PRE-FLIGHT AND IN-FLIGHT GEOMETRIC CALIBRATION OF SPOT5 HRG AND HRS IMAGES

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ABSTRACT:

SPOT5 Location model calibration addresses five main issues. The first issue is to get best relative and absolute location performances. It consists of relative orientation calibration for HRG, HRS and stellar location unit reference frames. Such a calibration started in-house, using theodolites; it ends in-flight using GCPs. The second issue is to get a model of THR pairs relative shifts good enough to deliver the best 2.5m sampled image. The first ever, true HRG images have been acquired during satellite design, a few months before launch. Such images contributed to THR processing validation and allowed ground calibration of THR detection lines relative shifts, way before launch. In-flight measures confirmed that such ground measures are reliable. Third issue is to turn HRS stereo pairs parallax in a precise enough altitude estimate. That means that HRS location models have to include an accurate model of objectives distortion. A fourth issue consists of HRG's steering mirror mechanism calibration, in order to get the same location performance, whatever the HRG mirror viewing angle is. Final issue deals with optimisation of time delay between two HRG off nadir images acquisition. Such time delay depends on mirror damping speed. For a given viewing angle, called "Autotest", one can acquire HRG images of a designed pattern located in the focal plane. A straightforward processing of this kind of images indicates if the mirror command can be improved. This new calibration process is available in flight as well as on ground. After the two months commissioning phase, objectives are met: images location models are accurate enough to meet all requirements. Absolute location performances provided by the stellar unit are such that new phenomena, never seen on initial SPOT satellites, appear. Initial results show performances trends that we should be able to model, once confirmed through further images acquisition. We specially think about orbital and/or seasonal effects. Work is still carried on.

This paper deals with geometric calibration of SPOT5 location model. Focus is set on commissioning phase results for which calibration has been performed in-flight as well as on ground. That is, relative reference frames orientation, CCD line distortion of HRG and HRS cameras, THR processing and tuning of steering mirror damping duration. To start with, I give a brief on main improvements of SPOT5 location model.

1. FROM SPOT4 TO SPOT5

SPOT5 payloads offers several improvements. Images sampling step can be reduced up to 2.5m thanks to a complete refurbishing of the focal plane. A stellar unit participates in minimisation of the absolute location performance. Two new cameras have been designed in order to provide on track stereo pairs. Following paragraphs focus on the main stakes of location model calibration.

1.1 Enhanced Focal plane

Technology improvement allows production of CCD array whose detector size is one fourth of today's SPOT1-4 detector and which numbers is increased almost by ten, on a single line: from 1700 to 12000. As a result, just changing CCD lines leads to the acquisition of 5m sampled images, still covering a 60 km swath. Studies on optimisation of an image chain (Latry 2000), applied to HRV-HRG telescope, shown a way to improve images resolution combining two CCD lines information's. A quincunx super-sampling principle called "**Supermode"** appears as a general optimisation of MTF, noise and sampling given the HRG telescope cut-off frequency (Latry 1998). THOMSON manufactured a dedicated specific sensor comprising two CCD lines, with a 3.45 pixel line shift and a 0.5 column shift. To achieve such a regular sampling on the ground, yaw steering and adaptive time delay in between lines acquisition had to be implemented. Yaw steering compensates earth rotation. Time delay compensates lines shifts, especially when off nadir viewing.

1.2 Improved Attitude restitution

New challenge given to SPOT5 payload is to provide accurate location model. Accuracy of SPOT location model mainly depends on attitude restitution performances. For SPOT1 to SPOT4, satellite attitude provided with images is just the same as the one computed on board, for platform earth pointing control. Attitude Control System uses gyro meters, to provide attitude angular speed, an infra-red earth-sensor and a digital sun sensor, for attitude determination. The Attitude Determination System combines these measures to deliver satellite attitude (Burello 1987). Computed angles inaccuracy contributes to 300 m location error (Pausader 1996). Attitude inaccuracy mainly depends on earth infra-red model quality.

For SPOT5, an extra attitude restitution process has been set in order to provide accurate attitude for images location model. It uses enhanced SPOT5 gyro meters, combined with absolute attitude angles measures given by a stellar sensor. This stellar sensor is a brand new one, having its first in-flight experience on SPOT5; it is designed around a CCD matrix observing numerous stars on each shot (Pochard 2000).

