

PLÉIADES SATELLITES IMAGE QUALITY COMMISSIONING

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Résumé

Pléiades est le système d'observation de la Terre civil le mieux résolu développé en Europe. Ce programme d'imagerie est conduit par le Centre National d'Etude Spatial français (CNES). Le premier satellite a été lancé le 17/12/2011 et le second le 02/12/2012. Chaque satellite est conçu pour fournir des images optiques aux utilisateurs civils et défense. Les images sont acquises simultanément en Panchromatique (PA) et multi-spectral (XS), ce qui permet en condition d'acquisition nadir d'obtenir des scènes de 20 km de large, en couleurs naturelles ou fausses couleurs, avec une résolution de 70 cm sur les produits PA+XS fusionnés. La couverture est quasi-mondiale avec une période de revisite de 24h avec les 2 satellites.

L'évaluation de la Qualité Image et les opérations d'étalonnage ont été réalisées par l'équipe Qualité Image du CNES pendant les recettes en vol de 6 mois qui ont suivi le lancement de chacun des satellites. Ces activités couvrent plusieurs thèmes comme l'étalonnage absolu, le calcul des coefficients d'égalisation, les opérations de refocalisation, l'estimation de la FTM, l'étalonnage du modèle géométrique, l'estimation de la précision de localisation, la registration multi-spectrale, les stabilités statiques et dynamiques, les précisions planimétriques et altimétriques. Ces opérations nécessitent des réglages spécifiques de la charge utile ainsi que des guidages particuliers de la plateforme du satellite. Les nouvelles capacités offertes par l'agilité des satellites Pléiades nous ont autorisées à imaginer de nouvelles méthodes d'étalonnage et de mesures des performances.

Après quelques rappels sur les caractéristiques principales des satellites, la présentation décrit les opérations d'étalonnage qui ont été menées pendant les recettes en vol et fournit les principaux résultats de Qualité Image.

Mots-clés : Qualité Image, agilité, étalonnage, Pléiades

Abstract

Pléiades is the highest resolution civilian earth observing system ever developed in Europe. This imagery program is conducted by the French National Space Agency, CNES. The first satellite has been launched December 17th 2011, and the second one December 2nd 2012. Each satellite is designed to provide optical images to civilian and defense users. Images are simultaneously acquired in Panchromatic (PA) and multi-spectral (XS) mode, which allows, in nadir acquisition condition, to deliver 20 km wide, false or natural colored scenes with a 70 cm ground sampling distance after PA+XS fusion. Coverage is almost world-wide with a revisit interval of 24 h for the 2 satellites.

The assessment of the image quality and the calibration operation has been performed by CNES Image Quality team during the 6 month commissioning phases that followed each satellite launch. These activities cover many topics such as absolute calibration, the normalization coefficients computation, the refocusing operations, the MTF assessment, the estimation of signal to noise ratio, the geometric model calibration, the assessment of localization accuracy, multi-spectral overlapping, static and dynamic stability, planimetric and altimetric accuracy. These operations required specific control of the payload and dedicated guidance of the satellite platform. The new capabilities offered by Pléiades satellites agility have allowed imagining new methods of image calibration and performances assessment.

Starting from an overview of the satellite characteristics, this presentation shows all the calibration operations that were conducted during the commissioning phases and also give the main results for every image quality performance.

Keywords: Image Quality, agility, calibration, Pléiades

1. Introduction

The Pléiades program is a space Earth Observation system led by France, under the leadership of the French Space Agency (CNES). It operates since 2013 two agile satellites designed to provide optical images to civilian and defence users. Since they were successfully launched on December 17th, 2011 and December 2nd 2012 (Fig. 1), Pléiades 1A and 1B high resolution optical satellite have been thoroughly tested and validated during the commissioning phases led by CNES.



Figure 1 : Pléiades image of Toulouse Convention Center, © CNES 2013.

