EXTERIOR ORIENTATION IMPROVED BY THE COPLANARITY EQUATION AND DEM GENERATION FOR CARTOSAT-1

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ABSTRACT:

In this paper the sensor model evaluation and DEM generation for CARTOSAT-1 pan stereo data is described. The model is tested on CARTOSAT-1 data provided under the ISPRS-ISRO Cartosat-1 Scientific Assessment Programme (C-SAP). The data has been evaluated using the along track model which is developed in UCL, and the Rational Polynomials Coefficient model (RPCs) model which is included in Erdas Photogrammetry Suite (EPS). A DEM is generated in EPS. However, the most important progress that is represented in this paper is the use of the Coplanarity Equation based on the UCL sensor model where the velocity and the rotation angles are not constant. The importance of coplanarity equation is analyzed in the sensor modelling procedure and in DEM generation process.

1. INTRODUCTION

CARTOSAT-1 represents the third generation of Indian remote sensing satellites. The main improvement from the instrument point of view is the two panchromatic cameras pointing to the earth with different angles of view. The first one is looking at +26 deg. of nadir while the second one at –5 deg. of nadir, giving the ability of collecting along track stereo images.

In this paper, the rigorous sensor model developed in UCL and the RPCs model included on the Erdas Photogrammetry Suite (EPS) are used to evaluate Cartosat images along with DEM generation on EPS. However, the most important progress that is represented in this paper is the use of the Coplanarity Equation based on the UCL sensor model where the velocity and the rotation angles are not constant. The importance of the coplanarity equation is analyzed and evaluated in the sensor modelling procedure and in the DEM generation process.

2. BACKGROUND

A pushbroom image consists of sequence of framelets which are independent one-dimensional images with their own exterior orientation parameters, as the scanning effect of line CCD scanner on the ground is due to the motion of the satellite. In general, the pushbroom sensor model can be seen as a sophisticated model, which should simulate simultaneously the along track motion, that is closely related to the satellite trajectory and the across track perspective projection of the framelets. The main drawback of this approach is that the exterior orientation parameters of neighbouring framelets are highly correlated.

The across track perspective could be represented with the well known collinearity equations which should be modified in a way that the satellite orbit is taken into consideration. The way that the satellite motion is represented leads to different sensor models. It is possible to have an even more correlated model in the case that more parameters are used in this procedure, than are really needed.

Moreover, especially for the along track stereo images it sounds very attractive to establish the coplanarity equation which could relate conjugate points of images. The coplanarity equation establishes a geometric condition along the track which can improve the stability of the orientation and the accuracy of the DEM generation as the x-parallax is at this direction (along track).

Kim (Kim, 2000) investigates the epipolar geometry of pushbroom images based on Gugan and Dowman model (Gugan and Dowman, 1988). In this model the position and kappa rotations are described by second order polynomials while the omega and phi rotations are constant. It is reported that the coplanarity in pushbroom is different than in frame cameras represented by epipolar curves instead of lines. However the most important conclusion is that for any two conjugate points the epipolar curves are different from each other, as the coefficients of the coplanarity equation that was developed are varied for each point.

Habib (Habib et al., 2005) represents a comprehensive analysis of the epipolar geometry for pushbroom scanners moving with constant velocity and attitude trying to produce epipolar lines (not curves) and normalized images. It is confirmed that for a given point in the left image, there will be multiple epipolar planes in the right image. It is mentioned that the key difference between frame and line cameras is that the base vector will change as the scanner moves along its trajectory. Finally, it is concluded that even in that simplified case (constant velocity and attitude) the production of normalized images are not feasible without having a DEM since the normalized and original images do not share the same exposure station.

3. CARTOSAT-1 SENSOR

3.1. Pan camera

The pixel size of the images is 2.5m on the ground with 1024 grey levels (10 bits). The time difference between the acquisition of the stereo images is about 52 seconds. The spacecraft body is steerable to compensate the earth rotation effect and to force both Fore and Aft cameras to look at the same ground strip when operated in stereo mode. Simultaneous stereo pair acquisitions are of great advantage since the radiometric parameters of the images will be identical. The stereo pairs have a swath of 26 km and a fixed B/H ratio of 0.62. Apart from the stereo mode, the satellite is also equipped to operate in the wide swath mode. When operated in this mode the satellite can be manoeuvred such that image strips will fall side by side so that wider swath images of 55 km are obtained by the cameras. The spacecraft also has a facility to provide various pitch-biases to vary the look angle conditions of the stereo pair. The cameras specifications are introduced in table 1.

