ALTERNATIVES FOR TRANSFERRING ORIENTATION DATA OF DIGITAL AERIAL IMAGES

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ABSTRACT

The use of digital aerial images has become a standard approach in mapping organizations. A trend is also apparent in that end-users are increasingly utilizing digital images as part of their geospatial databases. Today this occurs mainly with digital orthophotos that are used as background information for various vector-formatted geospatial data. In the future it is likely that central perspective images will also be increasingly used by the same group of users. A clear benefit over orthophotos is that 3-D data acquisition is also possible. A prerequisite for utilizing central perspective images is that their orientation data can be transferred easily from producer organizations and systems to user organizations and systems. Today, this is usually guaranteed only if all the systems used are supplied by a single vendor. Here we examine alternatives for transferring orientation data of digital aerial images, especially for central perspective images. Alternatives for modeling the interior and exterior orientation and relevant systematic errors are presented. The goal of the study is to find a simple and robust approach that is simultaneously complete for sophisticated representation of correction models for systematic errors. Special emphasis is placed on methods based on the use of reference points.

1. INTRODUCTION

The use of digital aerial images has become a standard approach in mapping organizations. A trend is also apparent in that end-users are increasingly utilizing digital images as part of their geospatial databases. Today this occurs mainly with digital orthophotos that are used as background information for various vector-formatted geospatial data. Orthophotos are clearly beneficial with regard to ease of use because they can be treated in a system as any other raster-formatted data. Conceptually the use of orthophotos is also easy because in most cases extensive photogrammetric training is not required.

In the future it is likely that central perspective images will also be increasingly used by the same group of users. A clear benefit over orthophotos is that 3-D data acquisition is also possible. A prerequisite for utilizing central perspective images is that their orientation data can be transferred easily from producer organizations and systems to user organizations and systems. Today this is usually guaranteed only if all the systems used are supplied by a single vendor, otherwise difficulties occur because no widely accepted standards are available for transferring orientation data, either for the semantics or syntax of the relevant model and parameters.

Here we examine alternatives for transferring orientation data of digital aerial images, especially for central perspective images. Alternatives for modeling the interior and exterior orientation and relevant systematic errors are presented. The goal of the study is to find an approach that is simple and robust, but simultaneously complete for sophisticated representation of correction models for systematic errors.

As stated above, our main interest is in the producer - end-user situation. The principles are, however, equally well applicable when digital images are transferred from one producer organization to another, or even between different, loosely integrated systems within a single organization. Here we focus on the models and semantics. The actual transfer means and related syntactic issues will be discussed only briefly at the end. The motive here is rather to open discussion and review some of the alternatives. The final goal should be to establish mutual understanding and functional standards for the task at hand.

2. THE BASIC TRANSFORMATION MODEL

2.1 The basic formulas

This development uses as its starting point the well-known collinearity equations for exterior orientation and a linear model for interior orientation.

The collinearity equations can be expressed as

$$\begin{cases} \dfrac{x}{z} = \dfrac{r_{11}(X - X_o) + r_{12}(Y - Y_o) + r_{13}(Z - Z_o)}{r_{31}(X - X_o) + r_{32}(Y - Y_o) + r_{33}(Z - Z_o)} \\ \dfrac{y}{z} = \dfrac{r_{21}(X - X_o) + r_{22}(Y - Y_o) + r_{23}(Z - Z_o)}{r_{31}(X - X_o) + r_{32}(Y - Y_o) + r_{33}(Z - Z_o)} \end{cases}$$

with the symbols:

X, Y, Z	coordinates of a point in the object-space
X_o, Y_o, Z_o	coordinates of the projection center in the object-space
$r_{11}, \ldots, r_{33}$	elements of the rotation matrix
z	principal distance (negative camera constant)
x, y	coordinates of a point in the camera-space

