

A MODEL FOR ALONG TRACK STEREO SENSORS USING RIGOROUS ORBIT MECHANICS

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KEY WORDS: along track, rigorous sensor model, orbit determination, Kepler motion, direct orientation.

ABSTRACT:

In this paper a new sensor model for along track stereo optical satellite sensors using orbit mechanics is introduced in detail. The fundamental point of an along track model is to benefit from the same orbit acquisition, in order to orientate simultaneously all the along track stereo images. The obvious reason is to reduce the number of unknown parameters which generally are high correlated. Moreover, the simultaneous solution extends the narrow field of view of each satellite image because all along track images are treated as one iconic image, with the field of view equal to the angle between the first and the last image. The developed model is based on the collinearity equations which are modified and combined with orbit determination-propagation methods. The model was evaluated on imagery acquired by SPOT5-HRS sensors. The model is also possible to be solved directly if the appropriate information is given in the metadata file.

1. INTRODUCTION

Along track stereo images are acquired on the same orbit by satellites which usually have on board more than one sensor looking at the earth with different angles, or satellites that can rotate their sensor in the along track direction. The advantages of along track stereo images compared with images that are taken from adjacent orbits (across track) are that they are acquired in almost the same ground and atmospheric conditions. The fundamental point of an along track model is to benefit, from the same orbit acquisition, in order to orientate simultaneously all the along track stereo images.

Generally, there are two ways to describe a phenomenon. The first one is to define and formulate the forces that cause it. The second one is to describe the phenomenon itself without trying to find the reason (force) why this phenomenon is happen. In pushbroom sensor modelling the second way of solving the problem is represented by models based on affine, polynomial or rational function methods. A critical disadvantage of this approach is as the forces that act on the satellite are not known is impossible to predict the behaviour of the model in parts of the image where no observations are presented.

In this paper the first way of reaching the sensor modelling issue is adopted. Great effort is made in order to define the essential forces which are involved in the acquisition of the pushbroom images, according to the required accuracy and the data provided. Moreover, as it is very important to understand how well the image acquisition process is described by the developed model, tie points are not used in any phase of the model solution as it is essential to find out how the model itself establishes the relative orientation of the images.

2. MODEL DESCRIPTION

The pushbroom model is a kinematic model. The scanning effect on the ground is due to the motion of the satellite. A single image consists of a number of framelets which are independent one-dimensional images with their own exterior orientation parameters. Thus, in a rigorous sensor model the satellite motion in space should be described as accurately as possible. In other words, a rigorous sensor model should describe the state of the satellite during the acquisition time of the images. Six parameters are enough to establish the state of the satellite at an epoch (time stamp), which are the state vector associated with position and velocity vectors. This final statement leads to the conclusion that for a single pushbroom

sensor the simplest model has nine unknown parameters; six to describe the state and three the attitude of the satellite.

On the other hand the model should be a generic one capable to be used in various along track sensors. Thus, it is based on the collinearity equations which are generic equations relating the image space with the ground space. However, for the simulation of the acquisition geometry of pushbroom images the collinearity equations are modified and combined with orbit determination-propagation equations. Although, different versions of this model are introduced, depending mainly on various orbit determination-propagation methods, the initial and fundamental research assumptions are common for all model versions as they have already introduced (Dowman and Michalis, 2003; 2004) and are found from the literature or adopted in this paper. The most important of them follows:

- The coordinates along the flight path have the same scale (constant time interval).
- The orientation of the satellite images should be carried out in a geocentric coordinate system in order to avoid distortions caused by earth curvature and map projection and to facilitate integration with sources of metadata information that may be available.
- The satellite motion during the acquisition time of along track stereo images is a Keplerian motion. In combination with the previous assumption an inertial coordinate system should be used.
- The rotation angles of the satellite remain constant during the acquisition time of each image.

2.1. Modified collinearity equations of pushbroom scanners

The well-known frame camera collinearity equations need modification before they are applied to pushbroom images. As already mentioned, a pushbroom image consists of a number of consecutive framelets which are acquired due to the satellite motion. Thus, the collinearity equations are modified in a way where the ground coordinates and the rotations of the perspective center are modelled as a function of time.

$$\begin{bmatrix} 0 \\ y - y_0 \\ -c \end{bmatrix} = \lambda M(t) \begin{bmatrix} X - X_c(t) \\ Y - Y_c(t) \\ Z - Z_c(t) \end{bmatrix}$$

where
 c is the focal length

t is the acquisition time of a framelet which is defined in terms of image coordinates

X, Y, Z are the ground coordinates of a point

$X_c(t), Y_c(t), Z_c(t)$ are the ground coordinates of the framelet perspective center as a function of time

λ is a scale factor which varies from point to point

$M(t)$ is a 3x3 rotation matrix which brings the ground coordinate system parallel to the framelet coordinate system as a function of time.

y is the y-framelet coordinates of the corresponding point

y_o is a small offset from the perspective center origin.