1.3 HRG Steering Mirror viewing angle restitution

For SPOT1 to SPOT4, the –27° to 27° off nadir viewing dynamic is sampled in 91 steps of 0.6° each: $1/7^{th}$ of the field of view. The viewing angle, exploited in the location model, is computed according to the only viewing step programmed value. Such a value differs from the true stop angle with an accuracy of 150 10-6 radians.

SPOT5 telescope design benefits from two major improvements. On one hand, an optical coding device provides a measure of the true mirror viewing angle. Measure resolution is 6 10-6 radians, equivalent to a 5 m ground pixel. On the other hand, off nadir mechanism has been improved in order to minimise angle drift with time.

1.4 Extra cameras dedicated to along track stereo: HRS

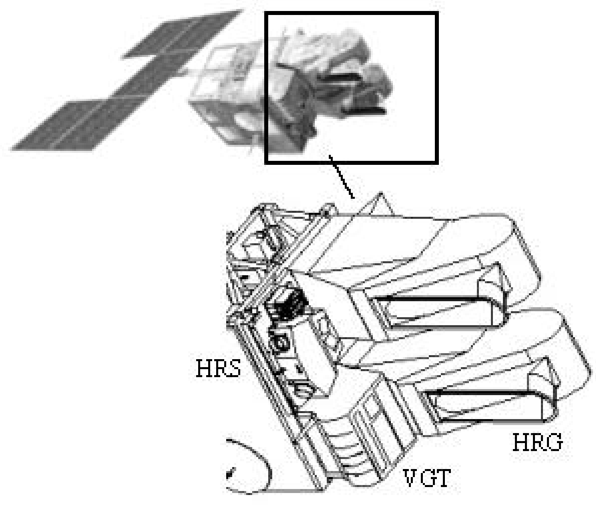

Figure 1: SPOT5 imaging payload

SPOT stereo pairs are known for their stereoscopic acuity. But time delay between images acquisition can’t guarantee absolute correlation completeness. Getting valuable Digital Terrain Model (DTM) requires an important human work load. Since three SPOT satellites are in flight, time delay has decreased, but the best guaranty of maximum correlation completeness is still to get along track stereo pair acquisition.

A dedicated along track stereo instrument, called HRS (High Stereoscopic Resolution) has been designed to acquire panchromatic images, with viewing angles of 20° forward and aft of the satellite (Fratter 2001). Images are sampled at 10 meters across track, and 5 meters along track: the parallax direction. Such pairs associated with accurate location models are the key to the production of a homogeneous, world-wide valuable, DTM.

2. HRG AND HRS LOCATION MODEL CALIBRATION

Accurate location model is not only a good transcription of the satellite position and attitude. It also has to do with calibration of instrument orientation on the platform (HRS camera, HRG telescope, Stellar Location Device …) and a good description of each detection line shape. For SPOT5 satellite we can classify geometric calibration in three steps, presented, here, according to their impact on the location performance. The first and main step deals with relative calibration in between cameras and the stellar unit frame, referring to J2000. The second step deals with cameras relative orientation: inter HRS, inter HRG and finally inter HRG and HRS. The last step, detailed in next section, deals with CCD detection lines distortion models. Satellite position determination with DORIS is now known has being sub-metric (Berthon 2000).

2.1 Payloads relative and absolute Orientation

When the satellite is on the ground and until a few days before launch, theodolites measures provide an initial, relatively coarse, alignment of the components. Such measures are precise enough to meet guidance performance objectives as well as provide sub-kilometric location model. For instance, the first in flight location measures, for SPOT5, were close to 600 m. We were just using guidance computed attitude, waiting for the Stellar Location Unit measure to be declared reliable. Such location error has been cut down when using "stellar" measures.

Once each device was declared valid, each image, which location model could be combined with Ground Control Points (GCPs), contributed to estimate location model error. GCPs shared by images acquired by different cameras allow calibrating inter-cameras viewing offset.