For transformation from object-space to camera-space the formulas can be written in a more explicit form:

$$\begin{cases} k = \dfrac{z}{r_{31}(X - X_o) + r_{32}(Y - Y_o) + r_{33}(Z - Z_o)} \\ x = k\left[r_{11}(X - X_o) + r_{12}(Y - Y_o) + r_{13}(Z - Z_o)\right] \\ y = k\left[r_{21}(X - X_o) + r_{22}(Y - Y_o) + r_{23}(Z - Z_o)\right] \end{cases}$$

A linear transformation from camera-space to image-space includes a maximum of 8 terms and can be written as

$$\begin{cases} l = a_0 + a_1 x + a_2 y + a_3 xy \\ c = b_0 + b_1 x + b_2 y + b_3 xy \end{cases}$$

with the symbols:

l, c	coordinates of a point in the image-space
$a_0, \ldots, b_3$	coefficients of the transformation.

An affine transformation (6 parameters) can obviously be treated with this formula simply by assigning zeros for a_3 and b_3. The coefficients of a Helmert-transformation can also be substituted for the coefficients of this formula.

It is remarkable that the transformation is here written explicitly from camera-space to image-space, not vice versa. This reflects the motive that in most application cases this order holds; however, since the coefficients for an inverse transformation can easily be computed, this is to some degree a matter of free choice.

2.2 Transferring the coefficients for the basic transformation model

The purpose here is to examine the alternatives for transfer of orientation data of digital aerial images from a source system to a target system. It must be emphasized that the primary goal in this task is not to transfer the orientation data but to attain a state such that the transformation from object-space to image-space is numerically equal, with sufficient accuracy, in the source- and target-systems.

Of the alternatives for reconstruction of the transformation model, the most important ones include 1) direct transfer of the coefficients, 2) use of original observations , and 3) use of reference points.

Direct transfer of the coefficients

Data: Uses coefficients of the transformation model, including X_o, Y_o, Z_o, $r_{11}, \ldots, r_{33}$, $a_0, \ldots, b_3$, and z (camera constant).

Method: Direct assignment.

Pros: Simple to perform.

Cons: The source- and target -system must support exactly the same model.
If the rotation angles are transferred instead of the full rotation matrix, agreement must be reached on the interpretation of their meaning.

Use of original observations

Data: Uses the same data as used in the source-system in the computation of orientation. This data set can be rather complex, e.g. if GPS-supported bundle block adjustment is used in the source-system.

Method: Total recomputation of the block adjustment or similar.

Pros: Data usually readily available in the source-system. In principle the method is rather robust with respect to misinterpretation of data because misinterpretation would usually show up as inconsistencies in the computations.

Cons: The target system should be capable of handling all possible situations. In addition, the approach is not suitable for imagewise reconstruction of the transformation model.

Use of reference points

Data: Uses a set of reference points for which the source-system produces coordinates in the respective spaces (object, camera, image), depending on the transformation. The set of these points is separate for each image.

Method: Recomputation of transformation model individually for each image.

Pros: The reference points offer direct means for assessing whether the transformation model in the target-system is correct. With a sufficient number of reference points, the approach is also able to detect possible errors in data transfer.

Cons: Compared with direct transfer, some computations are necessary in the target-system.

2.3 Use of reference points for reconstruction of the basic model

The use of reference points is further developed here. Our basic model, as expressed above, is comprised of two subsequent transformations, one for exterior orientation and one for interior orientation. The method of using reference points is applicable to both these transformations. The selection of reference points can be made variously.

The first approach is to use the same points and same coordinate values in the orientation computations as used in the source-system, which are for the interior orientation the calibrated coordinates of the fiducials and the respective image observations, and for the exterior orientation the adjusted coordinates of tie points and control points and the respective image observations. This approach has the advantage that these values are usually available in the photogrammetric source-system. On the negative side is the fact that the approach is not suitable when the source-system uses advanced adjustment methods in the orientation computations, including GPS-supported aerial triangulation, and other methods in which some type of combined adjustment is used in the block formation.

Another approach is to generate artificial reference points in the source system for which the coordinates are computed using its transformation model. Table 1. represents the required information in which the same points are used for interior and exterior orientation. It is equally possible to use two distinct tables, one for each transformation.

