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ISPRS Journal of Photogrammetry & Remote Sensing 60 (2006) 134–146

PHOTOGRAMMETRY & REMOTE SENSING

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SPOT 5 HRS geometric performances: Using block adjustment as a key issue to improve quality of DEM generation

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Received 12 August 2005; received in revised form 6 March 2006; accepted 13 March 2006
Available online 21 April 2006

Abstract

HRS instrument on board of SPOT 5 allows acquisition of stereoscopic pairs in a single pass. Its final purpose is to provide the worldwide database of Digital Terrain Models and Orthoimages, called Reference3D®, with no use of ground control points and a horizontal location specified as 16 m for 90% of the points. The stake is not only to fulfil the HRS' location specification of 50 m in root mean square but to obtain a location performance as best as possible and to check that the instrument can cope with the realisation of the Reference3D® database. That's why HRS has been the subject of specific attention even after the end of SPOT 5 in-flight commissioning phase.

This comprehensive paper summarizes the steps jointly taken by CNES, IGN, Spot Image and HRS end-users to calibrate, monitor and validate the HRS image accuracy as well as the accuracy of the final DEM products.

First, an overview of HRS on SPOT 5 will be given, with a specific attention paid to the instrument geometry and rigorous sensor model available through ancillary data given with the images.

Then, methods and means used by the French Space Agency (CNES) and the French Mapping Agency (IGN) to reach the objectives will be described and the final accuracy reached will be given. It concerns:

- calibration and monitoring of the HRS geometrical parameters, and the several on board improvements brought to the satellite by CNES to improve the location accuracy at the single pair level (i.e. no tie points nor ground control points used);
- the HRS block adjustment model calibration and the evaluation performed by IGN at the stereo pair level (i.e with tie points used within the pair) and block level (with tie points used between different HRS strips).

Finally, the article deals with several comparisons of HRS DEM's against available DEMs (eg. SRTM DTED level 2) and also reviews various evaluations of the HRS and the Reference3D® products made by independent users against ground truth issued from field measurements or high quality/high scale geodata.

Keywords: SPOT; HRS; stereoscopic; geometric; performance; calibration; monitoring; block; adjustment; DEM; accuracy

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0924-2716/$ - see front matter
doi:10.1016/j.isprsjprs.2006.03.002

1. Introduction

This paper presents the latest SPOT satellite, SPOT 5, and its innovative sensor dedicated to a DEM generation, HRS. A world wide DEM database, Reference3D®, is generated without any Ground Control Point by Spot Image and IGN thanks to the accurate knowledge of the HRS geometry and of the stereoscopic acquisition capacity of this instrument which allows bundle adjustment over large areas.

The HRS geometry is described and results obtained during the Commission Phase and afterwards are presented in part 3, showing the location accuracy improvements thanks to systematic errors corrections known through the HRS behaviour analysis and modelization.

Block Adjustment of the HRS data on very large areas is described in part 4, showing how this technique can improve the horizontal and vertical accuracy and especially according to the block size.

Assessments of the DEM accuracy and quality have been performed, through the ISPRS–CNES initiative but also with other Mapping agencies such as NGA (US Government National Geospatial-Intelligence Agency) or FÖMI (Hungarian Mapping Agency) and results are given in part 5.

2. HRS on SPOT 5

2.1. SPOT 5

SPOT 5 is the latest satellite of the SPOT family, launched during the night of the 3rd to the 4th of May 2002 from the European Spaceport in Kourou (French Guyana) with one of the last Ariane 4 to be used (Flight V151 with AR42P).

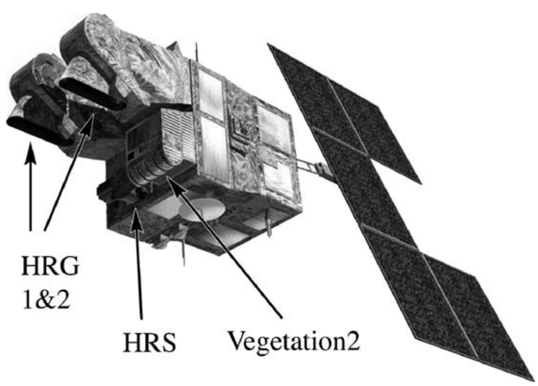

Fig. 1. SPOT5 satellite and sensors.

Table 1
Spot orbit parameters

Parameter	Nominal value
Altitude	818–833 km
Inclination	98.72°
Period	101 min
Descending node local time	10:15 am
Revolutions per day	14+5/26
Cycle duration	26 days

This satellite (Fig. 1) ensures data continuity with the previous satellites but provides also enhanced images (at approx. 2.5 m pixel size with its two HRG instruments) and new stereoscopic capabilities with the HRS instrument. A fourth imaging sensor, Vegetation 2 (recurrent model of Vegetation 1 on SPOT 4) gives a wide-swath (2500 km) daily coverage.

SPOT 5 is on the same orbit as SPOT 1, 2, 3 and 4. This is a polar, circular, sun-synchronous orbit. Its characteristics are recalled in Table 1.

More details about SPOT 5 system and ground segment can be found in (Gleyzes et al., 2003).

2.2. HRG cameras

Two High Resolution Geometric instruments (HRG) give SPOT 5 the capacity to pursue and to improve the HRVIR SPOT 4 service.

Each instrument has the same field of view (4.13°) and the same off-track pointing capabilities (±27°) as the HRVIR instrument on SPOT 4, which gives the opportunity to cover 60 km (vertical view), and up to 80 km for an oblique view.