2.2. Kepler model for along track sequence

This version of the model is based on the Kepler problem (Bate et al, 1971). In the simplest case of two along track stereo images the number of unknown parameters is twelve in total. The state vector of the base framelet of the first image represents six of these unknown parameters, while the corresponding state vector of the second image is calculated from the previous one by the Kepler equation, thus is not an unknown in the solution. The other six unknown parameters are the rotation angles of the two images; three rotations for each image as it is assumed that the rotations remain constant during the acquisition of each image. If these images are treated individually the number of unknown parameters are nine for each one, which means eighteen unknown parameters in total, thus the number of unknown parameters is reduced by six. The formulation of the Kepler model of two images case is described in detail by the following equations. The ground coordinates of the base framelet perspective center $X_c(t), Y_c(t), Z_c(t)$ of both images as a function of time is defined as follows:

$$X_c(t) = X_o + u_x \cdot \tau - \frac{GM \cdot X_o \cdot \tau^2}{2 \cdot (X_o^2 + Y_o^2 + Z_o^2)}$$

$$Y_c(t) = Y_o + u_y \cdot \tau - \frac{GM \cdot Y_o \cdot \tau^2}{2 \cdot (X_o^2 + Y_o^2 + Z_o^2)}$$

$$Z_c(t) = Z_o + u_z \cdot \tau - \frac{GM \cdot Z_o \cdot \tau^2}{2 \cdot (X_o^2 + Y_o^2 + Z_o^2)}$$

where

$\tau = t$ for the first image

$\tau = t + dt$ for the second image

and

t is the acquisition time a framelet which is defined in terms of each image coordinates (McGlone, 2004)

dt is the time interval between the acquisition of the base framelet of each image.

(X_o, Y_o, Z_o) is the position vector of the perspective center of the base framelet of the first image

(u_x, u_y, u_z) is the velocity vector of the perspective center of the base framelet of the first image

GM is the Earth gravitational parameter with value of $398600,4415 km^3 / s^2$

In case of more than two along track images, the Kepler model is extended in a way that the state vectors of the base framelet of all images from the second one to the final one are calculated from the state vector of the base framelet of the first image by the Kepler equation. For each image three unknown parameters are added representing its rotation angles. It is obvious that the number of unknown parameters is reduced dramatically as the number of images is increased compared to the method where all images are solved individually (Table 1).

In the Kepler model, all along track images are treated as one iconic image where its coordinates are found if the acquisition time interval of the corresponding image from the first image is added (in general case of more than two images) on the framelet coordinates of each image. In other words, in Kepler model the

transition factor from the first image to the others is their acquisition time interval.

Number of images	Individual solution	Kepler model	Gauss-Lambert model	Combined method
2	18	12	12	-
3	27	15	-	18
4	36	18	-	24
5	45	21	-	30

Table 1. Number of unknown parameters for single and along track models in case of 2 to 5 images

2.3. Lambert-Gauss model

This version of the model is based in the Gauss-Lambert problem (Bate et al, 1971). It can be used by itself only in case of two along track stereo images. The number of unknown parameters is twelve in total (Table 1). In the case of more than two images is used in combination with the Herrick-Gibbs method (Bate et al, 1971). The position vectors of the base framelet of both images represent six of the unknown exterior orientation parameters. The velocity vector of the base framelet of each images are related to the position vectors by the Gauss-Lambert method thus are not unknowns in the solution. The other six unknown parameters are the rotation angles of the two images as in Kepler model. The ground coordinates of the base framelet of the first image $X_c^1(t), Y_c^1(t), Z_c^1(t)$ are defined as follows:

$$X_c^1(t) = X_1 + u_{1x} \cdot t - \frac{1}{2} a_{1x} \cdot t^2 = X_1 + \frac{X_2 - f \cdot X_1}{g} \cdot t - \frac{GM \cdot X_1 \cdot t^2}{2 \cdot (X_1^2 + Y_1^2 + Z_1^2)^{3/2}}$$

$$Y_c^1(t) = Y_1 + u_{1y} \cdot t - \frac{1}{2} a_{1y} \cdot t^2 = Y_1 + \frac{Y_2 - f \cdot Y_1}{g} \cdot t - \frac{GM \cdot Y_1 \cdot t^2}{2 \cdot (X_1^2 + Y_1^2 + Z_1^2)^{3/2}}$$

$$Z_c^1(t) = Z_1 + u_{1z} \cdot t - \frac{1}{2} a_{1z} \cdot t^2 = Z_1 + \frac{Z_2 - f \cdot Z_1}{g} \cdot t - \frac{GM \cdot Z_1 \cdot t^2}{2 \cdot (X_1^2 + Y_1^2 + Z_1^2)^{3/2}}$$

