

Dynamic sensor model of HRS Geo-images using parallel projection theory

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Abstract: In last years, accurate spatial data from high resolution satellite images are getting more and more frequently used for modelling topography and other surveying purposes. To extract accurate spatial information, a sensor's mathematical models are needed. Those models classified to two branches: rigorous (parametrical or physical) models and non-rigorous models. In the paper a dynamic sensor model is proposed to extract spatial information from geo-rectified images named the geo-images which their geometry at the time of imaging have been lost. The developed model has been reconstructed basing on a transformation of central-perspective projection into a parallel one.

Keywords: High Resolution Satellite image, orthorectification, parallel projection, dynamic affine sensor model, co-linearity condition

1. Introduction

In September 1999 first commercial satellite IKONOS-2 with high resolution image of Ground Sampling Distance (GSD) not larger than 1 m was launched. The sensor model of high resolution satellite (HRS) image has became one of the most important topics of investigations in different research-oriented institutions. Reconstructed sensor model has to be true, alike in the imaging time instant. In practice, distributors of HRS images usually do not provide users with sufficient information on ephemeris data to reconstruct the sensor model. Therefore the users have to find corresponding accurate sensor model to do processing of the geometric orthorectification, and generating DEM.

HRS images with $GSD \leq 1$ m have extremely narrow angular fields of view (FOV) (Ono et al., 1998; Fraser et al., 2002). That firstly means that the projection of the images is well approximated by parallel rather than central-perspective one. Secondly, the problem of very high correlation between the exterior orientation elements of scene will occur. By those reasons the solutions for determining the exterior orientation elements sometimes do not converge. In order to overcome that problem one of the solutions based on orientation theory of one-dimensional affine images was

proposed by (Okamoto et al., 1992; Ono et al., 1996). The principle of that theory is in the transformation of the central-perspective images into affine ones using parallel projection.

The paper presents at first the basis of parallel projection and shows the affine transformation in a linear form, expressing the relationship between object and image points. In the third section the characteristics of the HRS Geo-images such as QuickBird Standard Imagery, IKONOS Geo-image are outlined. In the fourth section a dynamic affine sensor model is described. The model becomes reconstructed using the assumption that ground is projected into image by parallel projection, where sensor focal distance is set to infinity and the changes of linear and angular exterior orientation elements between scan lines are linear.

The dynamic affine sensor model is a rigorous model for processing HRS Geo-images. The model developed by the author is in the process of testing in the Institute of Photogrammetry and Cartography of the Warsaw University of Technology.

2. Basics of parallel projection

Let an object point $P(X, Y, Z)$ in the reference system $OXYZ$ be projected into a measured plane I – a so-called affine image, with the use of the affine transformation. The image point P_a in the affine image is determined by parallel projection coordinates x_a, y_a in $ox_a y_a$ system. In the parallel projection the directions of projection from objects into image plane must be parallel to each other and perpendicular to an image plane (Fig. 1).

The relationship between an object point P and its image point P_a in the image plane I can be written in a general non-linear form as follows (Morgan et al., 2004; Ono et al., 1996)

$$\begin{bmatrix} x_a \\ y_a \\ 0 \end{bmatrix} = s\lambda \mathbf{R}^T \begin{bmatrix} L \\ M \\ N \end{bmatrix} + s\mathbf{R}^T \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} + \begin{bmatrix} \Delta x \\ \Delta y \\ 0 \end{bmatrix} \quad (1)$$

where: $L, M, N = \sqrt{1 - L^2 - M^2}$ – components of the unit projection vector, $x_a, y_a, \Delta x, \Delta y$ – the coordinates of image point and their corresponding shifts, s – scale coefficient, λ – distance between the object and the image point, \mathbf{R} – rotation matrix transforming the object into image, X, Y, Z – coordinates of the object point.

