A RIGOROUS MODEL AND DEM GENERATION FOR SPOT5 –HRS

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ABSTRACT

This paper describes a new model developed at UCL for along track stereo sensors. The model is tested on SPOT HRS data provided under the SPOT Assessment Project (SAP) set up by CNES and ISPRS. The SPOT HRS data has been used to test a new sensor model for along track satellite data, and to generate a DEM using the Leica Photogrammetry Suite (LPS). The model described in this paper uses the collinearity equations in combination with astrodynamics. The main and fundamental point during the development of this model was to benefit from acquisition in the same orbit. The collinearity equations are modified to model the characteristics of a pushbroom scanner and the number of exterior orientation parameters. The state vector at the origin point of each image is computed. The results of testing the model with HRS data show that the model provides a stable, accurate and rigorous solution. The solution for the orientation from the LPS gives similar results to the new model and generates a DEM of a mountainous area which is within the expected accuracy of SPOT HRS data. The model can be used for any along track satellite sensor.

1. INTRODUCTION

Since the SPOT series of satellites were first launched in 1986, many models for push room sensors have been developed, some explicitly for along track sensors, designed to make use of data acquisition of both images from the same orbit. However little work has been directed to the generation of DEMs from along track stereo sensors. This paper describes the development and testing of a model derived specifically for along track sensors and for the generation of a DEM from SPOT HRS data provided by the SPOT Assessment Project (SAP) set up by CNES and ISPRS.

2. SPOT 5

2.1 SPOT 5 Mission

SPOT 5 is the latest satellite of the SPOT family, launched during the night of the 3rd to the 4th of May 2002. This satellite ensures data continuity with the previous satellites but provides also enhanced images (at 2.5 m resolution with its two HRG instruments) and new stereoscopic capabilities with the HRS instrument. A star tracker is used to get better attitude measurements and therefore better image location (Baudoin et al, 2003).

2.2 HRS instrument

The High Resolution Stereoscopic instrument (HRS) has two telescopes and acquires stereopairs at a 90-second interval, of 120-km swath, along the track of the satellite, with a B/H ratio of about 0.8. (Baudoin et al, 2003). Forward and backward acquisitions cannot be performed at the same time. As a consequence, the maximum stereo segment that can be acquired is a little bit more than 600 km (≈ 832 km altitude x 2 x tan(20°)). Forward and backward images are obtained in the same panchromatic spectral band as for HRG. The size of the pixels on the ground is 10m x 10m. However, the HRS instrument has been designed for a ground sampling distance of 5 metres along the track. In a direction close to the epipolar planes, this along-track over-sampling allows higher altimetric accuracy of the DEM to be obtained (absolute planimetric resolution from 10 to 15 meters).

2.3 Metadata

The SPOT 5 HRS Level 1A product is delivered in DIMAP format which is the standard format for SPOT 5 products.

3. REFERENCE DATA

The test area is located around Aix-en-Provence in SE France and covers IGN map sheet 3244. The area is shown on Figure 1. The data was made available to the CEOS WGCV Terrain Mapping WG by permission of UCL and IGN. A number of tests have been carried out over this site on different types of data.

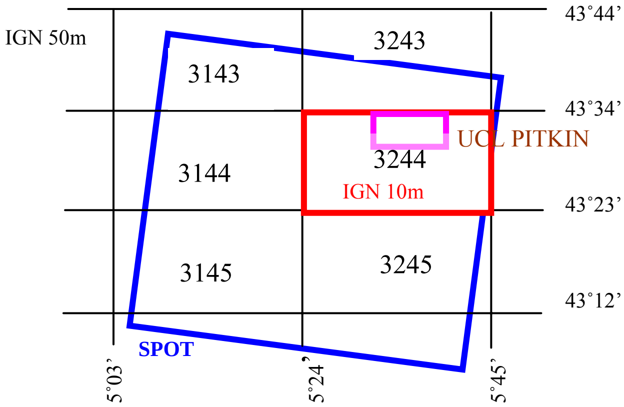

Figure 1. The test site

The following DEMs are available:

Source	UCL Pitkin	IGN	IGN
Grid	30m	50m	10m
Rmse	±1.3m	5-2.5m	1m
Source	Aerial	Aerial	Aerial
Extent (km)	12.4 x 6.9	61 x 63	30.6 x 21.7

Table 1. Reference DEM

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 38 GCPs were measured in HRS images having a very good distribution all over the whole HRS images. As will be mentioned later, the distribution of the GCPs all over the images is very important.