Improvements from SPOT 1, 2, 3 and SPOT 4 to SPOT 5 are the following:

- Panchromatic images (0.49–0.69 μm) are acquired using two staggered linear array detector lines of 12 000 elements of a size of 6.5 μm giving 5 m resolution at nadir. These two lines can be combined to achieve a better resolution and a pixel size of approx. 2.5 m.
- Multispectral images are acquired with 6000 pixels per line in three bands B1, B2, B3 and 3000 pixels in the SWIR band.
- Compression rate and transmission (up to a factor 2).

Improved location accuracy (10 m rms after ground processing) is reached using a star tracker not present on the previous SPOT satellites.

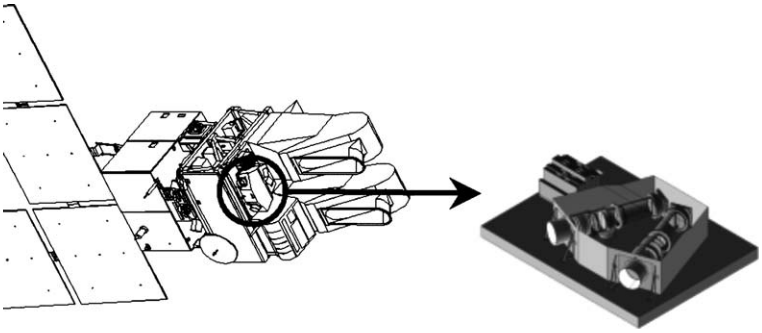

Fig. 2. HRS camera.

2.3. HRS camera

The High Resolution Stereoscopic instrument (HRS) has been designed for a DEM mass production all over the world. It is made of two telescopes allowing along-track stereoscopy with a 20° fore view and a 20° aft view (Fig. 2).

Stereo pairs could be already acquired from HRV and HRVIR on the previous SPOT satellites but from different orbits, either using the same satellite at different days or from two SPOT satellites on the same day only on few parts of the world. With HRS the two images of the stereo pair are acquired within an interval of only 90 s, following the satellite track and covering an area of 120 km wide by up to 600 km long (Fig. 3). This limitation of the acquisition length is due to the fact that the two images could not be recorded simultaneously and corresponds to the distance on the ground between the fore and aft viewing directions.

The main characteristics of this instrument are given in Table 2. A panchromatic band is used (0.48 to 0.7 μm) which does not include near infrared to avoid dark shadows in mountainous areas. The 120 km swath has been specified for insuring a compatibility with bi-HRG nadir viewing (an HRG image is 60 km wide) but also, and mainly, for ensuring a global coverage even at the Equator. The spatial resolution (10 m), as the B/H (0.8) have been chosen to get the expected DEM accuracy of 10 m (with 90% confidence on slopes less than 10%). From these parameters the number of detectors (12 000) within a single CCD array and their size (6.5 μm), as well as the integration time (0.752 ms) have been deduced.

Considering that epipolar lines of the stereo pair are parallel to the track of the satellite (for along track stereo) the sampling rate has been doubled in order to get a better correlation between the two images, leading to rectangular pixel (5 m along track × 10 m across track).

2.4. HRS' Geometry

The HRS is fully integrated on board SPOT 5 and ancillary data provided with each image of an HRS stereo pair has got same characteristics as SPOT 5 High Geometric Resolution principal mission ancillary data.

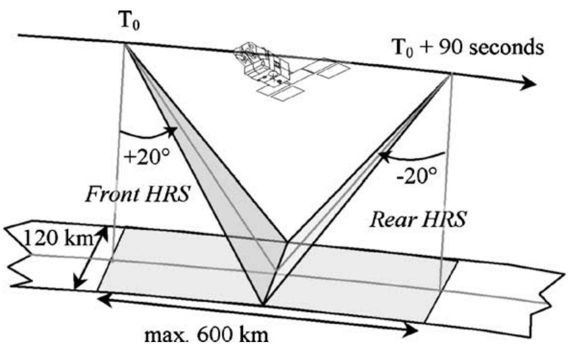

Fig. 3. HRS' stereo acquisition process.

Table 2
HRS characteristics

Mass	90 kg
Power	128 W
Size	$1.0 \times 1.3 \times 0.4$ m^3
Panchromatic band	0.48–0.70 μm
Ground sampling distance	10 m cross-track, 5 m along track
Field of view/swath	+/−4° 120 km
Focal length	0.580 m
Detectors per line	12 000
Detector size	6.5 μm
Integration time/line	0.752 ms
Fore/aft viewing angle	+/−20°
Signal/noise ratio	>120
MTF	>0.25

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

- Line dating is made through two models: a correspondence between board time (BT) and universal time (UT) is given by a Doris ultra stable oscillator and a correspondence between image line and board time is given by an 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;
- The satellite position and the velocity is given every 10 s by DORIS DIODE on board orbit determination. The best orbit arc is fit on a DIODE data thanks to a TRIODE software and the result in ephemeris points is given every 30 s.;
- The 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 psiX, psiY are calibrated on ground and given for each detector of the CCD array.

Details about how to proceed with the rigorous sensor model of SPOT 5 images are given in Spot Image (2002).

Pre-launch location requirement for a single HRS pair was fixed to 50 m rms. Before the launch, some 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.

2.5. Reference3D® database

The HRS data is currently used by IGN and Spot Image to build a worldwide accurate database called Reference3D®, which consists of three information layers: Digital Elevation Model at 1-arc-second resolution (approx. 30 m), Orthoimage[1] at ca. 5 m resolution and Quality Metadata. Since 2003, the Reference3D® database is progressively incremented at a yearly pace of 6 to 7 million sq. km. The low cost production process is based only on the use of tie points, no ground control points are required.

