Alternative Sensor Orientation Models For High Resolution Satellite Imagery

GEORGE VOZIKIS [1], CLIVE FRASER [2], JOSEF JANSA [3]

Zusammenfassung: Diese Arbeit befasst sich mit diversen Sensormodellen die man zur Auswertung von hochauflösenden Satellitenbildern nutzen kann. Da es sich bei hochauflösenden Satellitenbildern nicht um zentralperspektivische Aufnahmen handelt, versagt die herkömmliche Kollinearitätsgleichung. Weiters ist der Öffnungswinkel bei diesen Sensoren extrem klein, was die Sensorgeometrie sehr instabil macht und meistens stehen auch keine Kalibrierungsdaten der Aufnahmen zur Verfügung.
Anhand von IKONOS und SPOT5 Bildern, sowie simulierten Datensätzen werden das affine, das parallel-perspektive, das zentralperspektive Modell, sowie die DLT getestet und evaluiert. Zusätzlich werden zur Verfügung gestellte RPCs (Rational Polynomial Coefficients) auf Qualität überprüft und eine Strategie erläutert, durch welche man in der Lage ist, selbst sehr genaue RPCs zu berechnen.

1 Introduction

Since the successful launches of high-resolution satellites such as IKONOS (September 1999), EROS-1A (December 2000), Quickbird (October 2001) and SPOT5 (May 2002), a new era in data analysis for photogrammetric and remote sensing purposes has begun. Because of the new geometrical properties of these sensors, the common methods (central perspective geometry) used in airborne photogrammetry cannot be directly applied onto high-resolution satellite imagery - at least not without certain modifications.

One of the two major shortcomings of this imagery is the narrow field of view (FoV). The commonly used, well-known collinearity model based on central perspectivity delivers wrong, inaccurate or not well-definded results due to the badly defined intersection of the rays as the FoV approaches 0° (YAMAKAWA, 2001). The FoV of IKONOS, for instance, is 0.92°.

The second shortcoming is the lack of information regarding calibration data. Some of the providers of high-resolution imagery do not release any information about the interior orientation (calibrated focal length, principal point coordinates, coefficients for modelling the lens-distortion) of the sensor. Furthermore, quite often also no precise information is available about the actual position and orientation of the satellite, when acquiring the image.

Here, alternative sensor models are to be discussed and evaluated. It should also be mentioned that for evaluating these models both, simulated data, and true measurements (3d-GPS and 2d-image points) were used. This way, measurement errors or inaccuracies are also being taken into account when evaluating the diverse models thus reflecting a practical point of view, as by measuring with GPS or digitising in images the results are certainly not errorless.

---

[1] Dipl.-Ing. George Vozikis, Institute of Photogrammetry and Remote Sensing, Vienna University of Technology, Gusshausstrasse 27-29/E122, A-1040 Vienna (Austria), e-mail: e9826142@stud3.tuwien.ac.at

[2] Prof. Dr. Clive Fraser, Department of Geomatics, The University of Melbourne, Victoria 3010 (Australia), e-mail: c.fraser@unimelb.edu.au

[3] Prof. Dr. Josef Jansa, Institute of Photogrammetry and Remote Sensing, Vienna University of Technology, Gusshausstrasse 27-29/E122, A-1040 Vienna (Austria), e-mail: jj@ipf.tuwien.ac.at

In addition, it is examined how these diverse sensor models behave, when different coordinate systems and projections are being applied. The calculations were carried out in UTM, WGS84 geographic and WGS84 geocentric coordinate systems.

Another aspect is the evaluation of the Rational Function Model (RFM), which is the basis of the Rational Polynomial Coefficients (RPCs) usually provided (for additional money) by the image vendors. By investigating the geometric behaviour by employing artificially generated data one is, hopefully, able to estimate the RFM's potential of modelling the actual geometric properties.

Most computations were carried out using the program BARISTA, a rather new software package (outset October 2001) developed at the Department of Geomatics at the University of Melbourne.