4. SENSOR MODEL

4.1 Application of the sensor model

4.1.1. Fundamentals. For this assessment various versions of the UCL satellite sensor model are used, depending mainly on the reference coordinate system. All versions rely on the rigorous collinearity equations with the following assumptions:

- The satellite is moving along a well defined, smooth, close to circular elliptical orbit.
- The images are acquired with a pushbroom scanner using a constant time interval. As a result the coordinates along the flight path have the same scale.
- A single image consists of a number of consecutive one-dimensional scan lines. The relationship among sampling lines is characterized by the dynamic orientation parameters which are modelled with low order polynomials as a function of the sampling time.
- A stationary world is assumed, and a moving camera.
- The sensor array is approximately perpendicular to the direction of motion.
- Attention must still be paid to the solution instability that can arise from over-parameterization of the model.
- The attitude (ω, φ and k rotations) of the satellite remains constant during the acquisition time of each image with respect to earth reference coordinate system.
- During the satellite's flight a perspective projection is maintained across track. On the other hand a curvilinear projection is maintained along the flight direction.

A specific model for along track stereo satellites sensors using photogrammetry in combination with astrodynamics is also used in an Inertial Coordinate System. The fundamental point of this model is that, the motion of the satellite is a Keplerian motion during the acquisition of along track stereo images. For HRS stereo images the acquisition time interval between the two images is about 91sec. Generally, for all the models the position the velocity vector and the rotation angles are computed with respect to Reference Coordinate system.

4.1.2 Flexibility of the sensor models. The developed sensor model is very flexible. It is possible to have the following solutions:

- a direct solution using the information provided from the metadata file;
- a refinement of the direct solution using one or two GCPs, including also the self calibration process;
- using three or more GCPs without use any information for exterior orientation from the metadata file.

On the other hand, the specific model for along track stereo satellites sensors will be improved so that the information which is extracted from the metadata will be used not only to solve the model, but also, to refine and improve the solution.
Finally another model for along track images has already been developed, where the orbital elements are computed directly using three GCPs. The along track images are treated as one entity, where the unknown parameters are the orbital elements of each image instead of the state vector.

4.1.3 Image space coordinate system. For push broom data one sampling line can act as the base line for computing the exterior orientation parameters of others lines; this line is assumed to be the centre line of the pushbroom image, and the origin is the middle point of this line, because the acquisition time of this line is known, accurately. The directions of the image coordinate system are the following:

- The x-direction is the flight direction.
- The y-direction is perpendicular to x-direction

4.1.4 Object space coordinate system. In this assessment, mainly a geocentric coordinate system is used for the sensor model testing. The position and the velocity vector as they extracted from the metadata file are in the ITRF90 geocentric reference coordinate system. Because the WGS84 is very close to ITRF90 with accuracy better than a meter, the WGS84 is used as the default geocentric coordinate system.
Also the sensor model is solved in the default geodetic system of the area of interest which is the French NTF system. The reference ellipsoid is Clarke 1880. The Lambert III projection is used.
Finally an inertial coordinate system is used, in order to meet the principal assumption of Keplerian motion of the modified sensor for along track stereo satellite sensors.

4.2 Calculations from the metadata file

The following information from the metadata file is used in the sensor model in order to solve directly in WGS84:

- Position and velocity vectors of the satellite measured by the DORIS system every 30 seconds with respect to ITRF90 (International Reference Frame 1990).
- Absolute attitude data measured by the on-board star tracking unit for about seven times per second with respect to the local orbital coordinate frame.
- The look direction table for the central pixel of the array.
- The scene centre time and the sampling time.

For the direct georeference procedure some calculation should be made in order to find the position vector, the velocity vector and the attitude in the centre of each image.

4.3 Solution in Geocentric Coordinate system (WGS84)

4.3.1 Introduction. As already mentioned, the sensor model could be solved directly using the metadata information without ground control points. Unfortunately, because the rotation angles of the centre point of HRS images are not calculated correctly, the rotations are treated as unknown parameters. In this case two GCPs are needed for the solution where the state vector has already been extracted from the metadata, correctly.