After transforming a non-linear equation (1) into a linear one, one obtains

$$\begin{aligned} x_a &= a_1 X + a_2 Y + a_3 Z + a_4 \\ y_a &= b_1 X + b_2 Y + b_3 Z + b_4 \end{aligned} \quad (2)$$

where $a_1, a_2, a_3, a_4; b_1, b_2, b_3, b_4$ are the independent coefficients. The 8 orientation parameters a_j, b_j ($j = 1, 2, 3, 4$) of the affine image are equivalent to three rotations φ, ω, χ of the affine image, two translation elements between image coordinate system

ox_a, y_a and object space coordinate system $OXYZ$, two rotation parameters relating projected rays and the normal to the image plane and finally an image scale.

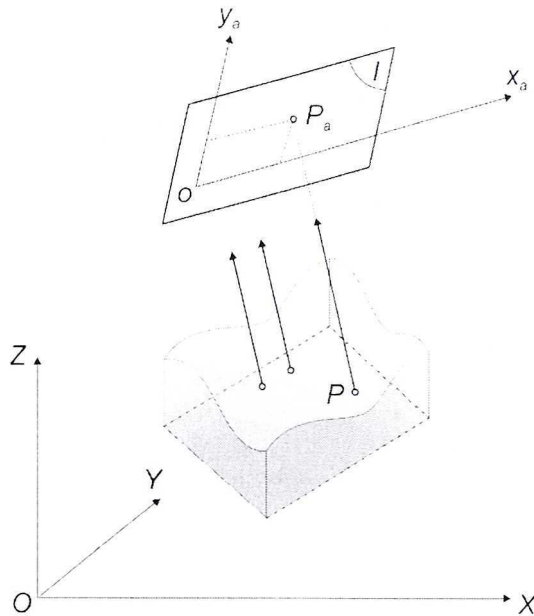


Fig. 1. Concept of the parallel projection

It is clear from (2) that for orienting single image the minimum number of Ground Control Points needed equals to four.

Let X_M, Y_M, Z_M be model space coordinates in the 3D. The transformation from object space X, Y, Z into model space X_M, Y_M, Z_M can be described in terms of three-dimensional affine transformation with the use of 12 independent coefficients A_j, B_j, C_j ($j = 1, 2, 3, 4$) as follows

$$\begin{aligned} X_M &= A_1X + A_2Y + A_3Z + A_4 \\ Y_M &= B_1X + B_2Y + B_3Z + B_4 \\ Z_M &= C_1X + C_2Y + C_3Z + C_4 \end{aligned} \quad (3)$$

In order to perform orientation of the model created from stereo images the minimum number of also 4 GCPs is needed. It once again confirms that the relationships (1) (2) (3) are true only for the parallel projection.

3. HRS Geo-image

HRS Geo-Image is the Geo-product of the raw HRS image, which is a geo-referenced image rectified to a surface with a constant height with respect to the Earth's ellipsoid using the direct sensor orientation data determined by the GPS, gyro and star sensor

acquired in the satellite orbit. IKONOS Carterra-Geo and QuickBird Standard Imagery are the two examples of HRS Geo-images (Jacobsen, 2003; Jacobsen and Passini, 2003). Usually, IKONOS and QuickBird images are not taken in the nadir direction. Thus the reference surface for the rectification is important if no control points are available. The information on the height level used is not given in the header data.

All Geo-products of IKONOS imageries are map projected - rectified to a datum and map projection system. To produce Geo-products, GeoEye uses a correction process that removes image distortions introduced by the collection geometry and then re-samples the imagery to a uniform ground sampling distance (GSD) and specified map projection. Geo-images are not orthorectified; their accuracy is limited by terrain displacement.

The QuickBird Standard Imagery is rectified to the rough DEM GTOPO30. They have to be handled in the same manner like the IKONOS Geo-image with only difference that, instead of the height difference against the reference surface for the QuickBird Standard Imagery the height difference against the GTOPO30 has to be used. Digital Globe distributes different products of the QuickBird, even raw images. Opposite to the Digital Globe, GeoEye distributes only the geo-referenced Carterra-Geo as lowest level product from IKONOS.