The ground coordinates of the base framelet of the second image $X_c^2(t), Y_c^2(t), Z_c^2(t)$ are defined as follows:

$$X_c^2(t) = X_2 + u_{2x} \cdot t - \frac{1}{2} a_{2x} \cdot t^2 = X_2 + \frac{\dot{g} \cdot X_2 - X_1}{g} \cdot t - \frac{GM \cdot X_2 \cdot t^2}{2 \cdot (X_2^2 + Y_2^2 + Z_2^2)^{3/2}}$$

$$Y_c^2(t) = Y_2 + u_{2y} \cdot t - \frac{1}{2} a_{2y} \cdot t^2 = Y_2 + \frac{\dot{g} \cdot Y_2 - Y_1}{g} \cdot t - \frac{GM \cdot Y_2 \cdot t^2}{2 \cdot (X_2^2 + Y_2^2 + Z_2^2)^{3/2}}$$

$$Z_c^2(t) = Z_2 + u_{2z} \cdot t - \frac{1}{2} a_{2z} \cdot t^2 = Z_2 + \frac{\dot{g} \cdot Z_2 - Z_1}{g} \cdot t - \frac{GM \cdot Z_2 \cdot t^2}{2 \cdot (X_2^2 + Y_2^2 + Z_2^2)^{3/2}}$$

where

(X_i, Y_i, Z_i) , (u_{ix}, u_{iy}, u_{iz}) and (a_{ix}, a_{iy}, a_{iz}) is the position, velocity and acceleration vectors of the perspective center of the base framelet of both images ($i=1,2$), respectively.

f, g, \dot{f}, \dot{g} are the transition functions (Bate, 1971; Michalis, 2005).

In Gauss-Lambert model, both along track images are also treated as one iconic image. However, it is assumed that the framelet coordinates are calculated from the corresponding base framelet of each image. In other words, this model divides the iconic image in two segments with their own perspective centers which are related to each other by Gauss-Lambert equations.

2.4 Combined Gauss-Lambert and Herrick-Gibbs model

For more than two along track images the Gauss-Lambert model can be used in combination with the Herrick-Gibbs method. In case of a triplet the combined model is developed in the following way: The position vectors of each image are unknowns in the solution (nine unknowns). Using Herrick-

Gibbs method the velocity vector of the middle image is calculated. On the other hand using the Gauss-Lambert model the velocity vectors of both edge images are also calculated. The rotation angles of each image are unknown parameters in the solution (another nine unknowns) thus, the unknown parameters is eighteen in total. The number of unknown parameters is reduced by nine, compared to the solution where the three images are solved individually (table 1). The velocity vector of the middle image is calculated as follows:

$$\vec{u}_M = -dt_{2M} \left(\frac{1}{dt_{M1} \cdot dt_{31}} + \frac{GM}{12 \cdot r_1^3} \right) \vec{r}_1 + (dt_{2M} - dt_{M1}) \cdot \left(\frac{1}{dt_{M1} \cdot dt_{2M}} + \frac{GM}{12 \cdot r_M^3} \right) \vec{r}_M + dt_{M1} \left(\frac{1}{dt_{2M} \cdot dt_{21}} + \frac{GM}{12 \cdot r_2^3} \right) \vec{r}_2$$

where

$\vec{r}_1, \vec{r}_M, \vec{r}_2$ are the position vectors of first, middle and third image respectively

(X_M, Y_M, Z_M) and $\vec{u}_M = (u_{Mx}, u_{My}, u_{Mz})$ are the position and velocity vectors of the perspective center of the base framelet of the middle image, respectively.

This combined method could be extended in the case of more than three along track images where the velocity vectors of the intermediate along track images are calculated by Herrick-Gibbs method.

3. MODEL EVALUATION

The evaluation process of the along track stereo sensor model is presented. In this process SPOT5-HRS images are used. The High Resolution Stereoscopic instrument (HRS) has two telescopes and acquires stereopairs at a 90-second interval, of 120-km swath, with viewing angles of $\pm 20^\circ$ along the track of the satellite, with a B/H ratio of about 0.8. A comparison is made between single image sensor model and the various versions of the along track sensor model.