Focal length (both cameras)	1945 mm
Integration time	0,336 ms
Quantisation	10 bits (1024)
Pixel size	7x7 μm
GIFOV Fore	2.452m (across-track
GIFOV Aft	2.187(across-track)

Table 1. Cartosat-1 camera specifications

3.2. Metadata file

The metadata file of CARTOSAT which is attached with each image is in text format and provides basic information of the imagery. In this file navigation data of the satellite is not given. Fortunately, the acquisition time interval between the along track images is measured and included in this file, which should be known in order to implement the UCL along track model.

4. REFERENCE DATA

The authors take part in the C-SAP as principal investigators with Test Site 3, which is the UCL test site in Aix-en-Provence, France. Also, UCL are co-investigators on TS-9 in Warsaw, Poland. Unfortunately additional GCPs should be measured in the Aix-en-Provence test site in order to have a appropriate number of GCPs within the area covered by Cartosat. On the other hand Mr. Zych (Goesystems Polska) who is Principal Investigator of TS-9 has provided the study team with DEMs and with 36 GCPs which are measured in the field. These GCPs are well distributed on the images. The area covered and the GCPs are shown on Figure 1.

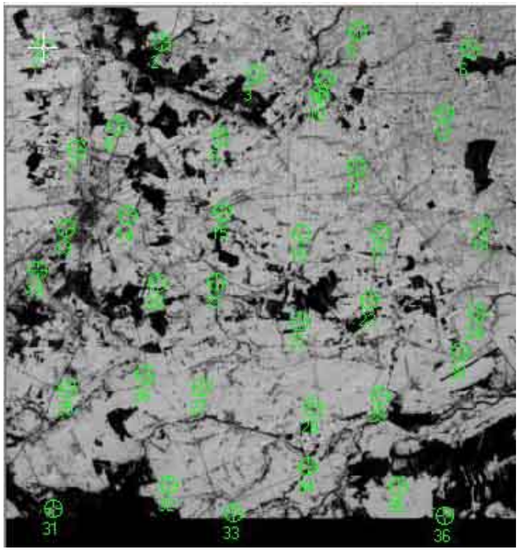


Figure 1. Warsaw test site and GCPs distribution

5. UCL SENSOR MODEL

5.1. UCL Kepler model for along track motion

The along track motion is described by the Kepler equation. 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 images. The simultaneous solution extends the narrow field of view of each satellite image because 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 one image to the next is its acquisition time interval.

The formulation of the UCL model for the along track motion of two images case is described 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:

$$X_c(t) = X_o + u_x \cdot \tau - \frac{GM \cdot X_o \cdot \tau^2}{2 \cdot (X_o^2 + Y_o^2 + Z_o^2)^{3/2}}$$

$$Y_c(t) = Y_o + u_y \cdot \tau - \frac{GM \cdot Y_o \cdot \tau^2}{2 \cdot (X_o^2 + Y_o^2 + Z_o^2)^{3/2}} \qquad (1)$$

$$Z_c(t) = Z_o + u_z \cdot \tau - \frac{GM \cdot Z_o \cdot \tau^2}{2 \cdot (X_o^2 + Y_o^2 + Z_o^2)^{3/2}}$$

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
dt is the time interval between the acquisition of the center framelet of the images.
(X_o,Y_o,Z_o) is the position vector of the perspective center of the center framelet of the first image
(u_x,u_y,u_z) is the velocity vector of the perspective center of the center framelet of the first image
GM is the Earth gravitational parameter with value of $398600{,}4415 km^3/s^2$

5.2. Modified collinearity equations for along track sequence.

The well-known collinearity equations need modification before they are applied to pushbroom images. They are modified based on the above Kepler equations (1) 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 principal distance
X, Y, Z are the ground coordinates of a point
Xc(t), Yc(t), Zc(t) are the ground coordinates of the framelet perspective center as a function of time, as described in equations (1)
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, where the rotation angles are simulated with first order polynomials
y is the y-framelet coordinates of the corresponding point
yo is a small offset from the perspective center origin.