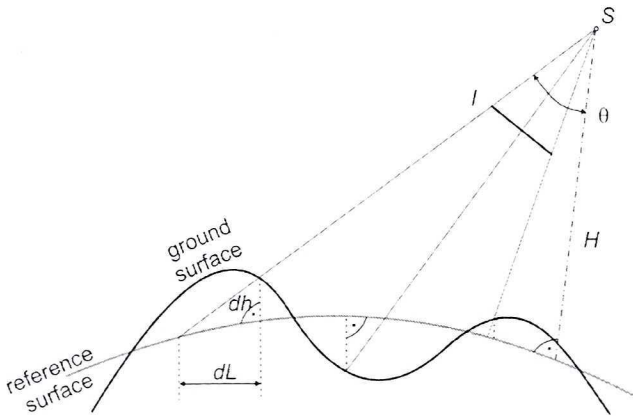


Fig. 2. Geometry of the IKONOS Geo-Image and QuickBird Standard Imagery

In the processing of the geo-referenced rectification to the surface with constant height the ground height differences dh were not taken into account. An error dL in the ground position caused by dh in relation with nadir angle of view direction θ is

$$dL = dh \tan \theta \quad (4a)$$

An error dr in image position caused by dL is

$$dr = \frac{dh}{H - dh} r \quad (4b)$$

where f is the focal distance of the sensor optical system, H is the height of the imaging flight, and r is a radial distance of image point.

4. Dynamic sensor model using parallel projection

In reality, satellite CCD line – scanner images such as IKONOS, QuickBird, SPOT, IRS and other are taken by central-perspective projection. In practice the sensors of satellite CCD line – scanner have extremely narrow angular field of view (FOV). For example, the IKONOS, QuickBird and SPOT sensors have the FOV of 0.93° , 2.12° , 4.13° , respectively. It causes very high correlation between the orientation parameters when using rigorous central-perspective projection. In the consequence, due to ill-conditioned system of normal equation the solution may not be convergent. One of the ways to overcome this problem is to employ the parallel projection theory instead of central-perspective one by transforming the central-perspective images into affine ones.

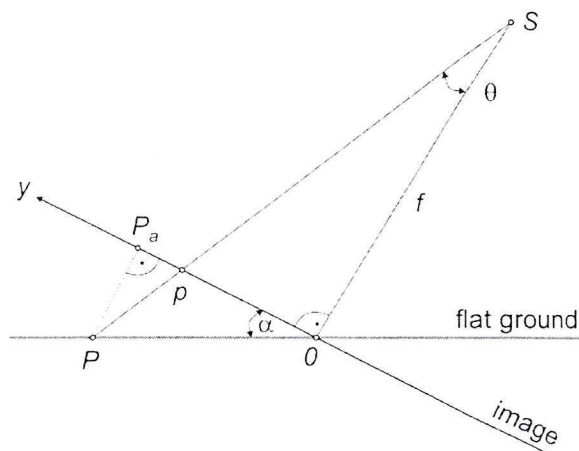


Fig. 3. Geometric relationship between central-perspective (point P) and parallel projection (point P_a)

Figure 3 shows the lateral angle α between flat terrain surface and central perspective line image, the point p denotes a real image point, P is the ground point and P_a is affine image point. The relationship between central-perspective image point $p(x, y)$ and the corresponding affine image point $P_a(x_a, y_a)$ with an assumption of the null interior orientation is given as follows (Okamoto et al., 1999)

$$\begin{aligned} x_a &\equiv x \\ y_a &= \frac{f}{f - y \tan \alpha} y \end{aligned} \quad (5)$$

where f is the focal distance of a sensor.