The Reference3D® specifications were set before launch, examining both the HRS performances expected and taking into account the production process. The Orthoimage layer absolute horizontal accuracy specified is 16 m (circular error for 90% of the points). The DEM layer absolute requirements are:

- horizontal circular absolute accuracy of 15 m at 90%;
- vertical absolute accuracy depending on the slope:
  - 10 m at 90% for slopes lower than 20%;
  - 18 m at 90% for slopes between 20% and 40%;
  - 30 m at 90% for slopes greater than 40%.

The production process can be basically described in three steps:

- relative orientation of each HRS pair;
- DEM processing by automatic correlation of each stereopair;
- global processing of the absolute geometry by bundle block adjustment over large areas.

The key to reach the absolute location performance specification is a good initial absolute location performance at the single pair level and an effective block adjustment process taking advantage of tie points. The validation of these two aspects is presented in following sections.

3. Assessment of HRS geometry

3.1. Geometric calibration of HRS during the in-flight 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 SPOT 5 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.

The HRS' geometric calibration during this phase has consisted in:

- measuring orientation bias of the two cameras on SPOT 5 platform thanks to ground control points (exterior orientation);

[1] These images are orthorectified from the DEM and have a high degree of geometric quality and location accuracy.

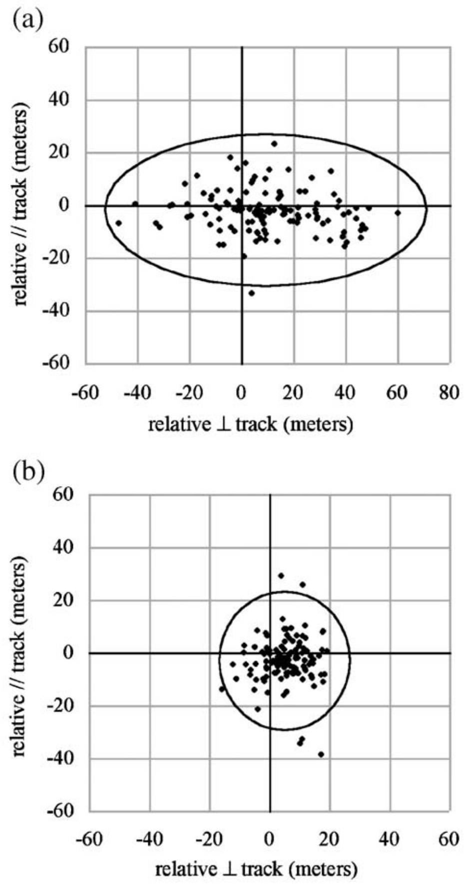

Fig. 4. HRS relative location (single pair) from Bouillon and Gigord (2004)—Ellipse shows the 3 × std boundary. (a) Before correction. (b) After correction.

– 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 resulted in updates of the list of viewing directions psiX, psiY given for each detector. Details about the geometric calibrations and the performance measurements carried out during the commissioning phase are given in Bouillon et al. (2002), Bouillon et al. (2003), Breton et al. (2002), Gachet (2004), Valorge et al. (2003).

At the end of the commissioning phase (November 2002), it was stated that the initial goal for HRS of 50 m rms location accuracy for a single pair, was clearly met. Therefore some steps obviously remained to get the location performance in accordance with on the one hand the 25 m-rms pre flight expectations and on the other hand the 16 m-at-90% Reference3D® product requirement.

3.2. On-board corrections performed after launch

After the end of the commissioning phase, the potential ways of improvement of the HRS location performance were already identified and explored by a working group involving the French Space Agency (CNES), the French Mapping Agency (IGN), the SPOT 5 satellite integrator (ASTRIUM) and the star tracker developer (SODERN). A full description of the process and detailed results are given in Bouillon and Gigord (2004).

These studies unveiled a noise caused by a variable deformation of the foot of the cameras. This effect was successfully corrected through a modification of the on-board thermal control performed on February 25, 2003. After this correction, HRS relative location accuracy is better than the pixel instantaneous field of view of 10 m (Fig. 4).

An important variation of the absolute location performance, correlated with the latitude, was successfully corrected on September 2003 through a

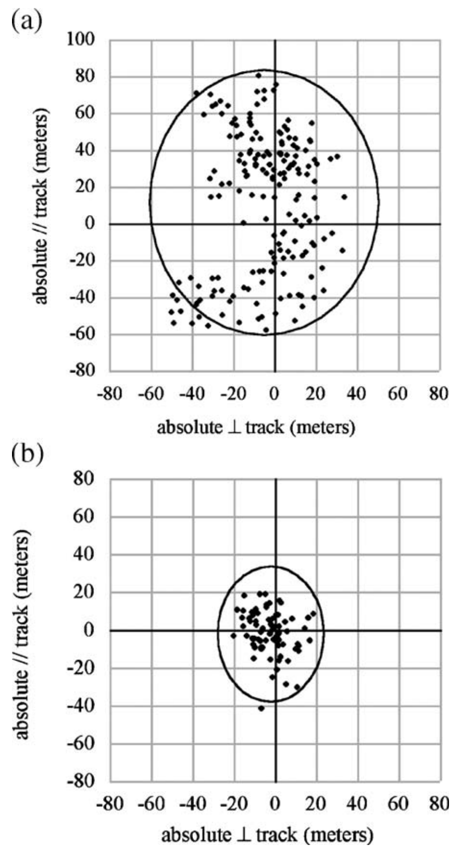

Fig. 5. HRS absolute location (single pair) from Bouillon and Gigord (2004)—Ellipse shows the 3 × std boundary. (a) Before correction. (b) After correction.