5.3. Modified coplanarity equation for along track sequence.

5.3.1 Introduction. In general, coplanarity for the perspective geometry is the condition that the two exposure stations of a stereopair, any object point, and its corresponding image points on the two photos all lie in the a common plane (Wolf et all, 2000), as illustrated in figure 2. In the figure the points L_1, L_2, a_1,a_2 and A all lie in the same plane. The coplanarity condition is

$$0 = B_x \cdot (D_1 \cdot F_2 - D_2 \cdot F_1) + B_y \cdot (E_2 \cdot F_1 - E_1 \cdot F_{21}) + B_z \cdot (E_1 \cdot D_2 - E_2 \cdot D_1) \qquad (2)$$

where

$$B_x = X_{L_2} - X_{L_1}$$
$$B_y = Y_{L_2} - Y_{L_1}$$
$$B_z = Z_{L_2} - Z_{L_1}$$
$$D = m_{12} \cdot x + m_{22} \cdot y - m_{32} \cdot c$$
$$E = m_{11} \cdot x + m_{21} \cdot y - m_{31} \cdot c$$
$$F = m_{13} \cdot x + m_{23} \cdot y - m_{33} \cdot c$$

In equation (2) subscripts 1 and 2 affixed to terms D, E and F indicate that the terms apply to either photo 1 or photo 2. The m's are function of the three rotations angles omega, phi, kappa as represented in matrix M(t). One coplanarity equation may be written for each object point which appears in the stereo photos. The coplanarity equation does not contain object space coordinates as unknowns. It contains only the elements of the exterior orientation parameters of the two photos of the stereo pair.

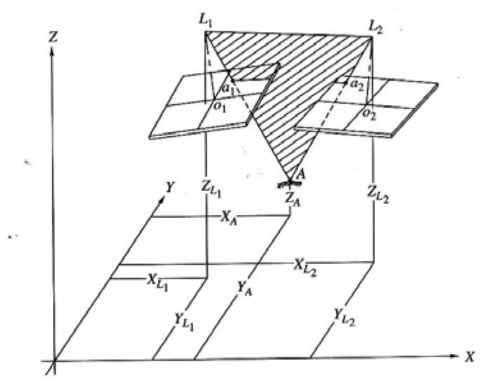


Figure 2. The coplanarity condition (Wolf et al., 2000)

5.3.2. Modification of coplanarity equation for pushbroom images. The development of the coplanarity equation for a pushbroom sensor could be based on the perspective images equation (2) where the fundamental characteristic that the pushbroom image consist of one-dimensional images, should be taken into consideration. In first instance the *D, E* and *F* in equation (2) should be modified in case of pushbroom images as follows, because of the one dimensional framelets:

$$\begin{aligned} D &= m_{22} \cdot y - m_{32} \cdot c \\ E &= m_{21} \cdot y - m_{31} \cdot c \\ F &= m_{23} \cdot y - m_{33} \cdot c \end{aligned} \qquad (3)$$

In general the epipolar curves for linear pushbroom images are not very easy to derive (Kim, 2000). The reasons are mainly the pushbroom geometry itself, along with the selected sensor model. Kim concludes that the problem is that the best sensor model has not been developed yet.

In this paper, a slight different approach is followed. We do try to use the model which is capable to describe the base vector change as the scanner moves along its trajectory. This model can be the UCL sensor model which simulates this as functions of the exterior orientation parameters of the center point of the center framelet of the first along track image.

The development of the coplanarity equation is based on the equation of the Kepler model (1). Thus, the velocity of the satellite during the acquisition time of the images is not constant. Moreover at present, the rotation angles are not constant and simulated with first order polynomials.

Based on equations (1) the *X* object space coordinates of the points L_1, L_2 are:

$$\begin{aligned} X_{L_1} &= X_o + u_x \cdot t_1 - A \cdot X_o \cdot t_1^2 \\ X_{L_2} &= X_o + u_x \cdot (t_2 + dt) - A \cdot X_o \cdot (t_2 + dt)^2 \end{aligned} \qquad (4)$$

where

$$A = \frac{GM}{2 \cdot (X_o^2 + Y_o^2 + Z_o^2)^{3/2}}$$

and t_1 and t_2 is the acquisition time of the corresponding framelets in image 1 and 2 respectively.