Substituting x_a, y_a from (5) into (2) gives the affine sensor model in parallel projection as follows

$$\begin{aligned} x &= a_1X + a_2Y + a_3Z + a_4 \\ \frac{f}{f - y \tan \alpha} y &= b_1X + b_2Y + b_3Z + b_4 \end{aligned} \tag{6}$$

Every line of CCD linear-scanner image (sometimes called push-broom image) is one-dimensional central-perspective (Fig. 4) and each line has its own exterior orientation at imaging time moment.

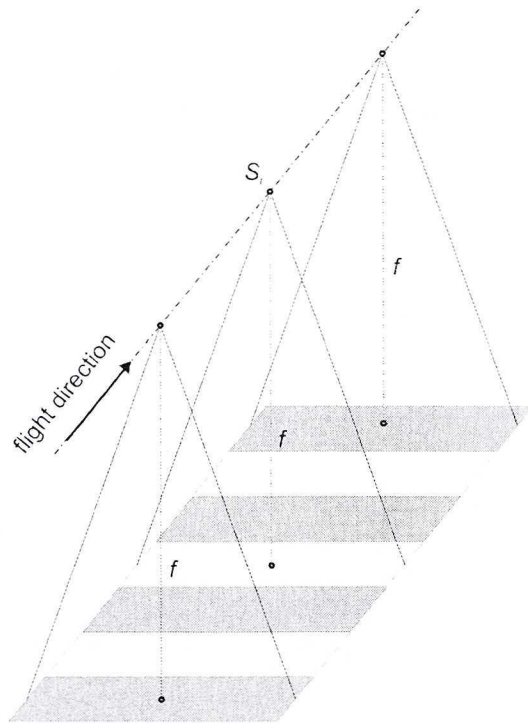


Fig. 4. One-dimensional central-perspective image of each scan line

The linear and angular exterior orientation elements of any i -line at time t will be denoted as $X_{S_i}(t), Y_{S_i}(t), Z_{S_i}(t)$, and $\varphi_i(t), \omega_i(t), \chi_i(t)$, respectively. Using co-linearity condition the relationship between the coordinates of any point belonging to each scan line $(0, y - f)$ and its corresponding object point (X, Y, Z) is described in central-perspective projection as follows

$$\begin{bmatrix} 0 \\ y \\ -f \end{bmatrix} = \lambda [\mathbf{R}(t)]^T \begin{bmatrix} X - X_{S_i}(t) \\ Y - Y_{S_i}(t) \\ Z - Z_{S_i}(t) \end{bmatrix} \tag{7}$$

with

$$[\mathbf{R}(t)]^T = \begin{bmatrix} a_{11}(t) & a_{12}(t) & a_{13}(t) \\ a_{21}(t) & a_{22}(t) & a_{23}(t) \\ a_{31}(t) & a_{32}(t) & a_{33}(t) \end{bmatrix}$$

and $a_{jk}(t) = F[(\varphi_i(t), \omega_i(t), \chi_i(t))]$ for $(j, k = 1, 2, 3)$ that are time-dependent elements of the rotation matrix \mathbf{R} where λ is a scale parameter, f is a focal distance of scanner and $X_S(t)$, $Y_S(t)$, $Z_S(t)$ are coordinates of central-perspective centre.

If the ground is projected into the image using parallel projection, a focal distance f is set to infinity, and therefore, third equation of (7) loses the meaning. The two remaining equations of (7) can be written as

$$\begin{aligned} 0 &= a_{11}(t)[X - X_S(t)] + a_{12}(t)[Y - Y_S(t)] + a_{13}(t)[Z - Z_S(t)] \\ y_a &= a_{21}(t)[X - X_S(t)] + a_{22}(t)[Y - Y_S(t)] + a_{23}(t)[Z - Z_S(t)] \end{aligned} \quad (8)$$