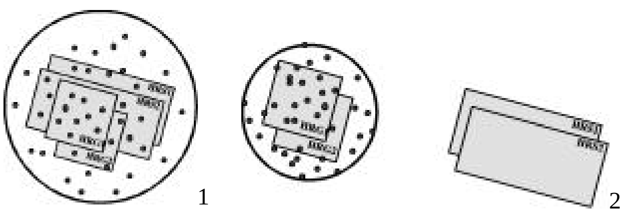

Figure 2: Images acquisitions configurations

Once relative calibration is considered as reliable, remaining location model errors are shared by all cameras. Such errors are corrected through a modification of cameras common reference frame and stellar unit reference frame, relative orientation. Data acquired during the two months commissioning phase lead to downsizing the overall location performances to 60 m for HRG and 35 m for HRS cameras.

Figure 3: Calibration test sites

After calibration, the analysis of residual location errors shows systematism obviously linked to the latitude of the satellite and thus heat exposure of the payload. The good performance of the stellar unit, combined with images coverage on a world scale, lead to the detection of this orbital effect. Further observations, at various latitude and seasons, should lead to an improved location model, taking into account these systematism.

2.2 HRG Steering mirror Off Nadir Viewing Model

HRG steering mirror (MCV) off nadir viewing model rely on optical reflection law, on a plane mirror, applied to each CCD detection line.

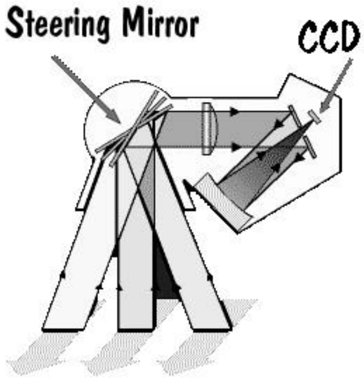

Figure 4: CCD viewing line reflection on HRG mirror

Numerous individual measures had to be collected, on the one hand, to minimise the impact of absolute measure's noise, on model estimation and, on the other hand, to get a sufficient viewing angle sampling.

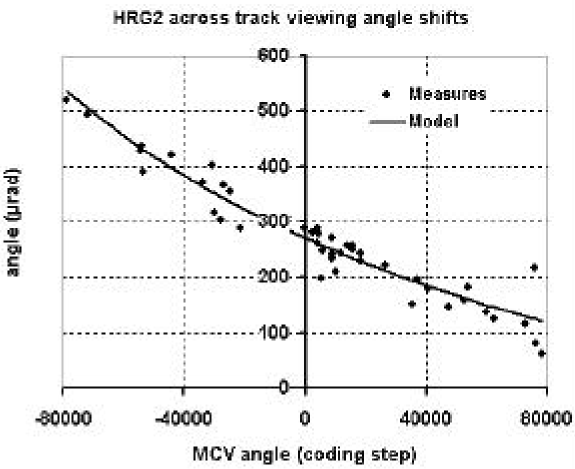

Figure 5: HRG2 mirror across track viewing model

3. DETECTION LINES DISTORTION MODEL

3.1 HRG detection lines

At a detection line level, main location errors are due to the distortion model quality. For HRG telescope, the narrow field of view, and the almost-central position of detection lines in the focal plane, doesn't induce much distortion. HRG focal plane calibration addresses, on one hand, the multi-spectral band registration for good colour rendering and, on the other hand, a sharp estimation of the actual shifts between the two 5 m detection lines dedicated to the process of a 2.5m sampled THR images (THR : french acronym for Very High Resolution).

Multispectral images registration requirements are that homologous pixels centres should fit in a 0.2 pixels wide, circular area (RMS). Since detection lines are, now, made of a single CCD detection line, colour lines shifts are small. They only depend on CCD shapes and CCD length differences. Pre-flight registration measures consist of observing, with a theodolite, a set of characteristic points on detectors. One can hardly talk about a ground calibration, since such measure reach theodolite's limitations; it rather consists of controls. Actual registration calibration is achieved in-flight through images correlation. Computed shift show that registration requirements are met except for the SWIR line which is a pixel shorter than visible spectral band. SPOT Image Ground Processing System includes an on-demand re-sampling of colour images in order to provide perfectly registered images according to in-flight calibration.