Images are simultaneously acquired in Panchromatic (PA) and multi-spectral (XS) mode, which allows, in nadir acquisition condition, to deliver 20 km wide, false or natural colored scenes with a 70 cm ground sampling distance after PA+XS fusion. An example is given Figure 2. The scan-line is constructed by 5 detector arrays for PA and XS bands with overlapping Inter-Array-Zone (IAZ) to ensure line continuity.

Coverage is almost world-wide with a revisit interval of 24 h with the two satellites.

The Image Quality requirements were defined thanks to user surveys from the different spatial imaging applications, taking into account the trade-off between on-board technological complexity and ground processing capacity.

The major constraints of weight and agility led to the development of a highly compact satellite (about 1 ton weight), to minimize the moments of inertia (Gleyzes et al., 2012; Gleyzes et al., 2013). Agility is a characteristic which allows the satellite to acquire off-nadir targets rapidly in a large flight envelope, in order to sequence a large number of images. This agility is imposed by several requirements stated by the users. For instance, a 100x100 km² zone can be acquired by the satellite from the same orbit thanks to a lateral multi-band coverage. As for stereoscopic capacities, 3 images from the same zone can be acquired in a single pass with B/H lying between 0.1 and 0.5.

During the commissioning phase these capabilities have been performed in many cases. For instance, a video mode has been realized thanks to more than 30 images of the same target acquired in 5 minutes. In another opportunity, the 'Clock Tower' of Mecca have been acquired every 90s in a single pass to see the minutes needle moving and obtain a three-faces view of the building (Fig. 2)



Figure 2 : Three pictures on Mecca "tower clock" acquired by Pléiades 1B every 90 sec in a single pass to see the minutes needle moving ! © CNES 2013.

The image quality activities were performed during the 6 months that followed each launch at the Pléiades Image Calibration Center (ICC) at CNES. New brand methods have been applied taking advantage of the platform agility.

2. Radiometric activities

2.1 MTF assessment and refocusing operations

Refocusing operations have been conducted thanks to several methods. The main one uses stars (Fourest et al., 2009; Lachérade et al., 2012) acquired for different adjustments of the refocusing system made of a thermal control of the telescope's secondary mirror

position. It allows to measure by the way a very accurate 2D assessment of the MTF, (Fig. 3) as the Point Spread Function (PSF) is the image of a point-like source of light as seen by the instrument (Lebègue et al., 2010). Thanks to this very efficient method, the instrument was refocused 5 days after launch.

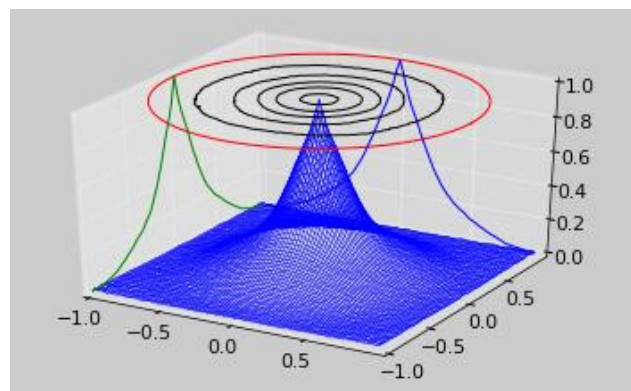


Figure 3 : Example of PA MTF measured on stars for different defocusing adjustments.

The second method uses the offset measured between homologous PA pixel of IAZ as this offset is geometrically related to the defocusing. This passive method is used to monitor the evolution of the instrument defocus (Fig. 4)

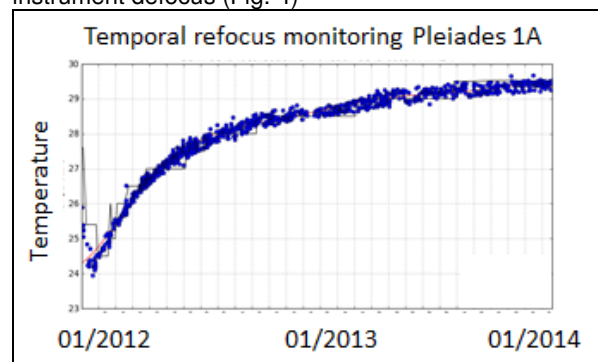


Figure 4 : Pléiades-1A defocus evolution between launch and March ,2014.