Combining the equations (4) based on (2), B_x is defined as follows:

$$B_x = X_{L_2} - X_{L_1}$$
$$= u_x \cdot (t_1 - t_2 - dt) + A \cdot X_o \cdot (t_2^2 + dt^2 + 2 \cdot t_2 \cdot dt - t_1^2)$$

The above equation clearly shows the important role of the UCL sensor model approach because it relates directly the B_x only with the state vector of the center point of the first pushbroom image, which are the unknown parameters in this equation.

Going one step further the acquisition time t_1 and t_2 can be described as:

$$t_1 = x_1 \cdot interval$$
$$t_2 = x_2 \cdot interval$$

where *interval* is the acquisition time of a framelet which is assumed to be constant (Michalis and Dowman, 2004).

Finally B_x is defined as follows based on the previous equations (with exactly the same procedure the B_y and B_z are also calculated) :

$$B_x = u_x \cdot [interval \cdot (x_1 - x_2) - dt] +$$
$$+ A \cdot X_o \cdot [interval^2 \cdot (x_2^2 - x_1^2) + 2 \cdot x_2 \cdot interval \cdot dt + dt^2]$$

$$B_y = u_y \cdot [interval \cdot (x_1 - x_2) - dt] +$$
$$+ A \cdot Y_o \cdot [interval^2 \cdot (x_2^2 - x_1^2) + 2 \cdot x_2 \cdot interval \cdot dt + dt^2] \quad (5)$$

$$B_z = u_z \cdot [interval \cdot (x_1 - x_2) - dt] +$$
$$+ A \cdot Z_o \cdot [interval^2 \cdot (x_2^2 - x_1^2) + 2 \cdot x_2 \cdot interval \cdot dt + dt^2]$$

The coplanarity equation f_c is developed as a combination of equations (3) and (5) where the unknown parameters are the elements of the exterior orientation of both stereo images which are:

- State vector of the center point of the first image (6 unknowns)
- The coefficients of the first order rotation polynomials of both images(12 unknowns)

Thus, the coplanarity equation f_c is defined as follows:

$$f_c = f_c(X_o, Y_o, Z_o, u_x, u_y, u_z,$$
$$, \omega_{11}, \omega_{12}, \phi_{11}, \phi_{12}, \kappa_{11}, \kappa_{12}, \omega_{21}, \omega_{22}, \phi_{21}, \phi_{22}, \kappa_{21}, \kappa_{22}) = 0$$

5.3.3. Coplanarity role in exterior orientation determination and in DEM extraction process. The coplanarity equation can be used in combination with the collinearity equations during the computation of the exterior orientation providing additional equations and stability. In more detail in the resection process three equations (two collinearity equations plus one coplanarity equation) for each GCP and one coplanarity equation for each tie point can be applied, improving the accuracy and the stability of the solution.

Traditionally in perspective center geometry the epipolarity is used for the production of normalized images. In this paper a different approach is followed as a first step. The coplanarity condition is a robust and rigorous equation which can be used easily and straightforwardly as a geometrical constraint in the matching procedure of the DEM generation process. In more detail: just after the correlation process the coplanarity equation can be applied to all the conjugate points that are extracted by the correlation in order to see if this equation is fulfilled, using a threshold related to RMSE of the resection solution. The points that do not pass this test are blunders or correlation errors in general.

6. EVALUATION

6.1. Introduction.

6.1.1. RPCs model. The Cartosat data are distributed with the rational polynomials coefficients. In EPS there is a module where Cartosat RPCs could be imported and used for the orientation of the images.

6.1.2. UCL model. The UCL sensor model could be solved directly using navigation data, without GCPs (Michalis and Dowman, 2004, 2005). Unfortunately, because in the case of Cartosat no navigation data is provided the exterior orientation parameters should be calculated using GCPs. The total number of exterior orientation parameters of the two Cartosat along track stereo images is eighteen. The state vector of the center 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. The other twelve unknown parameters are the rotation angles of the two images; six rotations for each image which are the coefficients of the polynomials. Thus, at least five GCPs are needed for the solution, when the collinearity equations are used. It will be shown that with the simultaneous use of the coplanarity equation it is possible to reach accurate solution with four GCPs. Moreover even in the case where enough GCPs are available for a solution only with the collinearity equation the coplanarity ensures a more precise solution.