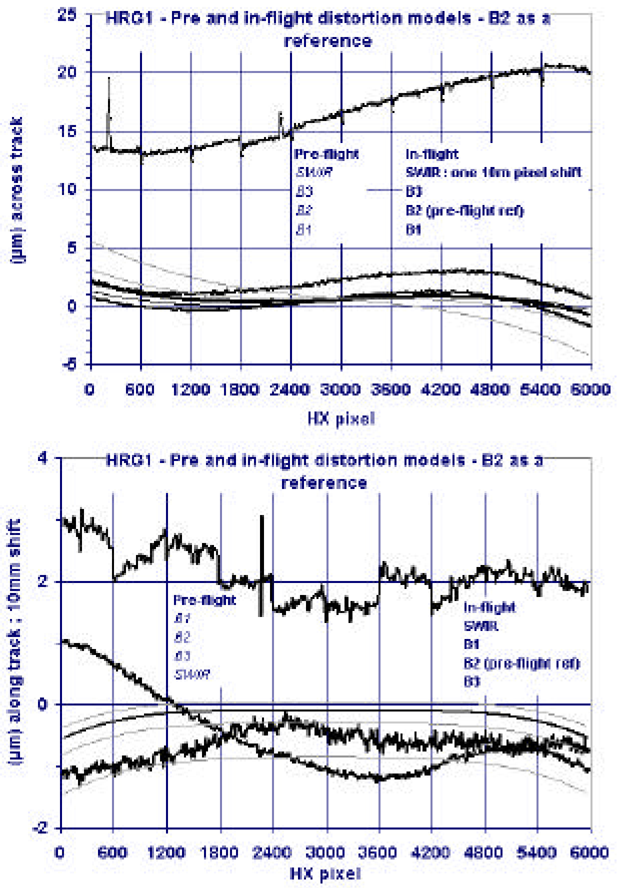

Figure 6: HRG1 raw colour lines superposition performance

3.2 HRS detection lines

HRS camera's objective includes multiple lenses. HRS field of view is twice as wide as the HRG one since the focal length is just half and detection line is the same. As a result, HRS camera distortion is important: 4 pixels across track. A decametric altitude estimation is submitted to accurate distortion calibration. As ground calibration model and ground measures show differences, in-flight tuning was a need.

Back and aft HRS images deformations are a mix up of altitude and cameras misalignment, in-flight distortion calibration is not as easy as multispectral images registration calibration. Various methods have been drawn up in order to be able to cross validate required assumption and results.

A method consists of correlation of HRS images with photographs turned in simulated HRS images. Aero-triangulated photographs provide images of a given landscape with calibrated location model, precise DTM and a sampling step suitable for 5 m x 10 m space image simulation. Overlapping shifts between satellite image and simulated image reveal lack in location model calibration.

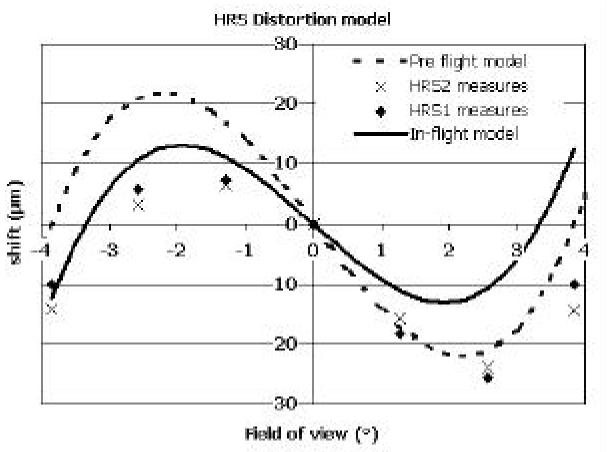

Figure 7: HRS detection line distortion model

Another method relies on the 26-days SPOT cycle to observe the same landscape on track. If cloud-free images pair is successfully acquired, one can compare two aft images or two back images. Since the satellite position won't be exactly the same in 26 day time: homologous pixels are spaced out by tens of columns, along the detection line. Image pair residual shifts represent a derivative to the distortion model.