2.2 Absolute calibration

Several methods are combined to synthesize the absolute calibration coefficients for every spectral band (Lebègue et al, 2012).

First methods are absolute as they relate Pléiades images digital count to the theoretical signal expected for different kinds of landscape and environmental conditions. For instance, numerous acquisitions over the oceans have been processed using Rayleigh properties for B0, B1 and B2 bands (B3 used to characterize aerosols contribution). The main difficulty was to avoid cloud coverage over oceans. We also used images of La Crau test site equipped with the CIMEL radiometer providing automatic measurement of multi-angular viewing of atmosphere and close neighbouring ground reflectance. Moreover, a video made of 24 acquisitions has been realized to study the measures sensitivity to satellite viewing angles.

Other methods are relative as they compare Pléiades images to another reference. For instance, we inter-calibrate several sensors such as SPOT, MODIS, PARASOL on steady landscape of sand deserts and Antarctic Dome sites.

Finally, we monitor temporal evolution of absolute calibration using Moon images (Fig. 5) with accuracy better than 2% as the Earth satellite is a perfect photometric benchmark accessible without cloud constraints and any operational programming conflict.



Figure 5 : PA image of the Moon used for absolute calibration.

2.3 Inter-detector normalization

Because of inter-detector sensitivity differences, the image of a uniform landscape is striped vertically. Detector normalization aims at correcting these relative sensitivities and delivering uniform images of uniform areas. As Pléiades radiometric model is multi-linear, the normalization parameters identification requires observation of several uniform landscapes and may be actually very difficult to run, because of the uniformity constraint. This reference method has been operated during the commissioning, but, in order to reduce the in-flight operations, the so-called AMETHIST method (Kubik et al., 2004) has been processed for the first time. An efficient way to bypass the quest of uniformity is to use the satellite agility in order to align the ground projection of the scan-line on the ground velocity. This weird viewing principle (Fig. 6) allows all the detectors to view the same landscape and produce weird raw images as shown in Fig. 6.

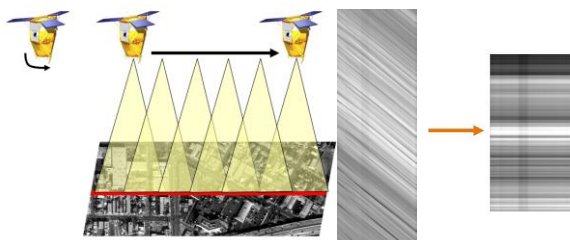


Figure 6 : AMETHIST acquisition principle and image formation.

After a pre-processing that globally shifts each column of the raw image, we get an image that contains all needed information. This means that every row contains the set of detectors response to the same landscape. Thus, non-linear normalization coefficients can be computed by a histogram matching method.

2.4 Signal-to-noise ratio assessment

Several brand new techniques were tested to assess the instrumental signal-to-noise ratio. The major one benefits from a dedicated guidance called “slow-motion” (Lebègue et al., 2008). The principle is to steer the satellite so that the projection of the scan-line on the ground remains constant along the image (Fig. 7).

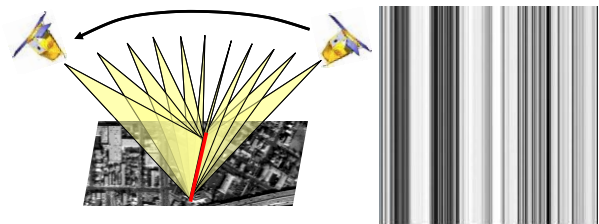


Figure 7 : Left: “slow-motion” mode acquisition principle (in red: target landscape line). Right: example of slow-motion image extract (Pléiades-1B). © CNES 2013.