Table 3
Absolute location performances as of year 2004 — HRS single pairs, with no ground control points used from Bouillon and Gigord (2004)

Meters (rms)	HRS absolute location performances (77 pairs)		
	⊥ track	// track	Global
Min	−20	−42	
Max	19	19	
Mean	−2	−2	3
SD	9	12	15
Max for 90% of pairs	15	18	27

modification of the on-board software. This effect was caused by a bad initialisation value in the star tracker software used to correct the stars position from annual aberration (effect due to relative motion of the Earth around the Sun). After the on board correction, the HRS absolute location accuracy reaches its best level (Fig. 5). Images acquired before the on board correction can be on ground corrected of this problem through a precise model.

3.3. HRS location performances at the single pair level

Table 3 gives figures of the absolute location performance of a single HRS pair (assessment for year 2004).

The obtained improvements allowed to reach a location performance of about 15 m rms (27 m at 90%) at the single pair level which is a high level of accuracy. The remaining deviations need to be closely monitored: location measures are performed on a set of specific sites on a monthly basis. This monitoring allows a constant evaluation of any potential ageing or temporal trend. It is completed with annual evaluation of inner orientation accuracy on a specific very precise site.

At this point, no further location improvement can be reached at the single pair level: the complementary effort needed to reach the 16 m-at-90% requirement for absolute location of the HRS Reference3D® product is obtained by the block adjustment process of the HRS strips with tie points. The next Section presents the validation of this process and the final accuracy reached.

4. HRS Block Adjustment process validation

To reduce the above 15 m rms value down to a 16 m–at–90% one, IGN designed an advanced HRS model integrated into a bundle block adjustment software: the HRS products are extracted from large image blocks, through a block adjustment process (also known as "space-triangulation"), run without any control points.

The decision to produce Reference3D® without any control point was not really a choice, considering the non availability of reliable horizontal control data over the majority of the globe. As a result, a continuous quality assurance process is necessary to master the Reference3D® location accuracy and to ascertain customers that the 16 m circular requirement is met.

Some preliminary evaluation of the HRS block adjustment process accuracy were performed during the SPOT 5 commissioning phase. These first results are given in Airault et al. (2003) and showed that the required accuracy was reached. These results have then been strengthened after the latest on board improvements (see (Orsoni et al., 2005)). The quality assurance process is now on a daily routine mode and the Reference3D® location accuracy is continuously monitored. In this section, latest evaluation results available are given, mainly extracted from Orsoni et al. (2005) and completed with new measures.

4.1. Data and test sites

IGN's quality assurance process is based on a subset of 18 "quality sites" chosen among the sites used by CNES (see (Bouillon and Gigord, 2004; Orsoni et al., 2005)) to represent a good coverage of the earth (Fig. 6) and so that the images treated cover the whole extend of the satellite life. Around 10 HRS pairs per month minimum are used and a total of 980 HRS images have already been treated for the 18 quality sites. The objectives are to be able to detect temporal and geographically correlated variations and to correct them.

An effort was thus done to enhance the quality of these sites by adding GPS points to sites equipped only with cartographic GCPs in order to check that the cartography was not biased, and by improving the transformation parameters used (using grid transformations for France and USA for example). The number of GCPs by site varies from 10 to several hundreds (the site with 10 GCPs is used because of the good quality of these points), and the geographic extent of the GCPs vary from 60 to 930 km.

Two additional specific sites are used in the quality assurance process: Middle East and France. Over Middle East, 4 groups of GCPs located near the 4 corners of the site are available, and over France an orthophoto reference (accuracy 3 m rms) is available. The main interest of these sites is their East–West

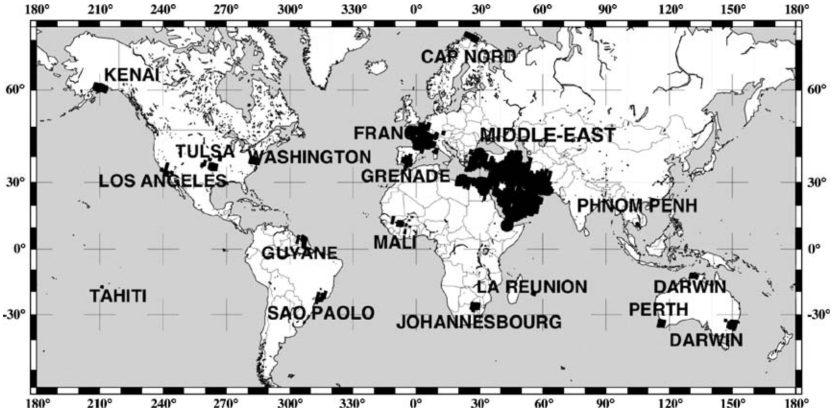

Fig. 6. Quality sites used for HRS modelling process.

geographic extent (around 1000 km for France and 2500 km for Middle East) and the number of images used (110 images for France and 960 for Middle East). The extent of those sites and the number of images are important for the inner orientation parameters estimation (see Section 4.3).

4.2. Method

4.2.1. Space-triangulation

Space triangulation is the technique used at IGN Espace to register satellite images. This method allows to simultaneously optimise the geometric models relating to a set of contiguous scenes grouped in blocks, using the viewing parameters associated to the scenes, ground control points and tie points between the scenes so that the global model computed for the block will be coherent for the whole block.

This method is based on a physical description of the image acquisition process. It allows to choose physical correction parameters as representative as possible and therefore to limit the number of unknowns to be determined.