4.3.2 Direct solution. The next step is to check the stability and the rigorousness of the model itself, because the position and the velocity vector are calculated from the metadata not from the resection process. Seventeen independent check points (ICP) are selected covering the whole area of the images. The same points are used within the tests. The main point is to understand the behaviour of the solution. Using 17 check points the intersection is solved and the results in WGS84 geocentric coordinates given in table 2.

Having in mind what is mentioned in the section 2.2, that the planimetric accuracy should be between 10-15 m the achieved accuracy is in within these limits. Although the following comments should be made:

- Since the along track direction of the sensor is the X direction of the coordinate system and the pixel size in this direction is 5m, whilst the pixel size in the across track direction is 10m , it is expected that the accuracy in this axis should be two times better than the accuracy of Y axis.
- There are some quite large residuals on some of the ground control points, and the solution would be improved if these were removed. However since such points are characteristic of the control points which can be determined in such areas, they have been left in.
- The accuracy in height is expected to be better than 5m, while in mountains areas this limit is 10m (Valorge, 2003); Airault et al (2003), in a preliminary investigation of HRS data achieved an standard deviation of 7.4m From the interpretation of the mean values it seems that there is a small systematic error in x-direction.

ICP	DX (m)	DY(m)	DZ(m)
Max	15.68	21.67	10.68
Min	-10.84	-12.50	-14.15
Mean	**0.69**	**3.30**	**-0.47**
RMS	**7.45**	**9.83**	**6.41**

Table 2. Accuracy of check points from a direct solution in WGS84

Having these points in mind and also the ability in the direct solution to make a self calibration process with significant accuracy, which is not possible when a sensor model is solved only with GCPs, a modified sensor model is developed in order to calibrate the focal length of the HRS lenses. The achieved accuracy is better than 0.085 mm for both lenses and the calculated focal lengths are 579.86mm for HRS1 and 580.36mm for HRS2.

Then the intersection is computed again using the calibrated values for the focal lengths and the results with respect to the geodetic system are given in table 3.

ICP	Dx(m)	Dy(m)	Dh(m)
Max	16.82	16.60	8.45
Min	-14.44	-15.80	-5.55
Mean	**1.83**	**-1.59**	**0.20**
RMSE	**9.66**	**11.46**	**5.07**

Table 3. Accuracy of the check points after the self-calibration process.

The accuracy of the check points is improved especially in the x-.direction and the systematic error is the half of the previous error but in y-axis. Further work will be done in order to calibrate and the principal point offset in across track direction.

4.4. Sensor model in the Inertial Coordinate System

4.4.1. Introduction. The model which is developed from the collinearity equations, which are modified in such a way that there is no need to use the velocity vector from the metadata file of each image, based on the assumption that the motion of the satellite is a Keplerian motion during the acquisition of along track stereo images. It is the most important of the models that have already developed because:

- The solution of the extended model as it is described in 4.4.2 is the most accurate.
- The unknown parameters could be less than the other models, totally twelve for both HRS images.
- The velocity vector information is not used in the solution giving the opportunity to be used it as independent variable for checking or as a condition.

4.4.2. Solution of the extended model. In this extended model the importance of the angular velocity is examined. In the developed model six parameters which express the angular velocity vector are added. The total unknown parameters for the exterior orientation are 18 for both HRS images.
This model could also be solved directly. As it has already been mentioned, because the rotation angles of the centre point of HRS images are not calculated correctly, the rotations are treated as unknown parameters. In this case two GCPs are needed for the solution where the state vector has already been extracted from the metadata, correctly. Also and in this solution a self calibration process is done with significant accuracy.

Then the intersection is computed again using the calibrated values for the focal lengths and the results with respect to the geodetic system are given in table 4.

ICP	Dx(m)	Dy(m)	Dh(m)
Max	18.04	10.12	10.67
Min	-15.47	-15.58	-5.74
Mean	**1.70**	**-1.64**	**-0.16**
RMSE	**9.78**	**7.37**	**4.68**

Table 4. Accuracy of check points from the solution in the inertial co-ordinate system.

4.5 Discussion.

It has been shown that the SPOT5 HRS data can be oriented using ground control points or metadata and that a solution can be found which is within the expected error bounds. The use of self calibration gives a slightly improved solution. We can conclude that the accuracy when only using orbital data is good, and that the solution with ground control points is probably constrained by the accuracy of the control.