3.1. Data sets-Reference data

A SPOT5 HRS data set that covers an area located around Aix-en-Provence in SE France which is provided under the SPOT Assessment Project (SAP) set up by CNES and ISPRS. The ground control points were originally provided by IGN for the OEEPE test of SPOT data and were mainly extracted from 1:25000 maps. A total of 33 reference points were measured in HRS images having a good distribution on the images (Figure 1). Twelve of them are used as Ground Control Points in this evaluation process while the rest 21 are used as Check Points.

3.2. Orbit mechanics models evaluation

An accuracy assessment of the different orbit determination-propagation methods used in the along track model is introduced. This evaluation process takes place in an inertial space in order to meet the fundamental assumption of the Keplerian motion. The extracted values of the models are compared with the navigation data of SPOT 5 which are included in the metadata file of HRS images with accuracy better than one meter, thus it is assumed that they represent the true values of the unknown exterior orientation parameters. The navigation data which are used in this evaluation is the position and velocity vectors of the satellite measured by the DORIS system every 30 seconds with respect to ITRF90 (almost identical to WGS84). These data need to be transformed to an inertial coordinate system and then to be interpolated in order to find the state vectors of the base framelets of each image. In the interpolation process, instead of Lagrange interpolation as suggested in the SPOT SATELLITE GEOMETRY HANDBOOK, (SPOT, 2002), third order polynomials are used. The achieved accuracy (RMSE) of the interpolation process is determined to be better than one centimetre for the position

vector and better than one millimetre per second for the velocity.

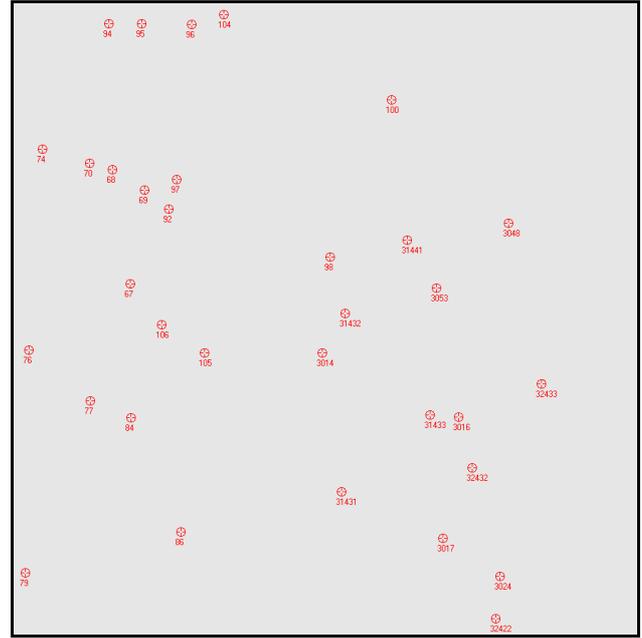


Figure 1. Distribution of Reference Points on HRS images

In the accuracy evaluation of Herrick-Gibbs model a third state vector is needed. For this reason, it is assumed that in the sequence of two along track HRS images an imaginary-nadir image is added. From the metadata file the time acquisition of this image is found assuming that it was acquired at the middle of the time interval between the HRS images. In table 2 the difference from the SPOT metadata values is presented for this imagery-image in order to have a direct comparison of all orbit mechanics methods.

	Kepler model	Gauss-Lambert model	Herrick-Gibbs method
Position X (m)	6.845	-	-
Position Y (m)	-8.474	-	-
Position Z (m)	3.629	-	-
Velocity u_x (m/sec)	0.293	0.144	0.012
Velocity u_y (m/sec)	-0.363	-0.179	-0.012
Velocity u_z (m/sec)	0.168	0.091	-0.016

Table 2. Difference from the true values and the calculated from the orbit mechanics methods

From this table the velocity vector, which is calculated within all methods, seems to be better approximated by Herrick-Gibbs method and by Gauss-Lambert method. It seems that the combination of three position vectors in the model instead of one position and one velocity vector (Kepler model) or two position vectors (Gauss-Lambert model) provides better accuracy. It seems that for the same orbit period the increase of the position vectors leads to an improvement of the accuracy of the model.