The coordinates of projection centre for any scan i -line at t (Fig. 4) are considered linear functions of time and defined as follows

$$\begin{aligned} X_{S_i}(t) &= X'_0 + \Delta X' \cdot t \equiv X_0 + \Delta X \cdot i \\ Y_{S_i}(t) &= Y'_0 + \Delta Y' \cdot t \equiv Y_0 + \Delta Y \cdot i \\ Z_{S_i}(t) &= Z'_0 + \Delta Z' \cdot t \equiv Z_0 + \Delta Z \cdot i \end{aligned} \quad (9)$$

where the constants X'_0 , Y'_0 , Z'_0 , $\Delta X'$, $\Delta Y'$, $\Delta Z'$ were determined from the metadata recorded on the board after each time interval t while the constants X_0 , Y_0 , Z_0 , ΔX , ΔY , ΔZ were determined using the numbers of scanned i -lines.

First equation of (8) can be re-written as

$$i = \frac{a_{11}(t)[X - X_0] + a_{12}(t)[Y - Y_0] + a_{13}(t)[Z - Z_0]}{a_{11}(t)\Delta X + a_{12}(t)\Delta Y + a_{13}(t)\Delta Z} \quad (10)$$

The line number i is counted in the flying direction and can be replaced by x coordinate. The equation (10) is thus equivalent to the following one

$$x = A_1(t)X + A_2(t)Y + A_3(t)Z + A_4(t) \quad (11)$$

Similarly, the second equation of (8) can be written as

$$y_a = B_1(t)X + B_2(t)Y + B_3(t)Z + B_4(t) \quad (12)$$

The system of equations (11), (12) represents a so-called dynamic affine sensor model in parallel projection in the hidden form. Substituting y_a of (12) by (5), the dynamic affine sensor model in parallel projection is

$$\begin{aligned} x &= A_1(t)X + A_2(t)Y + A_3(t)Z + A_4(t) \\ \frac{f}{f - y \tan \alpha} y &= B_1(t)X + B_2(t)Y + B_3(t)Z + B_4(t) \end{aligned} \quad (13)$$

The coefficients $A_j(t)$, $B_j(t)$, $j = (1, 2, 3, 4)$ are called time-variant coefficients or dynamic coefficients.

Suppose the dynamic coefficients $A_j(t)$, $B_j(t)$ are linear with respect to time t or line number i that is equivalent to x coordinate. Then

$$\left. \begin{aligned} A_j(t) &= A'_{0j} + A'_{1j}t \equiv A''_{0j} + A''_{1j}i = A_{0j} + A_{1j}x \\ B_j(t) &= B'_{0j} + B'_{1j}t \equiv B''_{0j} + B''_{1j}i = B_{0j} + B_{1j}x \end{aligned} \right\} \text{ for } (j = 1, 2, 3, 4) \quad (14)$$

where A_{kj} , B_{kj} , A'_{kj} , B'_{kj} , A''_{kj} , B''_{kj} ($k = 0, 1$) are constant. Substituting (14) to (11) and (12), and after performing some algebraic operations the final dynamic sensor model in parallel projection at the explicit form is

$$\begin{aligned} x &= \frac{T_{01}}{1 - T_{11}} \\ y_a &= \frac{T_{01}}{1 - T_{11}} T_{12} - \frac{T_{02}}{1 - T_{11}} T_{11} + \frac{T_{02}}{1 - T_{11}} \end{aligned} \quad (15)$$

where:

$$\begin{aligned} T_{01} &= A_{01}X + A_{02}Y + A_{03}Z + A_{04} \\ T_{02} &= B_{01}X + B_{02}Y + B_{03}Z + B_{04} \\ T_{11} &= A_{11}X + A_{12}Y + A_{13}Z + A_{14} \\ T_{12} &= B_{11}X + B_{12}Y + B_{13}Z + B_{14} \end{aligned}$$

Replacing in (15) y_a from (5) the dynamic sensor model in parallel projection is as follows

$$\begin{aligned} x &= \frac{T_{01}}{1 - T_{11}} \\ \frac{f}{f - y \tan \alpha} y &= \frac{T_{01}}{1 - T_{11}} T_{12} - \frac{T_{02}}{1 - T_{11}} T_{11} + \frac{T_{02}}{1 - T_{11}} \end{aligned} \quad (16)$$

It should be noted that (6) corresponds to a particular case of (16) when the denominator of (16) equals to 1 and a corrected term T_{02} equals to 0.

