

SPOT 5 HRS LOCATION PERFORMANCE TUNING AND MONITORING PRINCIPLES

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ABSTRACT:

HRS instrument on board of SPOT5 allows acquisition of stereoscopic pairs in a single pass. This instrument has been subject of specific attention even after the end of SPOT5 in flight commissioning phase. The stake was not only to fulfil HRS' location specification of 50 meters in root mean square but to obtain a location performance as best as possible and at least about 25 meters in root mean square as expected before launch. Moreover, it should be checked that the instrument could cope with the realisation of Reference3D world-wide Digital Terrain Model database, in particular for horizontal accuracy, set to 16 meters for 90% of the points without ground control points. The article gives an outcome of the work carried out to improve the location performance. First, an overview of HRS will be given, with a specific attention paid to the geometric model available through ancillary data given with the images which is the only data available to reach the location performance. Then, methods and means used to reach the objectives will be described : French Space Agency (CNES) and French Mapping Agency (IGN) worked in co-operation to carry on specific analyses at three levels of interpretation. Improvements brought to the performance after the end of the image quality commissioning phase will be detailed : most error sources have been identified and some of them reduced or removed thanks to satellite on board modification or ground models. Finally, a view of the current location performance and a list of error sources will be detailed as a balance of the location performance's level reached. The conclusion will remind of monitoring principles adopted and detail further work planned.

1. INTRODUCTION

In this introduction, we will deal with general presentation of HRS, its geometry and remind of geometric calibrations already carried on which will not be detailed in this article.

1.1 Presentation of HRS

SPOT5 is the latest of SPOT satellite family and one of its novelties is an on board stereo mission with its High Stereoscopic Resolution instrument called HRS (see figure 1).

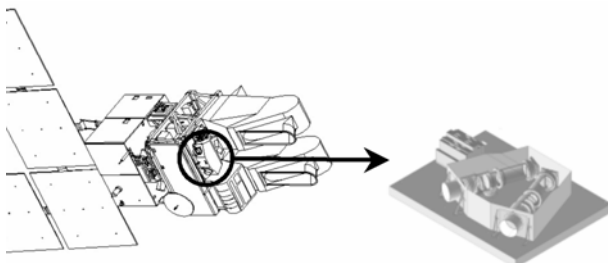


Figure 1 : Detail of HRS on board SPOT5

HRS has been designed for a DTM mass production all over the world. The instrument is composed of two telescopes with an along track viewing angle of 20° forward and 20° aft.

A stereoscopic pair acquisition is thus possible in a single pass with 90 s time delay between the two images (see figure 2). The correspondent base-to-height ratio is about 0.8.

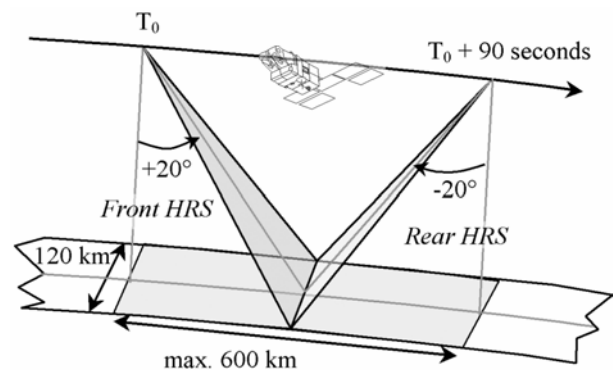


Figure 2 : HRS' acquisition process

Each camera has a focal length of 580 mm and its focal plane is composed of a single CCD array of 12,000 detectors at 10 m resolution, which makes a 120 km swath. Along track sampling rate is 5 m which provides a better resolution in the epipolar direction. Altimetric accuracy is thus expected to be better than 5 m rms.

For more details about HRS instrument, see <http://spot5.cnes.fr>, [Gleyzes, 2003] and [Baudoin, 2004].

1.2 HRS' Geometry

HRS is fully integrated on board SPOT5 and ancillary data provided with each image of an HRS stereopair has got same characteristics as SPOT5 High Geometric Resolution principal mission ancillary data.

All data necessary for a physical geometric modelling of an image are given in a DIMAP format file named METADATA.DIM :

- dating is made through two models : correspondence between board time (BT) and universal time (UT) is given by Doris ultra stable oscillator and correspondence between image line and board time is given by onboard oscillator. Image centre line time, line period and each ephemeris and attitude sample time are deduced from these models and given in universal time ;
- satellite position and velocity is given every 10 s by DORIS DIODE on board orbitography determination. The best orbit arc is fit on DIODE data thanks to TRIODE software and result in ephemeris points given every 30 s. ;
- satellite yaw, pitch and roll orientation angles are computed out of quaternions delivered by the on board stellar location unit (ULS) and given every 125 ms (8 Hz) ;
- pair of viewing angles ψ_X , ψ_Y are calibrated on ground and given for each detector of the CCD array.