Therefore, each elementary detector sees the same point on the ground along the column-wise direction with a slight change in the viewing direction. An example of the obtained image is shown in Fig. 7 where it becomes easy to compute the temporal evolution of each elementary detector response for a set of various input radiance. In the end, we can assess the instrumental noise model and its contribution in the radiometric signal to noise ratio budget.

2.5 Restoration and PAN-sharpening

Given that XS bands MTF is rather high, some aliasing effects are detrimental on images such as iridescence in the neighboring of high radiometric transitions (Fig. 8). These effects appear particularly on PAN-sharpened images where XS bands are zoomed by a 4 factor (Latry et al., 2012). Ground processing parameters including restoration, re-sampling and interpolation filters have been optimized to reduce these effects. Moreover a new technique of fusion has been implemented to suppress them.

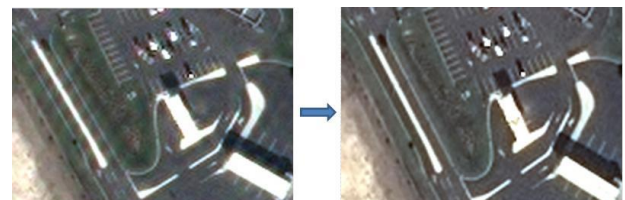


Figure 8 : Pléiades-1B acquisition: iridescence artifacts without improvements on Pan-sharpening algorithm for Pléiades (left) and current Pan-sharpened product (right). © CNES 2013.

3. Geometric activities

3.1 Localization performance

A fundamental user requirement concerns the image location without using Ground Control Points (GCP). The assessment of this performance is based on the statistics of the difference between real and image-given location of very accurate GPS GCP. CNES uses a large GCP database covering a wide range of latitude in order to observe orbital and seasonal phenomena (de Lussy et al., 2012).

The major contributor is the attitude estimation whose accuracy evolves during the commissioning phase as the calibration operations and the platform in-orbit behavior knowledge progress.

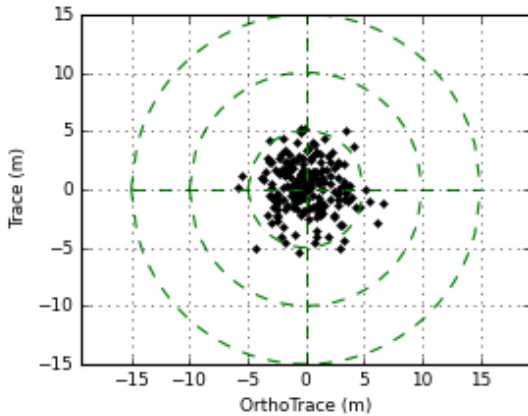


Figure 12 : Pléiades-1B location performance measured on the time period 2013 January to April.

In order to get rid of the use of expensive GCP, a new brand technique called Auto-Reverse (Lebègue et al., 2012) has been tested. The idea is to acquire two images of the same site along the same orbit with 180° angle difference between the azimuth tracks. Hence, correlation of the two images gives roll and pitch double location biases. The method gives actually very good results on flat landscapes.

For Pléiades-1A, the performance is close to 10m CE90 thanks to ground corrections implemented to counter some thermo-elastic effect on the relative star-trackers viewing directions. For Pléiades-1B results are excellent as the performances are close to 4.5m CE90% (see Fig. 12 and Table 1, statistical evaluation of 213 images taken within a cone of 30°)

On board real time attitudes	D+12h refined attitudes
5.3m	4.5m

Table 1 : Pléiades-1B location performance CE 90 for depointing angle < 30°.

3.2 Focal plane cartography

The absolute focal plane cartography, which means the assessment of the accurate viewing directions of every pixel in the instrumental frame, is achieved thanks to 2 methods. The first one, nominal for PHR1A, uses the

correlation of PA images with reference supersites (Greslou et al., 2009; de Lussy et al., 2012). These supersites are located in Toulouse (France) and Napier (New-Zealand) and are made of 10 cm resolution aerial images covering a 20x20 km wide area. Unfortunately, the weather conditions were very bad on these sites during the commissioning period and the activities planning suffered from lack of data.