2 Data Sets

2.1 Real Data

The test data are briefly described here (Tab.1). Both of the satellites used, i.e. IKONOS and SPOT5, are pushbroom-scanners. The images of the IKONOS satellite are PrecisionPlus-products and hence have a geometric resolution of 1 metre in the panchromatic channel. The revisit interval at the equator for this satellite is 3 days and the imaging swath is about 11.3 kilometres (IKONOS, 2002). The SPOT5 images were acquired by the HRG (High-Resolution Geometric) instruments in panchromatic supermode and hence have a ground sample distance of 2.5 metres. The revisit interval of SPOT5 lies between 1 and 4 days. The imaging swath is rather huge with 60 or even 120 kilometres in case the two HRG instruments working simultaneously (PRESSKIT, 2002).

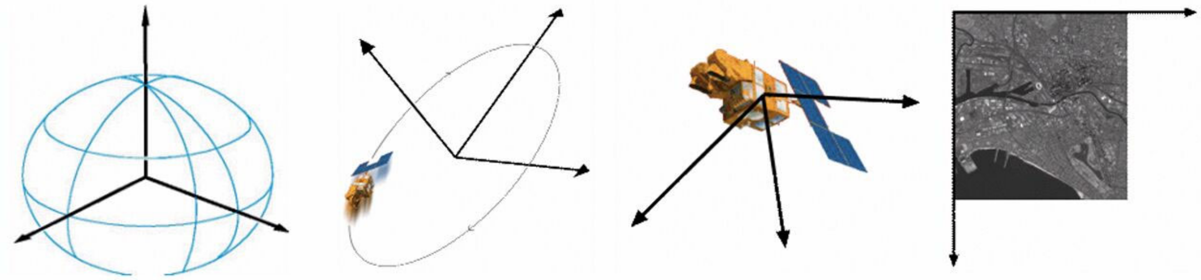
Tab.1: Available Data Sets for Testing

Satellite	Location	No of GCPs	RPCs	Image extents
IKONOS	Melbourne (Australia)	52	YES	7396m x 7942m
IKONOS	San Diego (USA)	23	YES	5480m x 1110m
IKONOS	Athens (Greece)	27	NO	11926m x 19747m
SPOT5	Attika (Greece)	30	NO	72551m x 72344m

The ground reference points were measured in object space by DGPS (Differential Global Positioning System); some of them were used as control points for calculating the model parameters and others as independent checkpoints for the evaluation (the acronym GCP may therefore be interpreted as ground control point or ground check point). The image co-ordinates were acquired by simple point digitisation, by ellipse-fitting techniques, or by line-intersection whatever was more appropriate. (FRASER ET AL. 2002). As a-priori accuracy a sigma of 5 centimetres in object space and half a pixel in image space have been assumed.

2.2 Simulated Data

In order to be able to thoroughly investigate the models' behaviour and effects on the resulting quality for a great diversity of along-track and across-track viewing angles, a simulation program has been employed for creating two perfect data sets. The software delivered the image co-ordinates (2D) from object co-ordinates (3D) by taking into consideration the viewing angles, the orbital position and the approximate physical characteristics of the respective satellite. Fig.1 shows the procedure flow that consists of the following steps: (a) the geocentric object space coordinates are transformed into orbital plane coordinates; (b) the latter are further transformed into satellite coordinates with the centre of mass as origin, (c) finally, the image space coordinates are obtained usually by applying an additional shift and rotation operation (Westin, 1990).



$$\begin{bmatrix} X_g \\ Y_g \\ Z_g \end{bmatrix} \Rightarrow \begin{bmatrix} X_{op} \\ Y_{op} \\ Z_{op} \end{bmatrix} \qquad \begin{bmatrix} X_{op} \\ Y_{op} \\ Z_{op} \end{bmatrix} \Rightarrow \begin{bmatrix} X_S \\ Y_S \\ Z_S \end{bmatrix} \qquad \begin{bmatrix} X_S \\ Y_S \\ Z_S \end{bmatrix} \Rightarrow \begin{bmatrix} x \\ y \end{bmatrix}$$

Fig.1: Transformation procedure of the simulation in 3 steps.

Both simulated data sets were located on the northern hemisphere within UTM zone 34. The simulated SPOT5-HRG set covers an area of 45 km x 72 km, while the simulated IKONOS data set has an extent of 11 km x 11 km.

3 The Sensor Models

A sensor model describes the relationship between object and image space thus allowing accurate image exploitation. Due to missing precise information about the sensor (calibration data etc.) in case of high-resolution spaceborne data, a mathematical description for expressing the relation between object and image space has to be found. This investigation is intended to provide valuable information about the mathematical model that optimally describes the true physical sensor geometry.