Table 1. Information required for the reference points.

Image-space		Camera-space		Object-space		
l_i	c_i	x_i	y_i	X_i	Y_i	Z_i

Table 2. Example of reference point data with 4 points (z = -153.19).

l	*c*	*x*	*y*	*X*	*Y*	*Z*
0	0	-121.155	-120.083	74358.326	45549.147	0
0	6000	118.881	-119.713	74391.708	44656.599	0
6000	6000	-121.512	119.922	75260.832	45587.334	0
6000	0	118.523	120.291	75288.784	44680.080	0

Table 3. Example of reference point data with 9 points (z = 1).

l	*c*	*x*	*y*	*X*	*Y*	*Z*
0	0	0.790881	0.783883	74358.3	45549.1	0
0	3000	0.007422	0.782675	74528.3	45104.1	200
0	6000	-0.776036	0.781467	74391.7	44656.6	0
3000	0	0.792049	0.000529	74809.2	45408.3	200
3000	3000	0.008591	-0.000679	74819.2	45114.1	200
3000	6000	-0.774868	-0.001887	74829.2	44821.7	200
6000	0	0.793211	-0.782832	75260.8	45587.3	0
6000	3000	0.009759	-0.784039	75114.9	45124.2	200
6000	6000	-0.773699	-0.785241	75288.8	44680.1	0

3. EXTENDED TRANFORMATION MODEL WITH IMAGE CORRECTIONS

The basic transformation model above is fully sufficient when no corrections are applied to the image coordinates. For accurate reconstruction of the transformation model in the target-system, it is necessary to apply the same corrections as used in the aerial triangulation in which the most commonly used corrections are those for 1) radial distortion of the camera lens, 2) atmospheric refraction, 3) Earth's curvature, and 4) correction due to self-calibration in block adjustment. Sometimes also the calibrated parameters for 5) geometric distortions of the image scanners are applied in block adjustment. In the following we analyze the characteristics of each. The selection of the object-space coordinate system used in block adjustment is also discussed.

3.1 Components of the extended model

Correction due to scanner calibration. Corrections based on calibration data of an image scanner are rarely applied when photogrammetric precision scanners are used. When desktop scanners are used, calibration can improve the geometric accuracy considerably (Sarjakoski, 1992; Baltsavias, 1995). The deformations occur fundamentally in the image-space but can equally well be expressed in the camera-space by applying the transformation for interior orientation.

Radial distortion of camera lens. Correction for radial lens distortion is a camera-space correction based on camera calibration data. Two main approaches are used for making the correction, in which the first one is based on a correction table and linear interpolation between the tabulated values. The correction table is often given directly in camera calibration reports. When this approach is used, the table must be transferred from the source-system to the target-system. The second approach is based on a polynomial model (e.g. Slama et al., 1980:480-483); its application requires that the coefficients of the polynomial be transferred from the source-system to the target-system. The source- and target-systems must also use exactly the same model. From the system point of view it is essential to note that the corrections are unique for each camera lens, not for each photograph.

Correction for atmospheric refraction. Atmospheric refraction is fundamentally a phenomenon causing light to follow a curved path instead of a straight line. For the purposes of aerial triangulation, its effect on radial displacement can be modeled as a function of the angle of light ray, flying altitude and altitude of the terrain point. Several formulas are given for this function (Slama et al., 1980:486-488), and various approximations can be used in their implementation in computer programs. The most fundamental difference is with respect to an assumption about perfectly vertical photography versus the utilization of actual tilt angles of the camera.

Correction for Earth's curvature and object-space coordinate system. The curvature of the earth can be treated in fundamentally very different ways (Slama et al., 1980:488-489). The first approach uses a rectangular 3-D object-space coordinate system in the block adjustment for aerial triangulation. This approach is conceptually sound and straightforward but its practical realization can result in considerable complexities. Obviously, all the coordinates of control points must be converted to this system prior to the computations, and all the results, including the parameters for exterior orientation, must be converted back to the map coordinate system. These conversions require knowledge of the map projections. The second approach uses radial correction of camera-space coordinates to compensate for the effect of Earth's curvature. The correction is a function of the flying altitude and the angle of the light ray and is thus also dependent on the tilt angles of the camera.