3.3. HRS data solution with GCPs

In table 3 the RMSE of GCPs and Independent Check Points (ICP), when HRS images solved as single images and in an along track sequence, is given. In the case where the HRS images are solved separately the number of unknown parameters is 18 while in along track models it is 12. The RMSE values are almost the same in X and Y direction while in

Y direction the single image solution gives slightly better value. However the RMSE of Check points in case of along track sequence is better than in single images solution, especially in Y direction where the improvement is about two times. Moreover the most interesting point where in the images this improvement occurs. If figures 2, 3 and 4 are compared where the coordinate difference of the check points are represented the larger improvements are at the edges of the images (check points 76, 77, 79, 94, 95, 96, 104, 3024). It seems that the along track sensor model overall is represent better the images acquisition geometry than the single image solution. The single image model is also based on Kepler equation (Michalis, 2005).

RMSE	Single images		Kepler model		Gauss-Lambert model	
	GCP (12)	ICP (21)	GCP (12)	ICP (21)	GCP (12)	ICP (21)
No						
X (m)	5.80	12.18	5.72	11.10	5.69	11.99
Y (m)	7.25	18.90	9.46	10.76	9.65	11.36
Z (m)	6.35	11.33	5.79	9.86	5.88	11.53

Table 3. RMSE of Ground Control Points (GCP) and (ICP) in Inertial Space

3.4. Solve HRS-data with a few GCPs

An additional test is made trying to solve the along track Kepler model using as few GCPs as possible. Theoretically, the number of unknown parameters in this model for two along track images is 12 in total. Thus 3 GCPs are enough to have a solution. In table 4 the RMSE of the same 21 Check Points which are used in the previous HRS test are used (in order to have a direct comparison) in each direction is presented in the following cases:

- Three GCPs used which are 68,86,3016.
- Four GCPs used which are 68,86,3016,31432.
- Six GCPs used which are 68,84,86,3016,3432,32433.

If table 4 is compared with table 5 the conclusions are:

- The along track model with just four GCPs has almost the same accuracy as single image solution with 12 GCPs. It is should be mentioned here that if the HRS images are solved separately the number of unknown parameters is 18; thus with 4 GCPs there is no solution.
- The along track model using 6 GCPs reaches the accuracy of along track model with 12 GCPs.

	3 GCPs	4 GCPs	6 GCPs
RMSE X (m)	13.268	12.569	12.207
RMSE Y (m)	26.357	19.930	13.782
RMSE Z (m)	16.372	13.338	12.579

Table 4. Kepler along track sensor model accuracy with different number of GCPs used

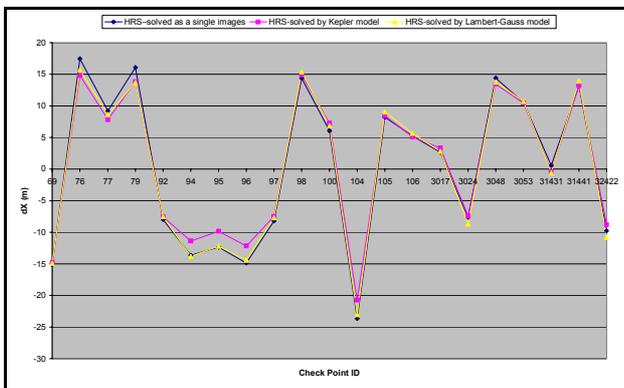


Figure 2. X-coordinate difference of the calculated values in the solution of along track and single image models

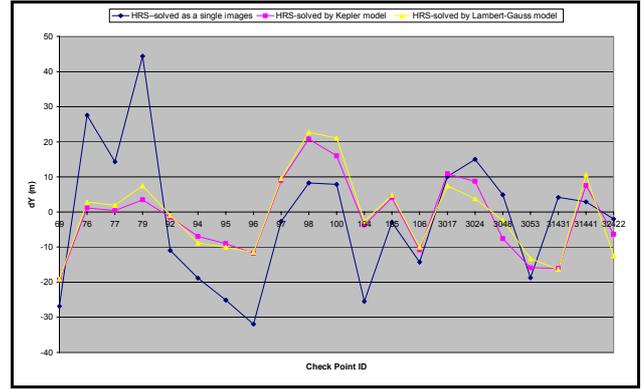


Figure 3. Y-coordinate difference of the calculated values in the solution of along track and single image models

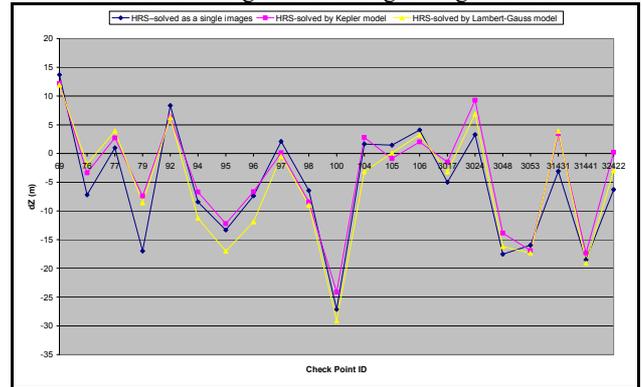


Figure 4. Z-coordinate difference of the calculated values in the solution of along track and single image models