6.2. Evaluation strategy

As it shown in figure 1 the GCPs are well distributed on the images. Nine of the total 36 available points are used as GCPs in the evaluation process of both models, while the rest 25 (two are not well identified on the images) are used as ICPs (Independent Check Points). The GCPs location is not important for the exterior orientation solution (Michalis and

Dowman, 2006), thus the GCPs are divided in groups of 1,2,3,4,5,6,9, GCPs, in order to examine and compare the accuracy of the models based only this issue.

Additionally 494 tie points are measured for the UCL sensor model evaluation, divided in two groups of 149 and 494 points, which are implemented in the coplanarity equation.

6.3. RPCs model evaluation.

In table 2 the accuracy of the ICPs are introduced based on the number of the GCPs (first column) when the RPCs are used for the orientation.

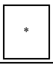
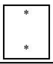
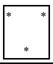
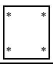
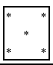
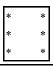
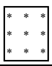
		RMSE of ICPs		
GCPs	**Distribution**	X(m)	Y(m)	h(m)
0		11.33	114.07	760.51
1		14.43	2.77	5.38
2		14.99	2.37	4.30
3		2.16	1.46	1.74
4		1.64	1.68	1.71
5		1.61	1.71	1.87
6		1.72	1.68	1.98
9		1.70	1.65	1.95

Table 2. RMSE of the 25 ICPs using RPCs model.

From the above table the following conclusions could be extracted:

- The accuracy of the RPCs model where no GCPs are used for refinement is not very good, especially in height, where the RMSE is close to 800m.
- With one GCP the accuracy is improved close to 20m.
- With two and three GCPs the accuracy is improved slightly.
- Four GCPs are enough in order to reach accuracy close to one pixel.
- From 4 to 9 GCPs the RMSE is almost the same.

6.4. UCL sensor model evaluation.

6.4.1. Introduction. The evaluation of the UCL sensor model is divided in three parts as follows:

- Evaluation of the model based on the collinearity.
- Evaluation of the solution based on four GCPs with the involvement of the coplanarity.
- Evaluation of the precision of the solution in combination with the coplanarity.

6.4.2. Solution of UCL sensor model based on the collinearity. Based on paragraph 3 the total number unknown exterior parameters is 18. This means that at least 5 GCPs are needed for the solution based only on the collinearity equation. In table 3 the accuracy of the ICPs are introduced based on the number of the GCPs (first column) when the UCL sensor model collinearity equations are used for the orientation.

It seems that using the UCL model sufficient (subpixel) accuracy is achieved even in case of five GCPs. Moreover it gets better accuracy than the RPCs model in all cases.

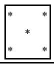
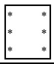
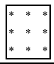
		RMSE of ICPs		
GCPs	**Distribution**	X(m)	Y(m)	h(m)
5		0.87	1.02	1.47
6		0.88	0.94	1.36
9		0.71	0.83	1.27

Table 3. RMSE of ICPs using UCL along track Kepler model based on the collinearity equations and first order rotations and

6.4.3. Solution based on four GCPs with the involvement use of coplanarity. In this paragraph the coplanarity equations are used in the solution providing one more equation per point (GCP, Tie Point) giving the opportunity to have a solution with 4 GCPs. In table 4 the accuracy of the ICPs are introduced based on the number of the Tie Points used.

It seems that using about 150 Tie points which in reality is information that can be extracted from the images the accuracy is reach the accuracy of the five GCPs solution.

		RMSE of ICPs		
GCPs	**Tie Points**	X(m)	Y(m)	h(m)
4	34	1.07	2.92	2.45
4	149	0.86	1.09	1.49

Table 4. RMSE of ICPs using UCL along track Kepler model based on the collinearity equations and coplanarity equation.

The challenge is to examine the possibility to reach an exterior orientation solution using less than four GCPs.