The tested models are (Fig. 2a to c):

- DLT Model
- Parallel Perspective Model
- Affine Model

All of them are non-parametric models, where the unknowns of the mathematical model do not directly describe the unknowns of the actual physical model. A parametric approach may be found in Toutin et al. (2003) although due to lack on information, this model could not be included in the tests.

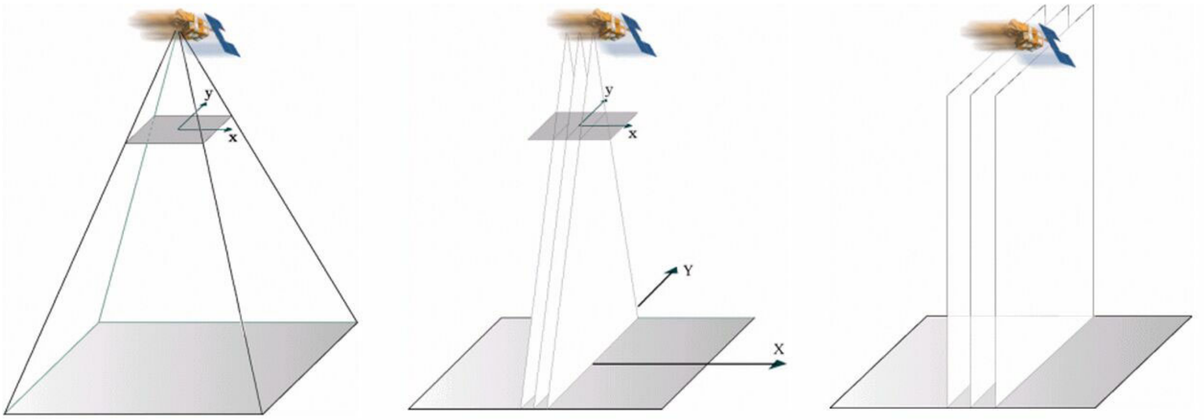


Fig.2: a) DLT (central perspectivity); b) Parallel Perspective Model; c) Affine Model

3.1 The Direct Linear Transformation (DLT)

This model describes a central perspective geometry plus an affine distortion (Fig.2a). It has found great use also in close-range photogrammetry applications. The image coordinates (x, y) can be obtained from the object coordinates (X, Y, Z) through the following equation.

$$x = \frac{L_1 X + L_2 Y + L_3 Z + L_4}{L_9 X + L_{10} Y + L_{11} Z + 1} \qquad y = \frac{L_5 X + L_6 Y + L_7 Z + L_8}{L_9 X + L_{10} Y + L_{11} Z + 1}$$

3.2 The Parallel Perspective Model (PP)

Since the acquisition instruments are line scanning systems, a simplification of the DLT which limits the above equation to one line seems to be justified. Between the lines the image is modeled by a sequence of parallel projections (Fig.2b). OKAMOTO ET AL. (1999) show how these equations can be derived from the collinearity model.

$$x = B_1 X + B_2 Y + B_3 Z + B_4 \qquad y = \frac{B_5 X + B_6 Y + B_7 Z + B_8}{B_9 X + B_{10} Y + B_{11} Z + 1}$$

3.3 The Affine Model (AM)

Unfortunately the images the vendors provide are resampled, sometimes even rectified, so that one scan line of the satellite does not correspond to one line in the image. Due to this fact and due to the narrow FoV a further simplification seems to be reasonable when assuming a parallel projection even within one scan line. (Fig.2c). If we think that the satellites travel at an elevation of 600 km and that the FoV is only about one degree, it is logical to assume near parallelism for the imaging rays in object space.

$$x = A_1 X + A_2 Y + A_3 Z + A_4 \qquad y = A_5 X + A_6 Y + A_7 Z + A_8$$

3.4 The Rational Function Model (RFM)

This model has gained considerable interest recently in photogrammetry and remote sensing, mainly due to the fact that some satellite data vendors have adopted the RFM as a replacement sensor model for image exploitation (Tao, 2002). It is a one-way model, which allows the user to do photogrammetric processing without need for revealing the parameters of the physical sensor model by the provider. The parameters of the interior (and exterior) orientation are kept confidential, because they cannot be derived from the RFM parameters, the Rational Polynomial Coefficients (RPCs).