5. DEM GENERATION

5.1 Introduction

This section reports on the generation of a DEM using the beta version of the Leica Photogrammetry Suite (LPS). This is the upgrade of OrthoBASE Pro which is able to read SPOT5. The DEM generation is based on area-based matching which is also called signal based matching. The LPS is used because the model described above has yet to be linked to stereo matching software.

5.2 Orbital Model of LPS

In the LPS user manual (Leica 2003) it is described as: "The Orbital Pushbroom model is a generic model, which is able to compute the transformation between image pixel (image space, which is the source image pixel location) and ground point (ground space, which is the ground point location) for pushbroom sensors suck as QuickBird, EROS A1, ASTER, and SPOT. Generic modelling is based on the metadata information about the sensor orbit.” At this time this is the only information for this model. All the following are the conclusions from use of the model.

In the case of SPOT-HRS data the software reads the data as SPOT-HRG, which is understandable because HRS images are not a commercial product. Fortunately, the metadata format for the HRS data is the same as HRG data thus the navigation data are written and also computed correctly (The interpolated position and the velocity vectors for the centre line are compared with the values which are computed in UCL model and they almost identical). Also all the inner orientation parameters which can not be changed by the user are the same except of one: The principal distance (focal length). The HRS principal distance is 580mm while the HRG principal distance is 1082mm. However, this discrepancy does not affect the accuracy of solution nor, moreover, the accuracy of the DEM, as will be shown later. Unfortunately it is not possible to solve the model in a geocentric or in an inertial coordinate system. The coordinate system should be geodetic (geographic is possible but not convenient).

In order to check and compare the accuracy of the direct solution of LPS orbital model with the UCL model the same check points as in UCL model are used . The results are shown in table 5.

ICP	Dx(m)	Dy(m)	Dh(m)
Min	-18.93	-0.15	-5.45
Max	19.39	20.51	7.35
MEAN	**-4.28**	**10.75**	**1.98**
RMSE	**9.64**	**10.99**	**3.35**

Table 5. Accuracy of LPS solution

The following comments should be made:

- The UCL model provides us with almost the same accurate results in the xy plane, but we should mention here that in the LPS model there is an important systematic error especially in y-axis. However it should be mentioned that the rotation angles in UCL model are computed using GCPs and if these GCPs are good, this could provide a better solution.
- The rmse in heights is smaller in the LPS model. However, having in mind that the HRG principal distance is used instead of HRS, it is not expected to have such good results.
- It is not clear why we are able to obtain such a good result with the incorrect principal distance. This may be due to the way in which the LPS sensor model works, for example that:
  - The principal distance is used as an initial value in a self calibration process where the correct principal distance is computed, although it is very difficult to do this without GCPs
  - The principal distance is not used. A direct transformation is computed between the object space coordinate system and the image coordinate system as it is defined in the specifications of this model.

5.3 DEM using LPS

5.3.1. Introduction. In the LPS all the strategy parameters can be changed adaptively, which may improve the results of the strategy application. Adaptive changes take place between iterative pyramid layer processing.

In order to check the accuracy of the produced DEM the following sources are used:

- The Ground Control Points
- The IGN 50m DEM
- The UCL PITKIN 30m DEM

The sensor model which was used in order to give reference to DEMs is the direct model without any Ground Control Points. The model is solved using the information from the metadata file. The grid size of the DEMs is square (20mx20m) having in mind that all the software can handle DEMs with only square pixels.

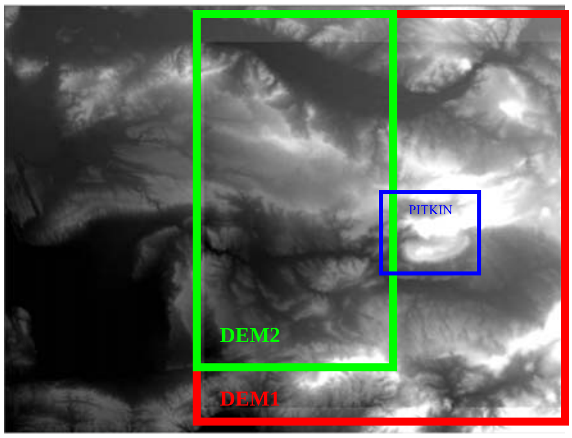

Figure 2. Extent of DEMs produced from HRS data

5.3.2. DEM quality. For the HRS data a lot of tests have been made in order to define the best strategy. The DEM with the best accuracy and detail was produced with the following strategy:

- Search Size: 5 x 5
- Correlation Size: 3 x 3
- Coefficient Limit: 0.85
- Topographic Type: Mountains
- Object Type: Forest
- DTM Filtering: Moderate

The search size and correlation size was allowed to change adaptively.