3.5. HRS data-Solution with use of navigation data

In SPOT satellite geometry Handbook (SPOT, 2002) a direct model (Viewing Geometry model) is proposed where the viewing angles of each pixel should be known. All the data provided with the images focuses on solving the specific geometry problem which is only valuable when the same structure of metadata as SPOT is used. Unfortunately as it is shown in the following paragraphs the viewing angles in SPOT metadata file are not calculated from the perspective center in order to meet a photogrammetric solution. When trying to establish a generic photogrammetric solution, additional information should be known. In this paper a modified model is proposed where these unknown quantities are calculated only once, using Ground Control Points.

3.5.1. Calculation of rotation angles

The transformation from Ground coordinate system to framelet coordinate system is done in following steps:

3.5.1.1. Rotations angles calculation from the Ground coordinate system to the Orbital coordinate system. The Orbital Coordinate system (O_2, X_2, Y_2, Z_2) is centered to the satellite where the Z_2 axis pointing from the Earth center of mass to the spacecraft center of mass. The X_2 axis is the normalized cross product of the instantaneous velocity vector with Z_2 axis. Y_2 is the third unitary vector of the system (SPOT, 2002). The rotation matrix which brings the Ground coordinate system to the Orbital coordinate system is the transpose of the M_{ORB}

$$M_{ORB}^T = \begin{bmatrix} (X_2)_X & (X_2)_Y & (X_2)_Z \\ (Y_2)_X & (Y_2)_Y & (Y_2)_Z \\ (Z_2)_X & (Z_2)_Y & (Z_2)_Z \end{bmatrix}$$

where X_2 represent the pitch axis

Y_2 represent the roll axis
 Z_2 represent the yaw axis

The rotation angles are calculated as follows (Michalis, 2005):

$$\begin{aligned}\varphi_{orb} &= \arcsin((Z_2)_x) \\ \omega_{orb} &= \arcsin\left(-\frac{(Z_2)_y}{\cos\varphi}\right) \\ \kappa_{orb} &= \arcsin\left(-\frac{(Y_2)_x}{\cos\varphi}\right)\end{aligned}$$

3.5.1.2. Rotation angles calculation from Orbital coordinate system to Navigation coordinate system. The Navigation Reference Coordinate System (O_1, X_1, Y_1, Z_1) is the body-fixed system used for spacecraft attitude determination and control. The coordinate axes are defined by the spacecraft attitude control system (ACS) which attempts to keep the navigation reference frame aligned with the Orbital Coordinate System so that the optical axis of instrument without mirror deviation is always pointing towards the center of the Earth. On SPOT, no distinction is made between the barycentre of instruments O_1 of the Navigation Reference Coordinate System and the spacecraft center of mass O_2 of the Orbital Coordinate System ($O_1=O_2$) (SPOT,2002).The rotation angles (attitudes) from Navigation to Orbital coordinate system are measured with on board instruments. Assuming that the attitudes in the specific epoch are computed by a linear interpolation of the attitude values of the metadata file and found:

a_p is the rotation angle around the pitch axis at time t_0
 a_r is the rotation angle around the roll axis at time t_0
 a_y is the rotation angle around the yaw axis at time t_0
Then the rotation angles from the Ground to Navigation coordinate system are given as follows:

$$\begin{aligned}\omega_{NAV} &= \omega_{ORB} - a_p \\ \varphi_{NAV} &= \varphi_{ORB} - a_r \\ \kappa_{NAV} &= \kappa_{ORB} - a_y\end{aligned}$$

The minus signs in equations are because the rotations angles from Orbital coordinate system to Navigation coordinate system are needed while the opposite rotation is given.