4.2.2. HRS block adjustments processing

The Reference3D® block adjustment process is based on a set of HRS stereo pairs covering an extended area connected by tie points identified on different stereo pairs. This method allows averaging the non-systematic errors.

So, the first aspect of the quality assurance process is to detect and remove all the systematic errors affecting the absolute location of the images. This work is performed through a specific block adjustment processing over the "quality sites" and results are detailed in Section 4.3.

After removing these errors, the block adjustment process performances are studied through the comparison of HRS pairs location obtained from a block adjustment using both ground control points and tie points as a reference processing and another one using only tie points which is representative of the Reference3D® production process. The comparison with the reference processing is made before and after the Reference3D®-like block adjustment processing in order to assess the performances both at the stereopair and the block level. Results are detailed in Section 4.4.

4.2.3. Physical model parameters used in the block adjustment process

The parameters considered in the different block adjustment processing are:

- satellite position bias (3 parameters by strip);
- second degree polynomial for satellite orientation angles roll, pitch and yaw (3 * 3 parameters by strip);
- time tagging bias parameter (one parameter by single image);
- inner-orientation parameters (a set by block, only in the case of calibration processing).

A strip is composed of at least one HRS pair, and it can be more as soon as ephemeris and attitude data of successive HRS pairs can be merged.

4.3. HRS block adjustment model calibration

In this section, the results of systematic errors evaluation are detailed: temporal and geographical variations as well as inner-orientation parameters refinement.

4.3.1. Temporal model of the attitude angles evolution

A first bundle block-adjustment process is performed on each test site, without inner-orientation parameters. The results are used to compute mathematical functions representing the temporal components of the satellite orientation for roll, pitch and yaw. The roll component shows a periodic evolution, with a significant linear tendency. The ageing effect is treated as a beginning-of-life linear tendency mostly for the yaw component (Fig. 7).

4.3.2. Inner-orientation parameters refinement

The data available for the validation of the block adjustment process also allowed to improve the inner orientation provided by CNES. The focal plane shape (i.e. optical distortion) is not improved by the process. The five inner orientation parameters considered in the adjustment process are:

– a scale factor along the CCD array direction for each sensor (equivalent to a focal length unknown);
– the CCD array orientation in the focal plane for each sensor (called front and back “pseudo-yaw”);
– the relative pitch of the 2 cameras (angle which determine the stereo base).

Inner orientation parameters were computed separately on the 18 test sites (18 independent determinations), then with the data of these 18 sites joined together (1 determination) and finally over France and Middle East blocks separately.

Evaluation for each site allowed studying of the eventual geographic correlation of these parameters while the global evaluation for the 18 sites gives an average result independent from the geographic position. Finally the most important correlation noted was a strong decrease of the rms of the solutions with the geographic extent of the ground control points and with the number of images for the site.

Studying the variations of the 21 solutions shows that the relative pitch is the most stable parameter with a global rms <2.5 micro-radians. For the sensors array

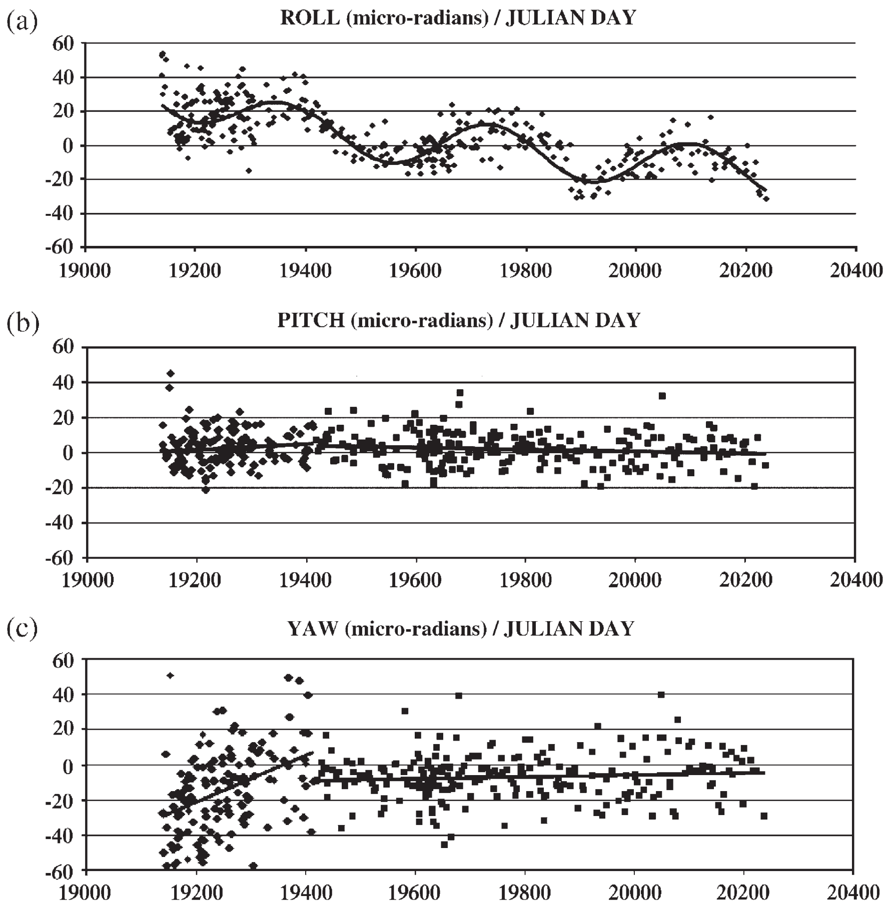

Fig. 7. Roll, pitch and yaw (micro-radians) evolution against Julian day. a: Roll. b: Pitch. c: Yaw.