Corrections due to self-calibration. Use of the corrections discussed above does not introduce any parameters for estimation in the block adjustment. This is in contrast to the parameters used in a self-calibrating block adjustment, the purpose of which is to model the systematic image errors that are still present even if *a priori* corrections are made. Several models (parameter sets) have been developed for this purpose (see Kilpelä, 1980, for some comparative results). Some of the models are based on modeling of the underlying physical phenomena, while others are purely geometry-based developments. The models by Brown (1976) and Ebner (1976) are likely to be the most widely used models from these two main groups of models.

From the system point of view, it is essential to note that the values of the parameters can be estimated to be common for an entire block, subblock, or strip. Considering the problem of transferring the model from a source-system to a target-system, it is essential for accurate modeling that each of these use exactly the same model and its implementation and same the coefficients in the model.

The effect of corrections on block adjustment results. As shown in several theoretical and empirical studies, use of these corrections improves the accuracy of block adjustment significantly, when measured at checkpoints in the object-space. The use of corrections is important especially when the ground control is sparse; in this case uncorrected systematic image deformations would cause large deformations in the block. On the other hand, the effect often remains rather minimal in blocks with such tight control that several well-located control points can be found on each image. This can be explained by the fact that most systematic image errors are strongly correlated with the parameters for exterior orientation; e.g., uncorrected refraction errors and Earth's curvature errors will be absorbed to a large extent by a shift in the Z-value of the projection center. Similarly, errors in the coordinates of the principal point are nearly fully correlated with the X- and Y-values of the projection center.

3.2 Transferring the coefficients for the extended model

As for the basic transformation model, we have here two main alternatives for transferring the data from a source-system to a target-system: direct transfer of all the related coefficients or use of reference points. Direct transfer is conceptually clear, once we have agreed on the model. With regard to concurrently used digital photogrammetric systems, however, several major and minor differences are present in the models and their implementation, often making this approach very difficult and prone to slight interpretation errors.

The second approach, use of reference points, follows the principle used for the basic model. To be able to track the transformation thoroughly, more values should be included. Here, we propose that two additional pairs of columns be included in the reference point tables: 1) camera coordinates including refraction and Earth's curvature correction and 2) camera coordinates including all the corrections (Table 4). The later one would normally incorporate the effect of applying a self-calibration, and camera and scanner calibration corrections.

A fundamental difference exists in the use of reference points here, compared with the basic model. We assume no definite agreement of the extended model to be used in the source- and target-systems. In consequence, no means are available for reconstructing the transformation model exactly in the algebraic sense. However, by using a sufficiently large number of reference points, it is possible to reconstruct the transformation model so well in the numerical sense that no harmful loss of accuracy occurs. A typical arrangement could be a set of 25 points in a 5 x 5 grid. The use of a regular grid pattern is essential for making their use easy in a target-system.

4. COMPUTATIONAL AND IMPLEMENTATIONAL ASPECTS

The task of reconstructing the basic transformation model from the reference points is actually the same as making interior and exterior orientation with error-free observations. Least-squares adjustment can be used, and as the outcome the related residuals should be zero-valued. Computation of approximate values requires some consideration. Since our focus here is on the use of nearly vertical aerial photographs, affine transformation can be used for the purpose. Use of direct linear transformation (DLT; Abdel-Aziz and Karara, 1971; Karara et al., 1980) and its 11-parameter variation (Bopp and Krauss, 1978) offers an alternative, and is also applicable for the general case. A remarkable aspect is that DLT enables us to reconstruct the basic model without any information on the camera, assuming that the points are not located in a single plane in the object-space. We could thus leave out the camera-space columns in Table 3.