Simple sensor affine model in the parallel projection (6) can be used in practice. That model is derived under the assumption that attitude of the sensor does not change during the acquisition of one scene image. The effects of Earth curvature and Earth rotation can be neglected in small area. The use of simple sensor affine model (6) is limited for large block of HRS image, where the effects of the change of sensor's attitude, Earth curvature, and Earth rotation are large (Jacobsen, 2006).

The minimum number of 5 GCPs for orienting scene by affine sensor model (6) is needed to determine 8 coefficients a_i , b_i ($i = 1, 2, 3, 4$) and two correction values of focal distance f and angle α . Using the sensor model (16) the minimum number of GCPs for orienting a scene gets increased to 9.

Softwares based on the algorithms for model (6) and (16) developed by the author are in the process of testing in the Institute of Photogrammetry and Cartography of the Warsaw University of Technology with the use of different scenes of HRS Geo-images. First results based on model (6) show the usefulness and effectiveness of the method developed (Iwanicki et al., 2007a). The results obtained compared with those of PCI commercial system (Canada) and of Hannover's software ones provide a further verification of the method and its practical usefulness (Iwanicki et al., 2007b).

5. Conclusions

The models (6) and (16) developed show that parallel projection can be expressed as the central-perspective projection with infinite focal distance. The affine projection is a special case of the central-perspective projection. The affine image has no projection centre and the direction of projected ray is the same for any point on the image.

The equation (6) represents a simple sensor model which requires minimum information on the geometry of the sensor (only focal distance f of the sensor), and does not need ephemeris data. The model (6) was reconstructed with an assumption that the effects of Earth rotation and curvature are neglected in the small area, and the change of attitudes and centre perspective coordinates are approximately linear.

Both equations (15) and (16) express the dynamic sensor model reconstructed on the basis of the assumption that exterior orientation elements of the each line are functions of time. This model is more accurate than the model (6), but it requires more GCPs for orienting a scene. Similarly to the model (6), the model (16) does not need ephemeris data in processing of scene orientation.

Both models (6), and (16) are useful for orthorectifying scenes, generating DEM and performing block triangulation of HRS images.

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Dynamiczny model sensora wysokorozdzielczych Geo-obrazów satelitarnych z wykorzystaniem teorii rzutu równoległego

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Streszczenie

Wysokorozdzielcze obrazy satelitarne coraz częściej są stosowane w praktyce dla celów topograficznych i innych prac geodezyjnych. Ze względu na brak dostatecznych informacji o geometrii sensora i danych efemeryd orbitalnych, ścisły model sensora oparty na fizycznym mechanizmie, używany do dokładnego tworzenia orthofotomapy, generowania DEM/DTM i innych celów, jest kłopotliwy do rekonstrukcji. Jednak, dystrybutorzy wysokorozdzielczych obrazów satelitarnych zazwyczaj dostarczają użytkownikom nie surowe lecz przetworzone obrazy zwane Geo-obrazami (geo-rectified image or geo-images), które zostały rzutowane na pewnej płaszczyźnie o stałej wysokości względem przyjętej elipsoidy. Model sensora dla Geo-obrazów musi być zmodyfikowany w odniesieniu do ścisłego (fizycznego) modelu. Niniejsza praca autora przedstawia dynamiczny model sensora dla Geo-obrazów, który został utworzony przy użyciu ścisłego warunku kolinearności z wykorzystaniem teorii rzutu równoległego.