A third method relies on HRS generated DTM analyses. If one has a DTM precise enough to stand as a reference, HRS DTM and reference DTM unlikelihood should be related to distortion model errors. If getting a reference's DTM reliable enough doesn't sound possible, we think about a statistical analysis of numerous differences between HRS DTM and existing DTM.

Images acquisition, images processing and results cross-analysis is a long process, so work is still carried on for distortion model improvement. At the end of the two months commissioning period, we've been able to provide a first correction using HRS images and aerial photograph's comparison. The calibrated distortion reaches 3 pixels on one camera and 5 pixels on the other one. Since existing photographs are getting out-dated, new aerial images have been acquired during the commissioning phase in order to get maximum likelihood with commissioning phase images. Since French Cartographic Institute now provides aerial digital images acquisition facility (Thom 2001), digital images have been acquired instead of photographs. They provide enhanced likelihood with satellite images and ease of processing.

4. STEERING MIRROR COMMAND TUNING

Off nadir viewing capability maximises targets observation possibilities. On the other hand, no image is acquired, when moving a mirror. Even with two telescopes onboard, one still wills to minimise mirror motion, and stabilisation, time. Dedicated commands are set in order to satisfy such requirements according to mechanism resonance frequencies and moving angle value.

Pre-flight moving laws have been set according to resonance frequencies close to 7 Hz for each HRG. In flight calibration identifies actual frequencies with almost a one hertz shift toward high frequencies (8 Hz). As a result studies are carried on in

order to modify mirrors commands accordingly. Mirror damping duration measures have lead to set an overall time delay between different off nadir acquisitions close to 11s ; this time delay should be reduced has soon has the new tuning will have been uploaded (Sept 01), improving image gathering opportunities.
Getting to such fine tuning for SPOT 4 was quite a hassle since the only data to be processed were images. One needed image pairs, cloud-free and DTM shifts free. That leads to 26 days time delay to get a suitable image pair (Pausader 2000).
On SPOT5, a dedicated calibration method has been set. When the mirror angle reaches a so-called calibration angle, detection lines observe the reflection of a pattern located in the focal plane, close to the B2 detection line.

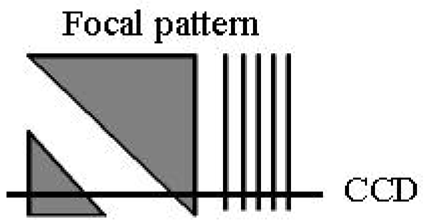

Figure 8: Focal pattern description

Images programmed on such a viewing angle give a moving view of the pattern till mirror stabilisation.

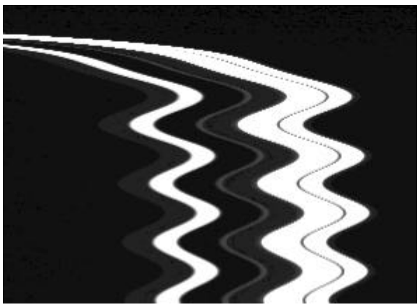

Figure 9: Autotest image, when mirror reaches calibration step

A straightforward processing delivers frequencies and stabilisation date.

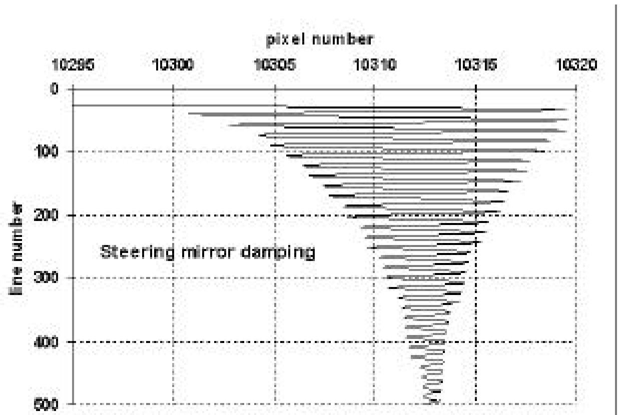

Figure 10: Mirror damping profile processed from Autotest

Such a calibration tool yields other results. It validates easily that moving a mirror on one HRG while the other telescope is acquiring an image, is of no impact on this image quality. Acquisition on a long period validates that there's no mirror drifts, according to the, 1 Hz resituated, mirror viewing step profile. It also provides radiometric calibration results (Meygret 2002)