For the extended transformation model the treatment of the corrections for the camera-space coordinates is the most important problematic area. Several alternatives are available:

- Use camera-space coordinates including all corrections (C2 in Table 4) in the exterior orientation. The parameters for exterior orientation will absorb most of the well-behaving systematic errors. The approach is suitable especially for large-scale photography when no additional parameters have been used in the block adjustment.

- Use the target-system's own model 1) for refraction and Earth's curvature corrections and 2) for other corrections (jointly for self-calibration, camera-calibration, and scanner-calibration). The model for the other corrections can utilize 2a) bilinear interpolation based on the values at the reference points or 2b) a self-calibration model (e.g. Brown, 1976) for which the parameters are estimated using the values at the reference points.

For making this procedure more transparent, we can conceive that a self-calibrating block adjustment would be carried out in the target system individually for each image. The only difference from the conventional block adjustment is that camera calibration data are not used, but the same information is recovered using the reference points.

Table 4. Reference point data for the extended model with image corrections.

Object-space			**Camera-space** (C0) Ideal		**Camera-space** (C1) Including refr. & Earth's curv. corr.		**Camera-space** (C2) Including all corrections		**Image-space**	
X	*Y*	*Z*	*x*	*y*	*x*	*y*	*x*	*y*	*l*	*c*

5. ISSUES RELATED TO PRERECTIFIED IMAGES

Commonly two types of prerectified images are used: image pairs with epipolar geometry and orthorectified images. An image pair rectified to epipolar geometry can (and should) be made such that all systematic image errors are removed in the rectification. In this case the geometry complies strictly with the basic model.

As already discussed in the introduction, orthorectified images can be used directly in many GIS-software packages. How to transfer their georeferencing data is not discussed here in depth. It is only noted that it is also possible to use stereo orthophotos for extraction of 3-D features (Baltsavias, 1993). The important prerequisite is that the elevation model must be available during the 3-D mapping phase. This is seldom possible if the related elevation data are not transferred with the image data.

6. STANDARDIZATION

In this paper the emphasis has been on aspects related to modeling and semantics. These must be solved and agreement about them arrived before useful transfer of data can occur. To date, only proprietary solutions exist for transferring the orientation data. Plausible implementations fall into two main groups: those using separate text files for the orientation data and those storing the orientation data jointly with the image data. The former has the advantage of being more open and accessible (Sarjakoski and Lammi, 1991) while the latter is more robust in the sense that the orientation data are an integral part of the image data file. The GEOTIFF (1996) specification, based on the TIFF-format by Adobe, follows the latter approach and satisfies the basic requirement for transferring georeferenced orthophotos.

In the ISPRS Working Group II/7 meeting during the Photogrammetric Week '97 in Stuttgart it was discussed that GEOTIFF specification would be extended or used as a starting point for a specification covering also the other types of photogrammetric images. In practical situations there seem to be needs to transfer orientation data sometimes as separate entities and sometimes jointly with images. For the latter the use of TIFF-format seem to be an alternative, once we have agreed about the contents of the data. Standardization of image-related data has been recognized in the work of Open GIS Consortium which has already released a "white paper" on the issue (Open GIS Consortium, 1998). International Organization for Standardization has recently added a related project into its standardization work on geographic information (ISO TC211, 1998).

7. CONCLUSIONS

In this work we have examined alternatives for transfering orietation data of digital aerial images. It must be emphasized that the primary goal is to be able to reconstruct the object-space to image-space transformation model in the target system. To main alternatives have been discovered. The first one is based on mutual agreement of the transformation model and direct transfere of the related coefficients. The second one is based on the use of reference points and reconstruction of the transformation model with sufficient numerical accuracy. The advantage of the second approach is that the requirement of mutually agreed transformation model is much less stringent. Use of a large number of reference points makes the approach redundant and robust with respect to errors.

This paper is meant to be a working paper related to the standardization of photogrammetric imagery. It is essential that photogrammetric images are considered also in the international standardization initiatives for geospatial information. In that respect cooperation between Open GIS Consortium, ISO TC211 and ISPRS working groups is important.

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