A backup method has been tested for PHR1A and became nominal for PHR1B. The geometric auto-calibration method (Lebègue et al., 2008; Delvit et al., 2010; Lebègue et al., 2010; Greslou et al., 2012; Kubik et al., 2012; Lebègue et al., 2012; Greslou et al., 2013) can give cartography without a reference site. The idea is to acquire two images of the same site along the same orbit with 90° angle difference between the azimuth tracks (Fig. 13). Hence, correlation of the two images gives static residues along lines and columns.

Nevertheless, the absolute cartography was achieved within 2 months and shows misaccuracy from ground models up to 2 PA pixels. The actual residues are smaller than 0.2 PA pixels along columns and 0.3 PA pixels along lines.

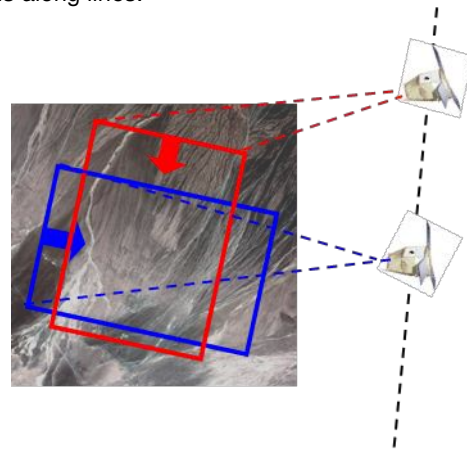


Figure 13 : Geometric auto-calibration acquisition scheme.

Concerning, the XS bands, the relative cartography is processed thanks to correlation with the PA band and between XS bands on dedicated flat landscapes. The results accuracy allows to meet the inter-band registration requirements essential for a good PAN-Sharpning.

3.3 Line-of-sight dynamic stability

Several techniques were used to assess the line-of-sight stability such as inter XS band correlation (Delvit et al., 2010; Lebègue et al., 2010; Delvit et al., 2012; Greslou et al., 2012), but the most powerful one uses once again the stars. The idea of our method is to use the stars as references. By definition, a star is stationary in an inertial frame. If the satellite sensor remains pointed at a star (Lebègue et al., 2008; Fourest et al., 2012), it will create a bright column in the image whose straightness depends on the line-wise behavior of the potential micro-vibrations. A dedicated guidance, called STARACQ, has been designed to fulfill these needs.

Thanks to this method, we were able to confirm 4 days after launch of each satellite, the presence of micro-

vibration with very low magnitude (< 0.15 PA pixel) without any consequence on image quality (Fig. 14).

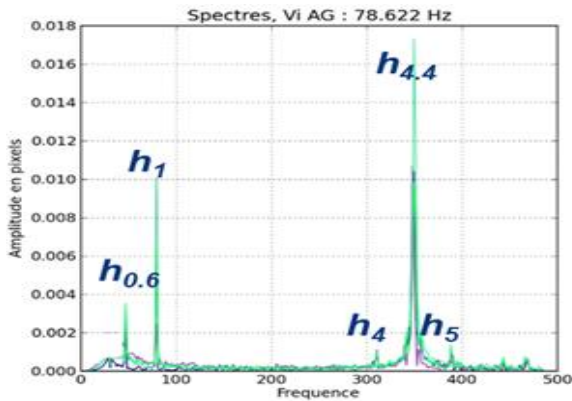


Figure 14 : Spectral analysis (magnitude vs frequency) of the micro-vibrations.

As the potential micro-vibration depends on the Gyroscopic Actuators (CMG) spin rate, the method has been applied for different monitoring of this rate in order to optimize agility and image quality. Fortunately, image quality is preserved for the best agility.

A second method uses the correlation of the XS bands and the very short time shift between the acquisitions to restore high frequency attitudes for roll (along lines) and pitch (along columns).

The two methods have given very similar results as shown in Fig. 15.