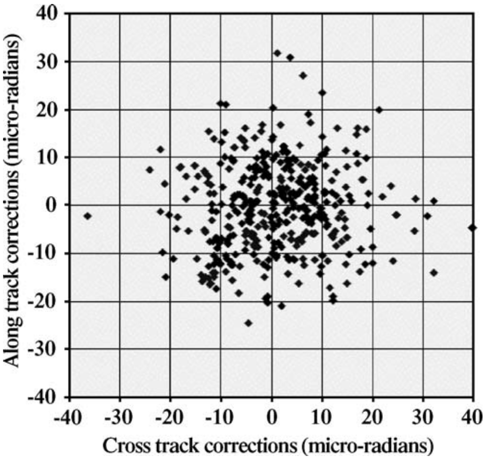

Fig. 8. Along track (Y) versus across track (X) corrections in micro-radians for single stereo pairs (1 micro-radian corresponds to ca.0.8 m on the ground).

scale factor, the rms decreases from 15 to 5 ppm when considering only the sites with a GCPs extension greater than 200 km. The sensor lines orientation parameters (front and back pseudo-yaw) show the strongest variations in the different results. Its rms decreases from 22 to 5 micro-radians when selecting only the sites with more than 100 HRS images.

Therefore, assuming that Middle East block has a great east–west extension and a great number of images, it was decided that the values computed for this site (confirmed by the other sites, including France) will be used in all the processes.

A good estimation of the inner orientation parameters is very important in the scope of the Reference3D® processing. The use of large blocks enables a good averaging of the attitude errors but a wrong estimation of these parameters would propagate the errors in the block.

To improve the precision of the values of line magnification coefficients and orientation angles, roll and pitch corrections variations estimated for each stereo pair are studied against the track longitude at Equator (for this purpose the block will be adjusted without GCPs constraint). A bad evaluation of the scale factors would be reflected by a linear tendency of the roll relatively to the track longitude at equator. In the same way a pitch tendency would reflect a bad evaluation of the sensor lines orientation. Measuring these tendencies with regular intervals of time is part of our quality assurance process.

4.4. HRS absolute location performance at the stereopair and block level

The above two steps provide an advanced HRS geometrical model, based upon the refined values for HRS inner-orientation parameters, as well as a set of functions to optimise attitude angles considering the acquisition date. These results are taken into account in every further block adjustment processing.

In this section, we present the Reference3D® block adjustment processing performances at the stereopair and the block level by comparison with a reference processing using ground control points.

4.4.1. Before bundle block adjustment

The performance before space triangulation is measured through the roll and pitch corrections applied during the bundle block adjustment:

– 10.1 m rms along track
– 9.2 m rms across track

The global absolute location performance for a stereo pair connected with tie points is then 13.7 m rms. (Fig. 8)

4.4.2. After bundle block adjustment

4.4.2.1. Estimation of horizontal performance. To assess the location performance of the models in the Reference3D® process, we first process all the test sites with all GCP XY coordinates activated and after with all XY coordinates de-activated. We finally compare the coordinates estimated during the two processes. These results include eventual biases of the references used for these sites (Fig. 9).

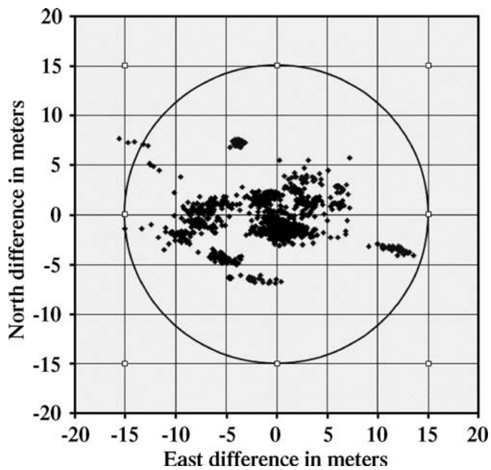

Fig. 9. Estimated location accuracy of the Reference3D® modelling process from Orsoni et al. (2005). North differences against East differences in meters. The circle represents Reference3D® location specification of 15 m for 90% of the points.

This shows a 4.1 m rms (Easting) and 3.1 m rms (Northing) performance. This represents a horizontal accuracy of 8.4 m for 90% of the points.

4.4.2.2. Estimation of vertical performance. The same method as above is used: 2 bundle block adjustment processed, one with the XYZ GCPs constraints, the other one with XYZ GCPs coordinates deactivated. Thus the comparison also includes eventual biases in the elevation references. The 90% threshold elevation performance is 4.5 m (Fig. 10).

4.4.2.3. Block size and performance. A study was performed using the Middle East block to quantify the absolute location performance relatively to the block size.

The block is composed of 480 stereo pairs. It was separated in 4, 8, 16, 32, 96 and 480 blocks (in this last case 1 stereo pair = 1 block). In each configuration all the blocks were computed twice: one process using the altimetric GCPs constraint and tie points and another using only tie points. For each block and process the stereo pairs corners position is compared with the same stereo pairs corners of the block computed with the GCPs horizontal and vertical constraints (Fig. 11).

According to these results, the minimum number of stereo pairs (connected by tie points) necessary for the block to meet the Reference3D® specifications is 10 pairs. This block configuration gives a horizontal performance of 7.5 m and altimetric performance of 4 to 5 m depending on the availability of elevation points.