The RFM relates geographical object space coordinates (normalized latitude U, normalized longitude V, normalized height W) to measured image space coordinates *l, s* (line, sample) (Dial et al., 2002).
It is given by eighty coefficients and ten scale and off-set terms. The mathematical description is given below.

$$l_n = \frac{Num_L(U,V,W)}{Den_L(U,V,W)} \qquad s_n = \frac{Num_S(U,V,W)}{Den_S(U,V,W)}$$

with:

$$Num_L(U,V,W)=a_1+a_2V+a_3U+a_4W+a_5VU+a_6VW+a_7UW+a_8V^2+a_9U^2+a_{10}W^2+a_{11}UVW+a_{12}V^3 +a_{13}VU^2+a_{14}VW^2+a_{15}V^2U+a_{16}U^3+a_{17}UW^2+a_{18}V^2W+a_{19}U^2V+a_{20}W^3$$

$$Den_L(U,V,W)=b_1+b_2V+b_3U+b_4W+b_5VU+b_6VW+b_7UW+b_8V^2+b_9U^2+b_{10}W^2+b_{11}UVW+b_{12}V^3 +b_{13}VU^2+b_{14}VW^2+b_{15}V^2U+b_{16}U^3+b_{17}UW^2+b_{18}V^2W+b_{19}U^2V+b_{20}W^3$$

$$Num_S(U,V,W)=c_1+c_2V+c_3U+c_4W+c_5VU+c_6VW+c_7UW+c_8V^2+c_9U^2+c_{10}W^2+c_{11}UVW+c_{12}V^3+ c_{13}VU^2+c_{14}VW^2+c_{15}V^2U+c_{16}U^3+c_{17}UW^2+c_{18}V^2W+c_{19}U^2V+c_{20}W^3$$

$$Den_S(U,V,W)=d_1+d_2V+d_3U+d_4W+d_5VU+d_6VW+d_7UW+d_8V^2+d_9U^2+d_{10}W^2+d_{11}UVW+d_{12}V^3 +d_{13}VU^2+d_{14}VW^2+d_{15}V^2U+d_{16}U^3+d_{17}UW^2+d_{18}V^2W+d_{19}U^2V+d_{20}W^3$$

In Dial et al. (2002) one can find an analytical explanation of how these 80 parameters are being calclulated by the high-resolution satellite imagery vendor.

Unfortunately these RPCs (as they are provided) are afflicted with non-negligible errors, although the resulting constant bias may be compensated with help of some GCPs. The mathematical procedure is thouroughly described in Hanley et al. (2001). Our tests show that one (preferably two) carefully measured GCPs provide enough information to be able to compensate the bias of the RPCs.

3.5 Self-Calculation of RPCs

The RFM with vendor-supplied RPCs is an effective alternative to collinearity-based sensor orientation and is supported by most of the available photogrammetric workstations. Unfortunately, the RPCs are not necessarily provided together with the images or are of bad quality as mentioned above. Therefore, an approach of determining the RPCs by the user is described below, so that the users may input this RPCs in their workstations and start compilations.

Measuring 40 GCPs or even more in order to calculate the over 80 coefficients of the RFM would be too time-consuming and too expensive. A solution can be found by applying a simple model, for example, the above mentioned Affine Model:

- Measuring of 4 or more well distributed GCPs.
- Deriving the parameters of the Affine Model by a single image resection in any coordinate system.
- Creating a 3D grid of thousands of points in the object-space coordinate system over the area of interest.
- Using the previously calculated affine parameters for computing the corresponding 2D point-grid in image space.
- Transforming the object space grid-points into the geographic coordinate system, if necessary.
- Calculating the RPCs with a least squares adjustment using the geographic grid-points.

It must be emphasized that this approach is valid only if the simple model (e.g. the Affine Model) is able to deliver accurate results.

4 Test Results

This section discusses the outcomes of the tests made on the various data sets. The evaluation was done by using independent checkpoints (GCPs) to see whether the calculated model parameters are acceptable or not (Tab.2). The values in the last column are root mean square errors measured in image space.