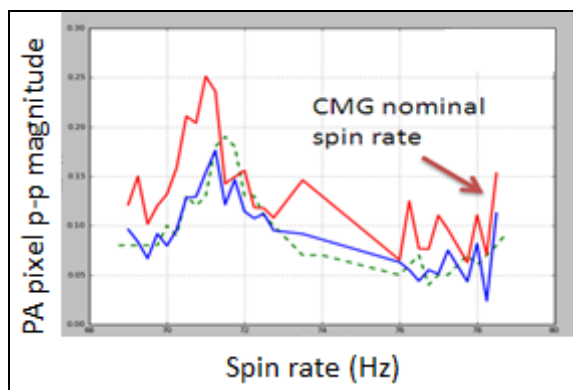


Figure 15 : Maximum micro-vibrations magnitude vs CMG spin rate measured with starAcq (green) and inter-XS correlation method (roll in blue, pitch in red).

Concerning, low and medium frequency perturbations assessment, we correlated couples of phased acquisition; this means images acquired with a 26-days Pléiades cycle delay, to ensure the reproducibility of the geometric viewing conditions and insensitivity to the relief. Results show magnitude perturbations levels achieved with image quality requirements.

3.4 3D rendering capabilities

The image quality commissioning was the opportunity to validate standard Pléiades image products such as “Perfect Sensor”, “Ortho” and “Mosaic” but also to test

Pléiades imagery capability of 3D rendering. In this scope, automatic epipolar geometry re-sampling is applied to stereoscopic pairs in order to produce anaglyphs or DEM generator input data. An example is shown in Fig. 16 on Awacs airplane, using CARMEN DEM generator developed at CNES for a stereoscopic pair with a B/H of 0.15. The altitude accuracy is better than 1.5 m for these objects. We also tested 3D rendering algorithm using multi viewing directions intersections to create 3D meshes as shown in Figure 1.

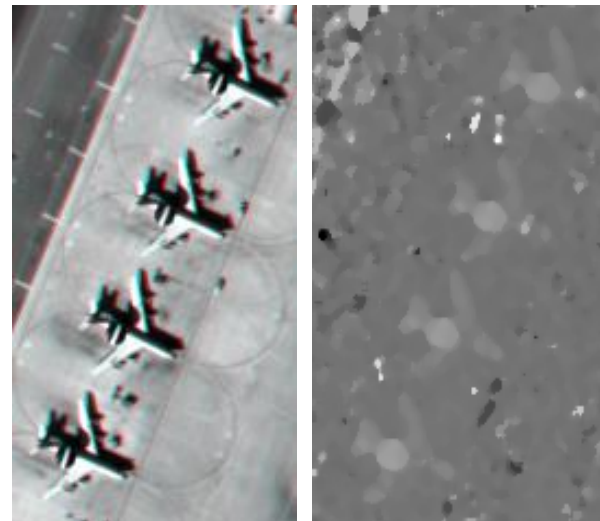


Figure 1 : Upper left: Awacs airplanes 3D rendering: anaglyph (upper left) and DEM (upper right). 3D mesh of Gizeh pyramids (bottom).

4. Main image quality performance

Table 2 shows the main image quality performances assessed for both satellites at the end of March 2014. As the performances are very close for the two satellites, a global figure is given for the Pléiades constellation.

Image Quality criteria	Performance	Performance
Localization CE90 (with accurate attitude and for depointing $< 30^\circ$)	All bands	6.5 m
PAN/XS registration in XS pixels (90%)	PA/XS	0.20
XS/XS registration in XS pixels (90%)	XS	0.18
Planimetry in PAN pixels (90%)	All bands	0.42
Altimetry for a stereo pair with a b/h of 0.15 (RMS)	PA	1 m
Absolute calibration accuracy	All bands	$< 5\%$
Multi-temporal calibration accuracy	All bands	1%
Inter-Pleiades accuracy	All bands	2%
MTF @ Nyquist	PA	0.15
	XS (X axis)	0.31
	XS (Y axis)	0.26
SNR @ L2	PA	156
	B0/B1/B2	158
	B3	190

Table 2 : Main Image Quality performances assessed March 2014.

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