We considered that the horizontal accuracy of the space triangulation process represents only 50% of the location budget performance of 15 m at 90% set by the Reference3D® specifications. The other 50% of the performance is due to on board high-frequency phenomena affecting the location model accuracy, and matching errors in the DEM generation process. Both affect the DEM and orthoimages generated. It is thus necessary to assess the DEM accuracy to get a global evaluation of the overall accuracy of the process and valid the compliance of the final product with the specifications. The next Section gives several results on this point.

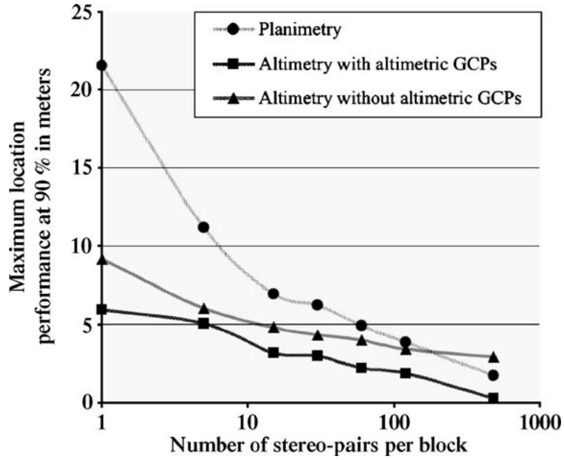

Fig. 11. Horizontal and vertical performance of the Reference3D® process in dependence of the block size from Orsoni et al. (2005).

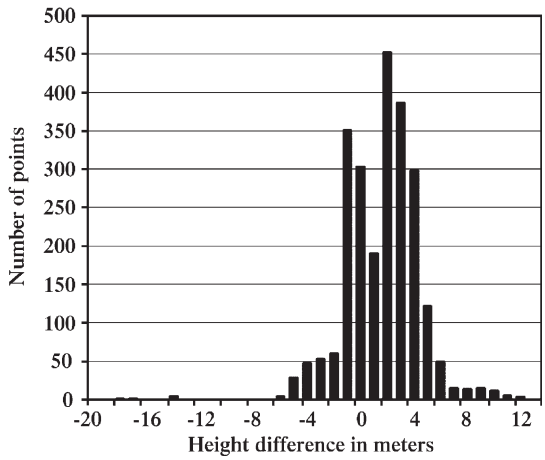

Fig. 10. Estimated vertical accuracy of the Reference3D® modelling process from Orsoni et al. 2005 (differences in meters).

5. Assessments of the altimetric accuracy of HRS and Reference3D® products

5.1. Several assessments at international level for the worldwide Reference3D®

Apart from technical comparisons carried out by IGN (against ASTER, against French National DEM,...), several assessments of the accuracy of the HRS and the Reference3D® products have been performed by independent users:

- a devoted ISPRS team, HRS SAP, gathered 10 + PIs to investigate the intrinsic potential of HRS imagery
- NGA and IGN performed in 2003–2004 a cross evaluation of the SRTM and the Reference3D® DEMs
- Joint Research Center Ispra (JRC) and FÖMI recently performed a very complete evaluation over Hungary
- Other labs or users from Canada, UK, China,...

Their results are briefly presented here below.

5.2. Assessment of Reference3D® against BD Topo

BD Topo is the French national elevation database mostly extracted from stereo plotting. It was used in the early stages of the production (a few weeks after SPOT 5 's launch) to assess the accuracy of the Reference3D® production process. The study has been performed by IGN Espace using the standard Reference3D® processing. The results were presented at the 2003 IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2003) held in Toulouse, France, in July 2003 and greatly contributed to consolidate our confidence in HRS data.

5.3. ISPRS "Scientific Assessment Program" Team

The HRS Scientific Assessment Program Team (SAP team) and the achievements are extensively described in Baudoin et al. (2004), Rudowski (2004). The PIs and CoIs presented their results during the 2004 ISPRS XXth Congress in Istanbul, and their studies were published in the Proceedings of the Congress. PIs and CoIs used raw HRS data and ground control points to produce DEM and compare them with a precise reference DEM.

Nine datasets were freely available to the investigators, and many of them were studied by several researchers (eg. Barcelona, Bavaria,...). Each dataset was made of HRS imagery complemented by "ground truth" (precise DEM and orthophotos) provided by the PIs.

Globally, the authors conclude that HRS is able to provide DEMs within a vertical accuracy better than 5 m in flat areas, and around 10 m in relief areas.

5.4. Cross evaluation of Reference3D® and SRTM DTED 2 with NGA

A joint comparison of Reference3D® with finished SRTM DTED 2 (from SRTM-C-Band data) for 12 preselected cells (over the Middle-East "quality site") that were exchanged with NGA was launched in early November 2003. The 12 selected cells were chosen to show out various landscapes, from very flat desert up to very high mountain areas.

The technical works have been carried out in parallel by NGA and IGN until March 2004. The detailed results were presented within the SRTM Workshop held in Reston (VA—USA) in June 2005, see Rudowski (2005). The short summary listed in Table 4 shows the full compatibility of the SRTM DTED level 2 and the Reference3D® products.

Table 4
Differences (in meters) in elevation between SRTM DTED2 finished product from NGA and Reference3D® (computed as SRTM–Reference3D®), from Rudowski (2005)

Cell #	Landscape	Figures at 90%			
		Min	Max	Mean	SD
E035n29	High relief	−5	15	4.4	4.0
E035n33	High relief	−10	4	−2.7	3.0
E048n32	Flat+relief	−21	1	−7.3	4.4
	High relief	−27	3	−9.4	6.0
	Flat terrain	−9	−1	−5.3	2.0
E049n30	Flat+relief	−6	5	−0.4	2.4
	High relief	−5	4	−0.5	2.2
	Flat terrain	−10	7	−0.5	3.7
E033n30	Medium relief	−6	10	3.7	3.3
E032n30	Medium relief	−6	11	1.5	3.7
E047n30	Flat terrain	−9	−1	−4.6	1.9
E048n29	Flat terrain	−12	−1	−6.7	2.5
E048n30	Flat terrain	−10	1	−5.5	2.2

Besides these figures, the studies stressed the complementarities of the SRTM DTED2 and the Reference3D® products: a very important ratio of SRTM voids could be filled in by the valid Reference3D® values, and on the reverse side, SRTM proved present with valid values to complement the HRS data where image matching was hindered by local conditions (smokes, small clouds, dark shadows,...).