Tab.2: Test Results

	Testfield	**Coordinate System**	**RMS (pixel)**
DLT	Melbourne - IKONOS	Geocentric	0.737
Affine	Melbourne - IKONOS	UTM	0.351
Parallel Perspective	**Melbourne - IKONOS**	**Geocentric**	**0.308**
Bias Compensated RPCs	Melbourne - IKONOS	Geographic	0.519
Estimated RPCs	Melbourne - IKONOS	Geographic	0.351
Affine	**San Diego - IKONOS**	**UTM**	**0.473**
Bias Compensated RPCs	San Diego - IKONOS	Geographic	0.658
Estimated RPCs	San Diego - IKONOS	Geographic	0.474
DLT	Athens - IKONOS	Geocentric	1.089
Affine	**Athens - IKONOS**	**UTM**	**0.723**
Parallel Perspective	Athens - IKONOS	UTM	1.952
DLT	Attika - Spot5	Geocentric	0.912
Affine	**Attika - Spot5**	**Geocentric**	**0.902**
Parallel Perspective	Attika - Spot5	UTM	2.367

The optimal coordinate system seems to be the UTM system, mainly because of its local character. Many times in the geocentric coordinate system nearly as good results as in the

UTM system were obtained. Working in the geographic coodinate system frequently led to numerical instabilities. Although the investigations were carried out using various combinations of GCPs, the the following table lists only the results obtained by using 8 well-distributed control points.The best model for describing the SPOT5 and IKONOS sensor geometry seems to be the Affine Model. This Model delivers in both the geocentric and UTM coordinate system very good results.

The DLT seems to deliver only acceptable results in the geocentric coordinate system needing a reasonable high redundancy.

Unfortunately the available images are not raw data. This is also the main reason why the Parallel Perspective Model does not always deliver good results although it would theoretically be the ideal approach for modelling push-broom scanner geometry. But still, the results come very close to the ones from the Affine Model. In case there are more than 8 GCPs available, the outcomes of the Parallel Perspective Model become even better than the ones from the Affine Model, although the data is pre-processed.

For these data sets a maximum of 8 parameters seems to be enough to model the relation between image and object space. One can conclude that all the models, except the Affine Model, are over parameterised, meaning that there exists a correlation between the parameters.

Not surprisingly, the best results for the simulated data sets were obtained with the Parallel Perspective model, as they were created according to the line scanning technique. The accuracies are about one pixel. Also understandable is the influence by the direction of the a viewing angle. For viewing angles in along-track direction almost no effect can be observed (e.g. the parallel projection of line scanning principle is still valid) while the results from images acquired with an oblique viewing angle in across-track direction show bigger residuals due to an oblique central perspectivity.

5 Conclusion

This paper gives an overview of the quality of diverse sensor models of high-resolution satellite sensors. The test results show that the Affine Model prevails as the most trustful model to exploit high-resolution images. The accuracies lie below one pixel, which is less than one metre for the IKONOS imagery. Unfortunately this model is not supported by the photogrammetric workstations on the market. Since most of them are prepared for the RFM a way of self-calculation has been described. Self-calculation of RPCs with the help of the Affine Model turned out to be the most promissing.
They are at least as good as the RPCs from the image vendor after bias compensation (Fig.3). One could even save money in cases where the RPCs have to be purchased in addition to the images. Just measure 4 (preferably 5 or 6) GCPs and calculate the coefficients using the strategy via the Affine Model and start working.

In summary, if economic factors are not considered, high-resolution satellite imagery can readily be used for accurate geopositioning, and even as substitute for small-scale aerial photography. But in such a case one should bear in mind that the software packages used for the image analysis must support models like the Affine or the Rational Function Model, besides the universally employed collinearity model based on central perspective geometry.