The general mass point quality is described by reference to a DEM covering the west area of the IGN reference DEM (DEM1 in red borders in image 1), which covers almost half of the area that HRS data covers. 92% of the points were of excellent or good quality, 8% were suspicious.

5.3.3. DEM accuracy. Accuracy of DEM1. The accuracy of the DEM1 covering an area of 1509.12 sq. km is described in table 6.

Min diff	-262.39m
Max diff	286.35m
Mean diff	-0.48m
RMSE	16.16m

Table 6. Accuracy of DEM1

The ICP accuracy information is in table 7.

Pt ID	DEM heights(m)	Residual Z for DEM (m)
98	46.0	5.7
2011	224.6	-3.2
3043	458.1	0.9
3048	291.3	1.2
3053	246.0	1.4
31441	23.0	4.2
31432	73.0	1.1
31433	324.0	4.2
32433	492.0	1.9
32443	501.0	5.3

Table 7. ICP accuracy in the DEM covering IGN DEM area

Having in mind that the covered area is mainly mountains, from these initial results the following points could be extracted:

- The correlation quality of the dem is 91% better than the 85% that it is expected in mountains areas (Valorge, 2003).
- The accuracy of the ICPs also meets the expectations.
- However the RMSE of the height difference between the reference DEM and the LPS DEM of 16m, is worse than it is expected. The expected value for the RMSE in mountains areas is better than 10m (Valorge, 2003).

The above conclusions indicate that there is correspondence between the height difference and the slope of the terrain. The correlation between the acquisition characteristics of HRS images and the slope should be examined in more detail. An examination of the errors was carried out and it was found that:

- There is a correlation between the height difference and the slope.
- In some areas the slope is bigger than 35°. However as it is shown in the height error can be better than 10m. In other areas where the slope is smaller than 35°, the height error in that area is bigger than 20m.
- The most interesting area is the Pitkin area (Figure 2 – blue borders) where the slope is almost perpendicular to the flight direction and parallel to the acquisition direction. In this area the height difference is very high. This area will be examined deeply in the section 5.3.4.
- Finally, it seems that the height difference not only depends on the slope itself but also to the direction of the slope. It seems that is main reason for the loss of the accuracy is the steepness of the along track slope. This is expected and it will be discussed in more detail in the following sections.

Another test was done covering the area with the green borders in image 1 (DEM2). In this area although the maximum slope is 40°, the along track slope is smaller than the 20°. The accuracy of the DEM2 covering an area of 695.97 sq. km is described in table 8. For the image matching process exactly the same strategy parameters were used as the DEM1. From table 8 it is obvious that the RMSE which is about 8 meters, is better than the expected value of the 10m. At this point it is also very helpful to introduce for this DEM2 a detailed height difference distribution in order to realize the improvement of the total accuracy. In table 9 this detail height difference distribution is introduced.

Min diff	-115.81m
Max diff	111.64m
Mean diff	-0.83m
RMSE	8.19m

Table 8. Accuracy of DEM2

Height difference	Percentage
Min/-50m	0.039%
-50m/-20m	0.768%
-20m/-10m	3.681%
-10m/-5m	20.415%
-5m/-2m	26.912%
-2m/-1m	6.579%
-1m/1m	11.900%
1m/2m	5.375%
2m/5m	10.936%
5m/10m	7.181%
10m/20m	3.989%
20-50m	2.021%
50m and above	0.204%
-10m/10m	**89.298%**

Table 9. Details height difference distribution of DEM2

From the above table it is shown that the almost the 90% of the points are within ±10m, while in the DEM1, 81% of height difference are within ±10m. Having in mind that the same matching parameters were used, it is obvious that the relief itself is responsible for this improvement. It is assumed that the DEM2 is the more characteristic of our evaluation process than the DEM1.