5.5. Evaluation of Reference3D® by JRC and FÖMI

The JRC Ispra and the FÖMI thoroughly evaluated the accuracy of the Reference3D® (the tiles were produced by IGN in the standard Reference3D® processing) against very precise geodata produced by FÖMI. The test was performed over a 1°×1° frame located South West from lake Balaton.

The Reference3D® horizontal accuracy, carefully checked against a 0.70 m orthophoto, was found better than 10 m at 90%.

The Reference3D® elevation values were compared to about 5000 geodetic points from the Hungarian network, and a 5.4 m rms error was reported.

From a comparison with the MADOP DTM (5 m nation-wide DTM), the global Reference3D® vertical accuracy was evaluated better than 3.5 m rms.

It is important to note that the study by FÖMI and JRC included detailed evaluations of the elevation accuracy, through segmented classes describing i) the local slope (10%, 20% and 40% thresholds) and ii) the land use (agriculture, forest, urban). All of them confirmed that the Reference3D® accuracy requirements were met (Fig. 12).

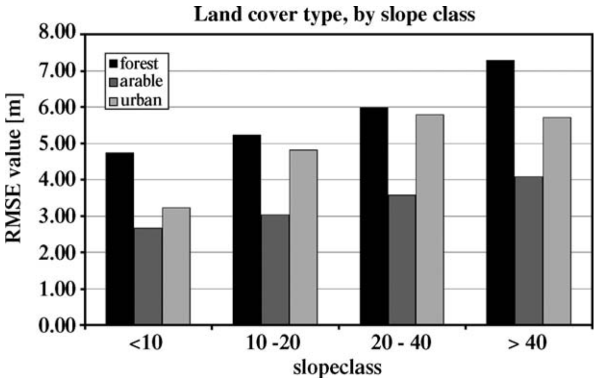

Fig. 12. Elevation accuracy of the Reference3D, displayed for different classes of slopes and land uses (from S.Kay—JRC).

The study was first presented in Budapest in November 2004. For further details, please see Kay et al. (2004).

5.6. Evaluation of Reference3D® over steep areas

Steep areas are without no doubt difficult areas for DEM extraction. Various evaluations over such zones were performed by several Reference3D® users in different countries. The most recent one took place in China, where a local user made an in-depth assessment of a Reference3D® cell located over a mountainous area.

The Reference3D® was first checked against 83 GPS points measured on purpose; more than 85% of the points were found better than 10 m in elevation, and the horizontal accuracy proved better than 10 m rms.

The Reference3D® was also compared to a DEM extracted from 1:48,000 scale aerial photos (converted from the Chinese datum to WGS84). The comparison was taking into account the slope classes mentioned in the Reference3D® requirements (20% and 40% slopes thresholds), and confirmed that the requirements were met.

6. Conclusion

A huge effort was necessary to get the maximum accuracy from the HRS data. Obviously, this effort shall be pursued as long as the HRS is “alive”, to unveil in due time any possible modification or evolution (of the sensor), and to make the necessary adaptations to the on-board and ground software.

The Reference3D® accuracy requirements were set at a very ambitious level. However, CNES and IGN and Spot Image enthusiastically took up the challenge, as well as the numerous Reference3D® users who performed detailed evaluations of many Reference3D® products.

In parallel, the international scientific community showed a large interest in the HRS data, and their papers corroborated the rich potentialities of the HRS data.

The results show that all the Reference3D® requirements are met, though considered as unrealistic by many in the past (including some of the authors), regarding the fact they had to be met without using any GCP. So the Reference3D® turns a once utopistic concept into daily routine.

Acknowledgments

The authors would like to thank Daniel Vidal-Madjar from CNES, Philippe Munier from Spot Image and Philippe Campagne from IGN who have given all the necessary financial support for the HRS Scientific Assessment Program.

Ian Dowman, Secretary General of ISPRS, Stanley Morain, President of Commission I and Manfred Schroeder, Chairman of WG I/2 on Sensor Calibration and Testing, during the 2000–2004 period should be gratefully thanked for organising within ISPRS the scientific assessment of the HRS instrument.

Acknowledgments should also be given to Christophe Valorge and Claude Fratter from CNES for their support in the creation of SPOT 5 working group for the improvement of HRS location performance; to Serge Potteck and Didier Rami from CNES, Sylvain Airault, Eric Breton, and Denis Toustou from IGN, Olivier Hameury and Patrick Rouchit from ASTRIUM and Philippe Jacob from SODERN members of SPOT 5 working group who actively participated to the achievement of the on board corrections performed after launch.

Very special thanks should be paid to J.Slater (NGA), S.Kay (JRC Ispra) and P. Winkler (FOMI) and their teams, who performed the priceless evaluations of Reference3D®.

Last but not least, the authors would like to give very special thanks to the Reference3D® Production Team, Michel Deloménie, Bernard Roche, J.F Albert, Brigitte Guénanten and the whole staff, whose day-to-day feedback and remarks allow the optimization of HRS performances.

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