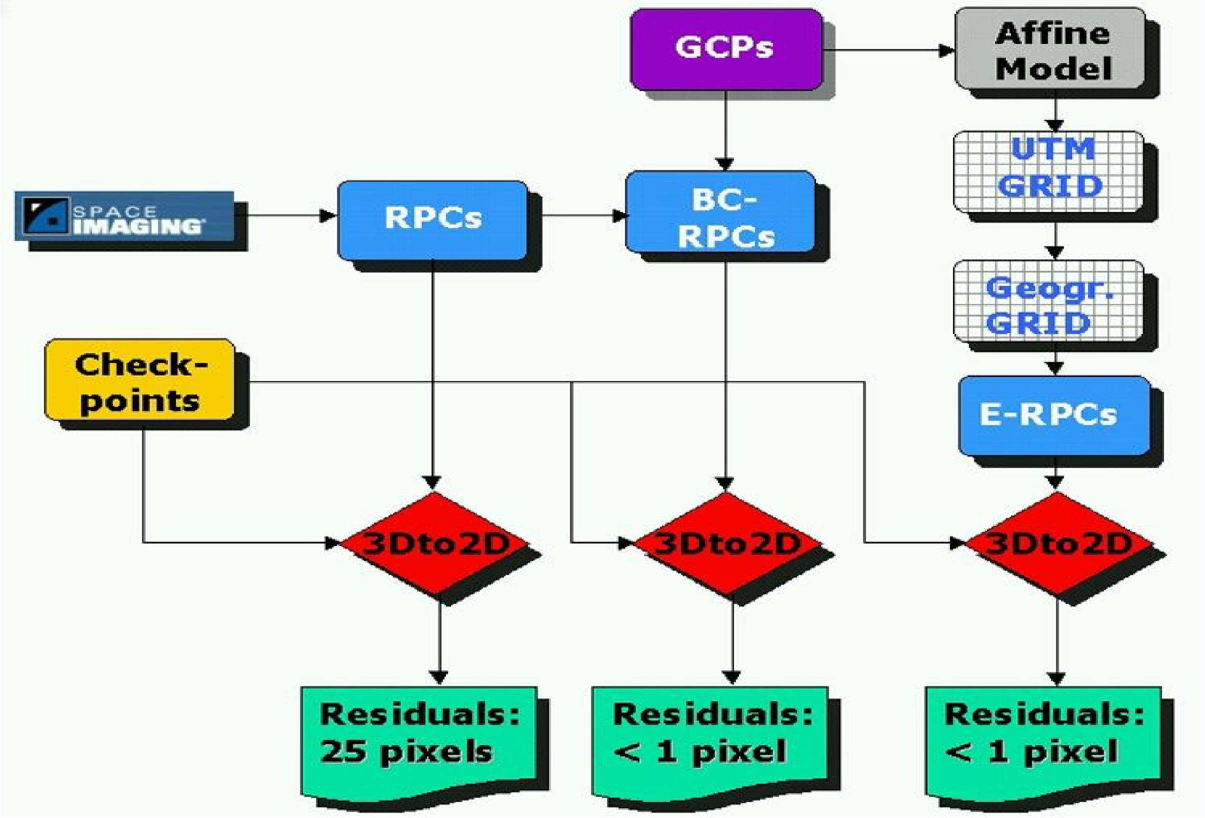


Fig.3: Comparison between vendor RPCs, Bias compensated RPCs and Estimated RPCs

6 References

DIAL, G. AND GRODECKI, J. (2002): Block Adjustment With Rational Polynomial Camera Models, Proceedings of ACSM-ASPRS Annual Conference, Washington DC, (on cd-rom)

FRASER, C. ET AL. (2002): Three-Dimensional Geopositioning Accuracy Of IKONOS Imagery, Photogrammetric Record, 17(99), 465-479

HANLEY, H. ET AL. (2001): Sensor Orientation For High-Resolution Satellite Imagery, ISPRS Archives Commission I, WG I/5, Denver

IKONOS IMAGERY PRODUCTS AND PRODUCT GUIDE (2002), Space Imaging, http://www.spaceimaging.com/whitepapers_pdfs/IKONOS_Product_Guide.pdf, (last accessed on June 10th 2003)

OKAMOTO, A. ET AL. (1999): Geometric Characteristics Of Alternative Triangulation Models For Satellite Imagery, Proceedings of ASPRS-RTI, Annual Conference, 64-72

PRESS KIT (2002): Technical Features Of The SPOT5 System, 6-10 www.cnes.fr/actualites/spot5/va/pdf/technique_va.pdf, (accessed January 27th, 2003)

TAO, V. AND HU Y. (2002): 3D Reconstruction Methods Based On The Rational Function Model, Photogrammetric Engineering & Remote Sensing, Vol. 68, No. 7, 705-714

TOUTIN, T. ET AL. (2003): Error Tracking In IKONOS Processing Using A 3D Parametric Model, Photogrammetric Engineering & Remote Sensing, Vol 69, No. 1, 43-51

WESTIN, T. (1990): Precision Rectification Of SPOT Imagery, Photogrammetric Engineering And Remote Sensing, Vol. 56, No. 2, 247-253

YAMAKAWA, T. (2001): Geometric Analysis Of Affine Models, Department Of Geomatics, University Melbourne, Australia, 1-12