5.3.4. HRS images comparison in the PITKIN area. In this section some examples are given of the distortions created by steep slopes in the along track direction on HRS images, where the along track slope is from about 28° to 43°. The different representation of the cliffs in HRS images is obvious. A lot of information is missing in HRS front image which is represented in HRS back image. As a result, it seems that it is impossible to extract heights correctly in those areas and generally in areas with large along track slope. The critical value for the along track slope it seems to be about 30°. Finally, it seems that with manual editing it is possible to extract the borders of the cliffs, but in any case, it is very difficult to extract the heights in the cliffs.

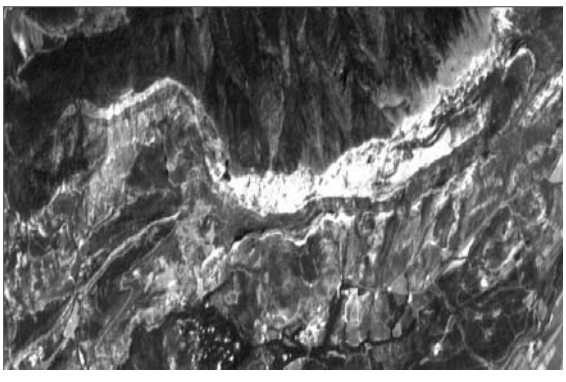

Figure 3. Example 1- HRS front image. Slope in cliff 1 is around 43° along track

Figure 4. Example 1- HRS back image**.**

As a general conclusion, the accuracy of the DEM which is produced by HRS using only the metadata information for the orientation process, is better than 10m in mountainous areas, except in areas where the along track slope is larger that 30°.

6. FURTHER WORK

In the field of sensor modelling the main object is to improve the generic along track stereo satellite model with respect to the Inertial Coordinate system in a way that:

- The information which is extracted from the metadata will be used not only to solve the model but also to refine and improve the solution.
- The self calibration process will be examined deeply and also, the role of the acceleration and the angular velocity.

In the field of DEM generation the next steps are

- Extract a DEM using the UCL software and the UCL model for the DEM orientation.
- If available, use nadir HRG images of Pitkin area with almost the same acquisition date as HRS images, in order to test how we can improve the DEM using the combination of HRS and HRG images in areas with along track slope larger than 30°.
- Improve matching accuracy by investigating new algorithms.

7. SUMMARY and CONCLUSIONS

This paper has described the testing of the UCL sensor model and the generation of a DEM using ERDAS Leica Photogrammetry Suite software (beta version). The results that are introduced within the paper guides us to the following conclusions:

- The SPOT5 HRS data can be oriented using ground control points or metadata and that a solution can be found which is within the expected error bounds. Especially, the accuracy of the heights compared with the GCPs is very close to 5m.
- use of self calibration gives a slightly improved solution.
- The accuracy when only using orbital data is good, and that the solution with ground control points is probably constrained by the accuracy of the control.
- The almost simultaneous acquisition time of the HRS images is the key to achieve high correlation during the image matching process better than 90%. Comparable figures for SPOT HRV are around 82%.
- The accuracy of the sensor model and the high correlation of the image matching are the two principal factors of getting the expected DEM accuracy.
- The accuracy of the DEM which produced by HRS using only the metadata information for the orientation process, is better than 10m in mountainous areas, except of the areas where the along track slope is larger that 30°.

Finally, in general, SPOT5-HRS shows that the use of the along track stereo sensors is a very promising for DEM generation.

8. REFERENCES

Airault S, Gigord P, Cunin L, Breton E, Bouillon A, Gachet, Bernard M, 2003. Reference3D location performance review and prospects. ISPRS workshop on High Resolution mapping from space, 2003, Hanover.

Baudoin A., Schroeder M., Valorge C., Bernard M., Rudowski V. “HRS-SAP initiative: A scientific assessment of the High Resolution Stereoscopic instrument on board of SPOT 5 by ISPRS investigators”. ISPRS workshop on High Resolution mapping from space, 2003, Hanover.

Leica 2003. “Leica Photogrammetry Suite:User Guide”.

SPOT Image, 2002. “Spot Satellite Geometry Handbook”,S-NT-73-12-SI Edition 1_Revision 0 ,15-1-2002

SPOT Image, 2003. “DIMAP Dictionary version 1.1- SPOT Scene profile” - Edition 01 September 2003

Valorge C., 2003 “3D Restitution and rendering through high resolution imagery: State of the art and new challenges”. ISPRS workshop on High Resolution mapping from space, 2003, Hanover.