Details about how to proceed with the geometric modelling of an image out of its METADATA.DIM are given in [Spot Image 2002].

With those, HRS location performance is expected to be better than 50 m rms (specification). Before launch expectations even showed that a 25 m rms performance could be reached.

This performance level, much better than for the previous SPOT satellites, is mainly due to the onboard stellar location unit. This system uses both star tracker and gyroscopes data to compute absolute orientation of the satellite. The result is a good low frequency accuracy thanks to the star tracker, and a good high frequency accuracy thanks to the gyroscopes.

1.3 Geometric calibration of HRS performed during the quality image commissioning phase

The image quality commissioning phase was divided into two parts. The first two months were dedicated to first calibrations and characterisation in order to ensure that SPOT5 was fulfilling its specifications and ready for commercial exploitation. During the next 4 months, image quality commissioning went on, with a fine characterisation, and improvement of the first calibration processed.

HRS' geometric calibration during this phase has consisted in :

- measuring orientation bias of the two cameras on SPOT5 platform thanks to ground control points (outer orientation) ;
- calibration of the optic distortion and relative orientation of the two cameras by comparison of HRS images with a precise aerial reference (inner orientation).

This process has resulted in updates of the list of viewing directions ψ_X , ψ_Y given for each detector (See [Bouillon, 2002], [Breton, 2002] and [Gachet, 2004] for more details about geometric calibrations and performance measurements carried out during the commissioning phase).

At this point, the goal for HRS was to meet the location specification of 50 m rms and it was attained. Still, HRS challenge is to provide a worldwide database of Digital Terrain Models and Orthoimages, as automatic as possible, called Reference3D. This database is produced from HRS acquisition with no use of ground control points and a horizontal location specified as 16 m for 90% of the points (see [Airault, 2003] and [Bernard, 2004]).

So, at the end of the commissioning phase, some steps remained to get location results in accordance with pre flight expectations and it was also necessary to check that Reference3D specifications were held.

2. PRINCIPLES FOR OPTIMISATION OF HRS LOCATION PERFORMANCE

After the end of the commissioning phase, some possible improvements of HRS location performance were already identified. In this section, we will describe method and means used to complete the work performed during the commissioning phase in order to get the best possible location performance for HRS.

2.1 Adopted working method

A working group involving French Space Agency (CNES), French Mapping Agency (IGN), SPOT5 satellite integrator (ASTRIUM) and star tracker developer (SODERN) has been created. The method held back was to carry on an analysis of every potential error source affecting HRS' location performance at three levels of interpretation :

- elementary sources of errors, such as attitude restitution's accuracy, structure deformations or geometric calibration remainders ;
- system location performance : in this context, each image, even of an HRS stereopair, is considered independently and the location performance is computed separately for each camera ;
- location performance obtained with the added value of tie points between the two images of an HRS stereopair (stereoscopic location performance) and of several HRS stereopairs considered in a bundle block adjustment process (with only tie points between the different strips, no ground control points are used).

Each level of interpretation allows the detection of different phenomena likely to have some impact on the location performance. Each phenomenon has been analysed to understand its source and exact impact. Potential improvements have been examined, but only in terms of on board modification of existing threshold or parameter, or of ground algorithms. Finally, improvements considered as necessary have been carried out and validated, as well as monitoring activities necessary to uphold the performance.

2.2 Available means of measure

For the 1st interpretation level, analyses only concerned stellar location unit attitude restitution. In fact, different sources for attitude restitution are available and can be compared : the theoretical requested attitude, the stellar location unit attitude, the on board attitude control system (AOCS) which do not involve the star tracker, and finally the star tracker does its own attitude restitution. All these data are stored each time the satellite is in visibility of Toulouse, the main ground station, and available in a data base for further analysis.

For the 2nd interpretation level, system location monitoring data is used. It consists in a database of images on specific location sites all over the world, constantly updated : approximately one image for each SPOT5 instrument is acquired each month on each site for this monitoring. Sites have been chosen for their cartographic data availability and also for their repartition all over the world in particular with latitude (see figure 3).