3.5.1.3. Rotation angles calculation from the Navigation coordinate system to the Framelet coordinate system. The Framelet Coordinate System is a right-handed three dimensional coordinate system and it is directly involved in the reconstruction of bundle of rays (Michalis, 2005). The process of interior orientation converts the coordinates from the measurement coordinate system to the framelet coordinate system. The positive x-axis is along the platform motion while the positive z-axis is along the direction of the optical axis and away from the earth. The positive y-axis completes the right-handed coordinate system. The look direction matching for each CCD is defined by the two angles ψ_X (along the track) and ψ_Y (across the track) expressed within the (O_1, X_1, Y_1, Z_1) Navigation Reference Coordinate System. For SPOT5, look angles are given for every detector in the auxiliary data. If it is assumed that the perspective center of the image is identical with the navigation coordinate system origin the rotation angles from the Ground to the sensor (Framelet) coordinate system is

$$\begin{aligned}\omega_{CCD} &= \omega_{NAV} - \psi_X \\ \varphi_{CCD} &= \varphi_{NAV} - \psi_Y \\ \kappa_{CCD} &= \kappa_{NAV}\end{aligned}$$

The final transformation is a simple rotation counter-clockwise to the Z axis because in the Navigation coordinate system and thus in the CCD coordinate the Y axis is along the track while in the Framelet coordinate system the X axis is along the track.

$$\omega_{FRE} = \omega_{CCD}$$

$$\begin{aligned}\varphi_{FRE} &= \varphi_{CCD} \\ \kappa_{FRE} &= \kappa_{CCD} - 90^\circ\end{aligned}$$

3.5.2. Questions arise from the above procedure.

In the previous paragraphs the rotation angles from the Ground to the Framelet coordinate system are calculated using the metadata information of SPOT-HRS. The critical question is the following: Is the origin point of the navigation and Orbital coordinate system the perspective center of its image which is the origin of the Framelet Coordinate system? The across track values (Ψ_iY) for each detector of HRS1 image are imported in a file. The scatter plot in figure 5 represents how the Ψ_iY is changing along the sensor line. It is assumed that the origin is the middle pixel (6001 pixel) trying to represent the perspective geometry. The look angles across the track are changing linearly from -0.07146 rad (-4.094°) to 0.07103 rad (4.069°) while the value for middle (6001) detector is -6.789500000e-05. The basic statistics of the above angles are in the table 5.

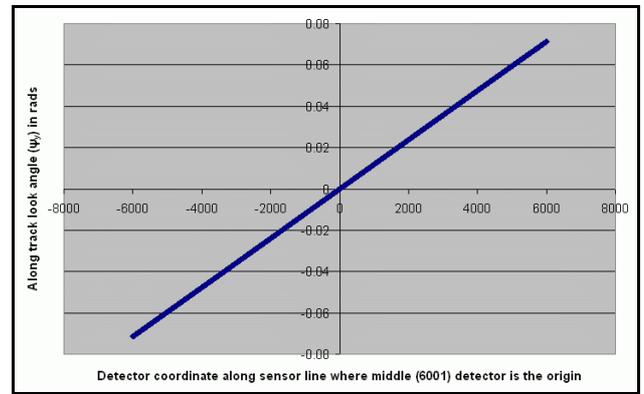


Figure 5. Change of across track look angles along the sensor line

Minimum (rad)	-0.07146
Maximum(rad)	0.07103
Median(rad)	-6.78950e-05
Mean(rad)	-7.50205e-05
Standard deviation(rad)	0.041268024

Table 5. Statistics of across look angles

To explain the above scatter plot the most likely measurement frame is represented in figure 6 (the dimensions are not in correct aspect ratio). In this figure the paper plane is the Oyz plane of a coordinate system. This system is defined by the sensor line and the direction of the origin of measurements to the middle pixel. The flight direction (x-axis) is towards paper plane. As the look angle value of the middle point is -6.789500000e-5 and starting from negative to positive values the direction of the origin of measurements and the middle pixel is almost perpendicular to sensor line. The look angle of pixel 1 is the angle α which has negative value. In the same way the look angles of all the pixels can be defined. As the angle α and the distance P1 to P6001 are known the dimension OP_{6001} which could represent the focal length. It can be calculated as follows:

$$OP_{6001} = \frac{P_1 P_{6001}}{\tan \alpha}$$

and it is found that is 544.8501 mm. As the focal length is 580mm it is obvious that the look angles are not measured from the perspective center. If the same distance is calculated from each pixel and found the same it seems that the Navigation Coordinate system is parallel to the previous defined coordinate system. Unfortunately, these values are changed slightly along

the sensor line (Michalis, 2005). Similar results are achieved from the look angles calculations of HRS2 image.