6.4.4. Precision of the solution in combination with the collinearity. The reference standard deviation S_o represents the precision of the adjustment. The form of the reference standard deviation for the unweighted case is

$$S_o = \sqrt{\frac{\mathbf{v}^{\mathbf{T}} \cdot \mathbf{v}}{r}}$$

In table 5 the reference standard deviation S_o of the exterior orientation solution in cases of 9 and 34 (all) GCPs involved are introduced with different combination of Tie Points used in the solution through the coplanarity equation. It seems that using the coplanarity increases the precision of the solution significantly.

No of GCPs	**No of Tie Points**	S_o
9	9	0.393
9	34	0.368
9	149	0.284
9	494	0.217
34	34	0.303
34	194	0.272
34	494	0.227

Table 5. Reference standard deviation using UCL along track Kepler model based on the collinearity equations and coplanarity equation with various number of tie points.

7. DEM GENERATION

7.1. Introduction.

This section reports on the generation of a DEM using the Erdas Photogrammetry Suite (EPS) version 9.2. The DEM generation has a pixel size of 10m and is based on area-based matching which is also called signal based matching. The EPS is used because the UCL sensor model has yet to be linked to stereo matching software.

In order to check the accuracy of the produced DEM the DEM provided by the PI (15m pixel size) is used as a reference. The area covered is a hilly area where the difference in heights within the whole area is 120m.

7.2. DEM quality.

For the CARTOSAT data the following strategy of the software is used as it produced quite good results. This strategy is the following:

- Search Size: 19 x 3
- Correlation Size: 7 x 7
- Coefficient Limit: 0.80

7.3. DEM accuracy.

The accuracy of the DEM is described in table 6. The produced DEM has not been edited for blunders (manually or automatically) and it is evaluated as it is extracted by EPS.

No of GCPs	MIN (m)	MAX (m)	Absolute linear error LE90 (m)
1	-39.20	138.62	13.30
2	-41.87	231.73	13.45
3	-40.26	220.94	4.13
4	-36.51	222.85	4.07
5	-32.64	89.12	4.04
6	-32.63	104.10	4.10
9	-31.23	89.07	3.88
34	-39.25	87.80	3.97

Table 6. Accuracy of DEM with different number of GCPs used in the orientation

From the results in table 6 it seems that at least 3 GCPs should be involved in the orientation in order to reach Absolute Linear error LE90, close to 4m. However because of the min and max high errors it is needed to edit the produced DEM manually or automatically.

As a general conclusion, in the DEM generation from Cartosat data when RPCs model is used, 4 GCPs should be measured in order to reach the accuracy as described in table 6 which is not improved, in reality, if the number of GCPs is increased.

8. COPLANARITY IN DEM GENERATION AS A GEOMETRIC CONSTRAIN

As this UCL sensor model is not linked with DEM generation software the importance of the coplanarity equation as a geometric constrain after the correlation process is tested in the similar correlation procedure of auto- tie point generation in EPS software. Under Auto-Tie generation procedure 4096 tie points are produced which are checked for their accuracy manually, where the wrong correlated points are found. On the other hand the coplanarity equation is applied on all tie points and it is found that all these 'wrong' points give values much higher than the expected value (close to zero). The above procedure denotes the important role that the coplanarity equation could have in the DEM generation procedure, which should be approved in the near future.

9. CONCLUSIONS

This paper has described the testing of the UCL Kepler Along Track Sensor model and the RPCs model on Cartosat data. Also a DEM is generated using Erdas Photogrammetry Suite software. The results that are introduced within the paper leads us to the following conclusions:

- RPCs model reaches close to pixel accuracy when at least 4 GCPs are used.
- UCL model sufficient (subpixel) accuracy is achieved even in case of five GCPs, better than the RPCs model in all cases.
- For DEM generation it shown again, as in case of SPOT5-HRS, (Michalis and Dowman, 2004) that the use of the along track stereo sensors is a very promising for DEM generation, as the image matching quality and the achieved accuracy is very high.

However the most important achievement in this study is the development of the coplanarity equation. This has the following benefits:

- When the coplanarity equation is involved in the solution one more equation per point (GCP, Tie Point) is provided, giving the opportunity to have a solution with less GCPs, with sub-pixel accuracy.
- The coplanarity equation increases the precision of the solution significantly.
- The coplanarity equation is a robust and rigorous equation which can be used easily and straightforwardly as a

geometrical constraint in the matching procedure of the DEM generation process.

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