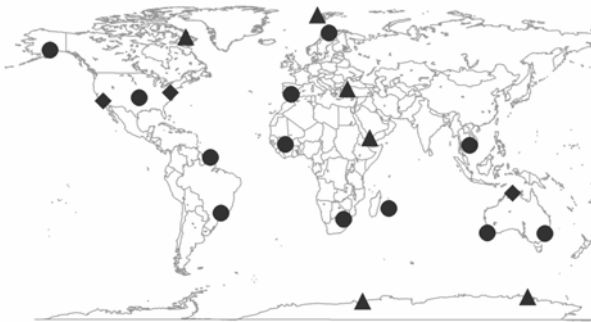


Figure 3: SPOT5 location sites around the world : circle = main site, diamond = secondary site, triangle = no more used

Ground control points are taken on every image of this database and specific tools allow computation of the system location performance and also interpretation of the errors in terms of chosen parameters. Available parameters are polynomials up to degree 2 for attitude angles, bias for satellite position, bias for detectors viewing angles, focal length adjustment and potential rotation of CCD array in the focal plane. Thanks to the worldwide repartition of the sites, and the constant update of the database, analysis of errors dependencies with satellite orbit position and with acquisition time can be done.

The 3rd interpretation level has been performed in co-operation with French National Geographic Institute Space Department (IGN Espace) involved in the working group. IGN has put on some important means in order to ensure that Reference3D horizontal location performance is met. Analyses of bundle block adjustment process and errors for both monitoring sites and Reference3D production blocks has been performed. The large size of some production sites allows detection of specific behaviours which can not be seen in any other ways.

Finally, when necessary, specific information about thermal behaviour, available thanks to on board thermistances, have also been analysed.

3. ANALYSIS RESULTS AND IMPROVEMENTS CARRIED OUT

In this section, we will describe for each level of interpretation the main phenomena detected and studied and the improvements brought out of it.

3.1 Attitude restitution analysis

Stellar location unit attitude restitution is a new one on board a SPOT satellite and it had to be finely checked out because it determines the major part of HRS' location performance.

Its high frequency performances have been assessed by comparison of image matching grids with location grids using the stellar location unit attitude data. It showed out remainders lower than 1 m (0.1 HRS pixel) when a disturbance such as a mirror movement is present, and usual microvibration lower than 50 cm (0.05 HRS pixel). See [Valorge, 2003] for more details about it.

Comparisons between different attitude sources showed out an accordance between all of them, and highlighted several phenomena which do not put in question ULS' performances level but whose impact on the location performance has been studied. From it, two possible improvements have been identified.

First, some roll perturbation of ULS attitude was present because of a deformation of the structure supporting the star tracker. This phenomenon has been removed thanks to an adaptation of the on board thermal control parameters. It allowed to gain a few meters on absolute location performance and time registration performance.

Second, a possible improvement of the filtering process of the stellar location unit algorithm has been identified in order to remove measures gap due to confusion between stars and proton's impacts. This phenomenon only impacts a very small proportion of images and should soon disappear thanks to an on board modification.

3.2 System location performances analysis

Analysis carried on location performances measured for each HRS camera concerned both relative location (difference of location between the two HRS), and absolute location (mean location of the two HRS).

At first sight, relative location appeared to be very noisy across the track. This was a problem because as measuring HRS' relative roll gives an estimation of the satellite yaw, it meant that satellite's yaw estimation was noisy too. This noise has been related to a deformation of the foot supporting the cameras and greatly decreased thanks to an adaptation of thermal control thresholds.

Before the modification, the standard deviation for HRS relative location across the track was about 20 m, and it went down to 7 m after (see figure 4). In the same time, the standard deviation for satellite yaw estimation out of HRS' relative roll went from 100 microradians before down to 12 microradians after.

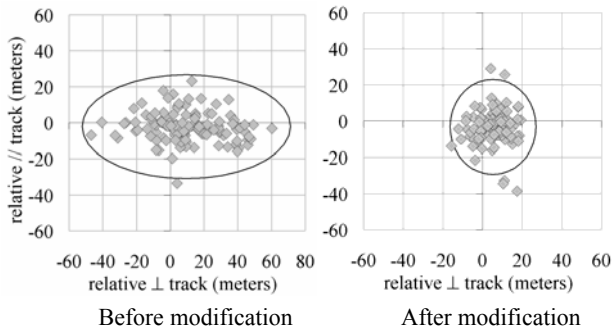


Figure 4 : improvement of HRS relative location (ellipse is the $3 \times \text{std}$ boundary)

As for HRS absolute location performance, the analysis showed an important variation of the performance depending with the latitude of the acquisition. This variation was firstly thought to be related to a specific thermoelastic effect affecting the whole payload as it also touched HRG's location performance. The explanation of this variation finally appeared to be a bad initialisation of the star tracker relativist compensation process. After on board correction of this problem, no more variation of the performance with latitude has been observed and HRS absolute system location performance without using any ground model went down from 50 m rms to 20 m rms (see figure 5).