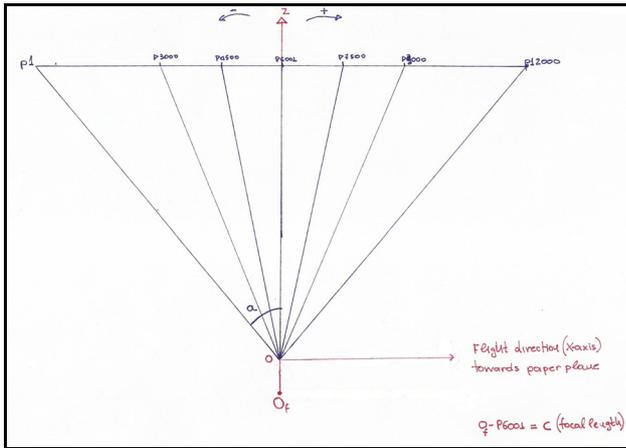


Figure 6. Across-track look angles measurement frame

From the above calculation it seems that the Navigation system is not parallel to the above system which is defined by the sensor line and the direction of the origin of measurements to the middle pixel; thus to the Framelet coordinate system, (from the defined system the Framelet coordinate system is parallel, there is only an offset between these systems).

On the other hand it is explain as here why the look angles are defined for each pixel. This is to avoid using the framelet coordinate system, as additional measurements should be done (offset and rotation angles) from the navigation system, which is not very easy to calculate directly. As a result the focal length could not be used in direct orientation of the sensor.

3.5.3. Proposed model

It is possible to involve the offset and the rotations (unknowns) from the Navigation system (Body-fix system) to the Framelet coordinate system (image system) for each one of the HRS images. This calibration should be done once as the relation between these coordinates systems does not change with time. On all the models which are developed until now the Ground coordinates of the perspective center of the base framelet (X_o, Y_o, Z_o) should be reformed as follows:

$$\begin{pmatrix} X_o \\ Y_o \\ Y_o \end{pmatrix} \rightarrow \begin{pmatrix} X_o \\ Y_o \\ Y_o \end{pmatrix} + M_{NAV}^{FRE} \begin{pmatrix} DX_{NAV}^{FRE} \\ DY_{NAV}^{FRE} \\ DZ_{NAV}^{FRE} \end{pmatrix}$$

M_{NAV}^{FRE} represents the rotation matrix from Navigation to framelet coordinate system and

$DX_{NAV}^{FRE}, DY_{NAV}^{FRE}, DZ_{NAV}^{FRE}$ the offsets from the from Navigation to framelet coordinate system.

Unfortunately, the data set given for this evaluation was acquired before September 2003 where SPOT5 location performances have been impacted by a bad initialization of the on board star tracker's relativist compensation process (Bouillon and Gigord, 2004; Bouillon, 2004 personal communication). A formulation is given to correct the metadata information. However this formulation is based in Viewing Geometry Model which is incompatible with the model introduced in this paper. Thus, in order to solve the above problem new data sets are needed which are acquired after September 2003. After this calibration only the viewing angles of the base framelet are needed to be known in the model.

4. CONCLUSIONS-FURTHER WORK

This is the first time that a rigorous along stereo sensor model is developed in this way, where the collinearity equations are used directly with orbit determination-propagation methods. It is proven that using this combination, the accuracy, precision and stability of the solution is improved compared to the single image models. It is a simple model from a user point of view, as little information should be known in advance, and the effort of the user is only to measure the reference points (if needed). The points or weights on the estimator are not used in order to investigate the behaviour of the model itself during the acquisition of the along track images.

The fundamental assumptions is that Keplerian motion is maintained along the acquisition time of the along track images. Various versions of the model are developed based on different orbit determination-propagation methods. From the evaluation process the following conclusions are extracted:

- In the same orbit period the increase the number of position vectors leads to an improvement of the accuracy of the orbit model.
- The along track sensor model is a better representation of the image acquisition geometry. The larger improvements are at the edges of the images.
- The number of GCPs needed in order to have accepted accuracy is definitely less in case of the along track model than in case where the images are solved separately. For HRS images which cover an area of 120km by 60 km it seems that 6 well distributed GCPs are enough.
- The Kepler and Gauss-Lambert model give generally almost identical accuracy.

The most important work that should be done is the in-flight calibration of SPOT5-HRS. Thus, new data which is acquired after September 2003 is needed. The next step is the self-calibration process. In depth investigation should be carried out to reduce the number of unknown attitude parameters. Another very important step is to test the model on the forthcoming ALOS-PRISM high resolution three line scanner where it is believed that the stability of the solution is increased with the three line geometry. The sensor model which is based on the orbital elements (rather than state vectors) should be tested in along track sequence. Finally, the model should be linked with DEM generation software. It is a field where the use of a good sensor model is critical. It is obvious that it is great opportunity to test the precision, accuracy and the stability of the model.

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