and/or a reference orthoimage. Pope and Scarpace (2000) propose a method based on “Image-to-Image-Matching”. This method makes use of a reference orthoimage and a DEM. The aim is to reconstruct a virtual flight path that can be used for subsequent direct georeferencing. Initial position and attitude data serve as approximations that are improved later on. Schläpfer et al. (1998) also try to reconstruct the flight path but based on ground control and initial position and attitude data.

6.3 Mixed approaches

A mixed approach contains elements from both, the parametric and the non-parametric methods. These methods are often applied in cases where the initial information for position and attitude are available with low accuracy only. The method that was described by Breuer and Albertz (1996) is a mixed approach. In a first step a transformation of the flight path is calculated using the position and attitude data in combination with ground control. This is done using a parametric model. In a second step a polynomial transformation is applied to wrap the image data to the terrain taking into account a DEM and ground control points.

7 CONCLUSIONS

High quality geocorrection is crucially important for everyone who wants to use hyperspectral data. On the other hand auxiliary data are not always available in an appropriate manner. This reality must be recognized. Therefore up to now different methods were developed to solve the problem on the background of very special initial circumstances. But the paper states that a special adoption due to an individual sensor system is needed for the first processing step only (see 5.1). The subsequent steps should be treated holistically taking into account all auxiliary information that can be available (see Fig. 2). Following this principle an optimal accuracy level should be reachable if the appropriate algorithm is used in an individual case (see Fig. 3). The future development has to be concentrated to put together the existing models to create a modular system that can respond to the need of the user who wants to get an optimized solution based on the real data that he has. At the same time future investigation is needed to work out the accuracy level concept in more detail especially regarding the quantitative statements.

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