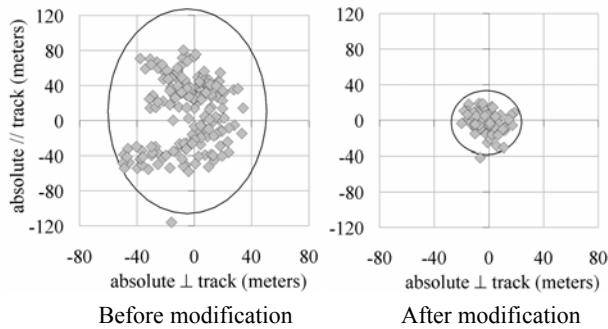


Figure 5 : improvement of HRS absolute location (ellipse is the $3 \times \text{std}$ boundary)

An analytic model has been calibrated in order to improve on ground the location performance before the modification (see [Bouillon, 2003]). This model is not to use for images acquired after the modification. Moreover, it should be replaced by a rigorous description of the effect as known for a correct description of the impact on images acquired before the modification.

Finally, taking into account all this knowledge, the analysis of remaining location errors for all images shows a temporal trend, combination of ageing, seasonal stability and discontinuity due to the on board modification of HRS' foot thermal control (see figure 6). This trend can be modelled and taken into account on ground for further improvement of the location performance.

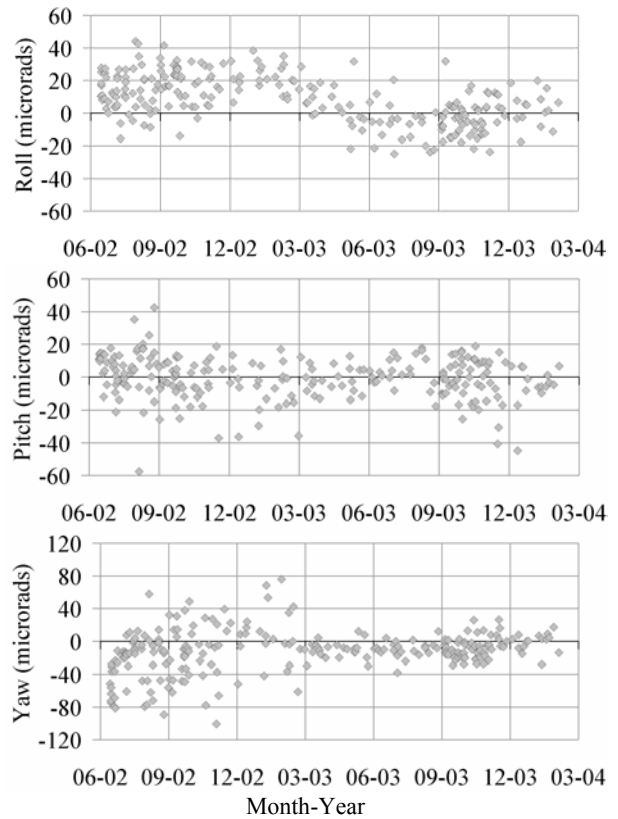


Figure 6 : Satellite Roll, Pitch and Yaw temporal trend computed out of HRS' absolute location performance

3.3 Stereoscopic and Reference3D performances analysis

Analysis of the horizontal accuracy of HRS stereopairs, and blocks of HRS strips (Reference3D performances) have been assessed in collaboration with French National Geographic Institute. Main results are presented in [Airault, 2003] and [Airault, 2004].

First of all, the processing of HRS blocks takes into account a specific model for images acquired before removal of the on board relativist error, and a temporal model for all images including remaining effects described above. These are necessary to obtain the best location performance possible for all available images.

Remaining errors are measured through bundle block adjustment by taking into account tie points between two images of an HRS stereopair, and between different HRS strips. The analysis of the process showed out that considering HRS instrument as rigid was a necessary hypothesis to manage it. It is therefore admitted that HRS' internal parameters do not vary with time : this reduces the degrees of freedom and allows a good solution.

Moreover, some possible improvement of HRS inner orientation parameters were pointed out. In particular, among Reference3D production, a 3000 km wide block is available which allows a very precise measure of camera's focal length.

Finally, this work was carried out on every location site available, and also on some Reference3D production sites (total of more than 20 sites all over the world). It showed out that availability of precise ground control points is the key for a good interpretation of errors. As a matter of fact, priority was given to sites with GPS points in order to get rid of some possible biases of local cartographic systems.