5. QUINCUNX OVER-SAMPLING

Another challenge for SPOT5 payload was to provide enhanced resolution images according to the Supermode® technique. Such processing relies on the acquisition of raw images which line and column shifts are close to 0.5 pixel. Since it appears that raw images processing is very sensitive to the images shifts, the actual shifts value have to be provided with a precision close to 0.1 pixel. Then two main objectives had to be met : a 0.5 pixel shift objective and a 0.1 precision of the actual shifts measure.

5.1 Relative CCD shape model: nadir viewing

Given the processing sensitivity to shifts computation the pre-flight Supermode® validation process included acquisition of HRG images. For the first time, an optical configuration has been set in order to acquire an image during the SPOT satellite design. On the one hand such images contributed to validate THR images post processing and on the other hand allow to get actual CCD lines shifts.

5.2 Quincunx over-sampling and off nadir-viewing

CCD provides a 0.5 pixel shift between images lines for close to nadir viewing. The lines ground shift evolution with viewing angle can lead to the acquisition of images with no line shift; no THR image can be processed from such images. In order to compensate for such a drift, an on board electronic deregistration device delays images acquisition. The time delay is adapted to each THR acquisition according to uploaded values. It's a dedicated ground processing which provides suitable time delays to get an actual 0.5 pixel ground shift, according to each viewing angle. The ground processing relies on rough location models: nominal attitude, 24 h predicted orbital position, programmed viewing angle.
In-flight commissioning validated that such a model is sufficient to get the right acquisitions time delay. Time shifts are set with a 0.03 pixel equivalent step. A statistical analysis shows that computed line shifts are spread out around the 0.5 expected shift value with a 0.04 pixel dispersion: equivalent to 1.5 correction step. Objective of 0.5 pixel shifted images acquisition is met. The 1.5 step dispersion is quite small but, from a statistical point of view, one would expect a dispersion value close to 1. We intend to improve the model by using calibrated HRG viewing directions instead of pre-flight ones.

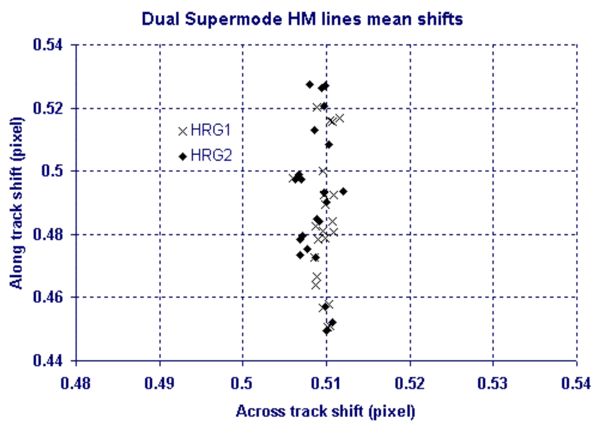

Figure 11: THR lines 2D shifts statistic

5.3 Images shifts computation

The image shift computation relies on location model. The same way we use location models to delay lines acquisition time, is the same way we use location model for actual shifts computation. But manipulated model is the one distributed with images: actual satellite location and attitude, true viewing angle step. A few image pair correlation confirmed that correlation estimated shifts and location model estimated one are close enough to trust location models estimates. In flight, first raw images pairs were successfully merged in a THR image with pre-flight CCD line shifts calibration (Latry 2002). Processed images and, later, in flight detection lines shifts calibration, confirmed that ground measured shifts are fulfilling the requirements. No sensitive correction is expected from in-flight measures.

6. CONCLUSIONS

The main objectives given to the two months SPOT5 commissioning phase are met : THR products are available, first HRS DTM are produced and location model are accurate. The calibration results have been given to SPOTIMAGE production department. Any user gets an accurate location model together with requested images. Location model data are provided in a XML file called "METADATA.DIM".
Work is still being carried on, in order to improve the absolute accuracy of models. An update of location models is foreseen towards the end of this year, after 6 months in orbit.

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