4. HRS' CURRENT LOCATION PERFORMANCES

In this last part, we will first give the latest figures about HRS' location performance available from the ancillary data provided with the images. Second, we will give a breakdown of errors sources making up the performance.

4.1 Latest figures for HRS' location performances

Figures given in this paragraph concerns HRS latest performance assessment for year 2004. Two types of figures are presented : Table 1 shows the relative location performances (difference between the two HRS' cameras location) and Table 2 gives the absolute location performance (mean performance for the two cameras).

Statistical are computed out of location difference and mean for each HRS stereopair. For a single stereopair, location difference and mean are computed out of mean location of each image of the stereopair.

| <i>meters</i> | HRS relative location performances (77 pairs) | | |
|-----------------------------|--|-----------|-----------|
| | ⊥ track | // track | Global |
| Min | -16 | -39 | |
| Max | 19 | 29 | |
| Mean | 4 | -5 | 6 |
| Standard deviation | 8 | 10 | 13 |
| Max for 90% of pairs | 14 | 14 | 20 |

Table 1 : HRS relative location performances (with no tie points used)

| <i>meters</i> | HRS absolute location performances (77 pairs) | | |
|-----------------------------|--|-----------|-----------|
| | ⊥ track | // track | Global |
| Min | -20 | -42 | |
| Max | 19 | 19 | |
| Mean | -2 | -2 | 3 |
| Standard deviation | 9 | 12 | 15 |
| Max for 90% of pairs | 15 | 18 | 27 |

Table 2 : HRS absolute location performances (with no ground control points used)

4.2 Error sources affecting HRS location budget

In this paragraph, we'll give the size and nature for each elementary source of error making up HRS' absolute location performance. All error sources are summarised in Table 3.

Geometric calibration remainders are high frequency errors varying in the field of view. Their contribution should be smaller than 1 meter rms in both directions (across and along track) thanks to the high accuracy of reference data used to perform the inner orientation (see [Gachet, 2004]).

Doris ephemeris provided with the images have an accuracy better than 1 meter rms in both directions (along and across the track). Ephemeris errors are mainly bias depending on the image and can be lowered by ensuring ephemeris join for different images acquired from the same orbit.

Image line dating accuracy is a low frequency error : it is mainly a bias depending on the image (accuracy of the center line dating) combined with a very few linear dependence due to line period measure precision. Its contribution is about 3 meters rms and only impacts along the track.

Structure deformations of HRS, or between HRS and stellar sensor unit are supposed to be low frequency errors as an hypothesis for our analysis. The temporal trend observed (see paragraph 3.3) allows to evaluate this error about 8 meter rms across the track and 5 meters rms along the track.

Finally, attitude's restitution accuracy delivered by the stellar location unit combines both low frequency and high frequency contributions due to its specific nature (see paragraph 1.2 and 3.1). Given all other error sources and the final location performance measure, its accuracy should be better than 5 meters rms across the track and 10 meters rms along the track which is in accordance with expectations.

| <i>meters</i> | HRS absolute location budget | | |
|-----------------------|------------------------------|----------|--------|
| | ⊥ track | // track | Global |
| Geometric Calibration | 1 | 1 | 1 |
| Ephemeris | 1 | 1 | 1 |
| Line Dating | 0 | 3 | 3 |
| Structure | 8 | 5 | 10 |
| Attitude restitution | 5 | 10 | 10 |

Table 3 : HRS absolute location contributors (root mean square figures)

These figures are deduced on the one hand from our knowledge of each error source and on the other hand from observations and analyses carried out. As potential structure deformations are still not very well known and cannot be precisely measured, the exact repartition between structure and attitude restitution is linked with our current interpretation of available measures and may be subject to some evolution if this interpretation happens to change.

5. CONCLUSION

The joint working group activated after the end of the commissioning phase in order to improve HRS' location performance has achieved significant results. Several improvements were brought, and objectives were met : HRS location performance is now about 15 m rms and compliant with Reference3D planimetric specification.

Now the main contributors left are closely monitored on a monthly basis. This constant monitoring of location accuracy is coupled with a close attention paid to the on board stellar location unit in order to detect every potential problem as soon as possible.

Further work is still planned with HRS in the context of its monitoring. First the temporal trend identified needs to be constantly evaluated as it is taken into account into HRS worldwide database Reference3D's production process. Second, it is planned to test and compare different inner-calibration of HRS on different sites in order to improve the inner orientation parameters and validate the hypothesis of time stability of these parameters.

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