Pleiades system is fully operational in orbit

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Abstract. Following the Turino's agreement, France, under the leadership of the French Space Agency (CNES), has set up a cooperative program with Austria, Belgium, Spain, Sweden, in order to develop a space optical Earth Observation system called Pléiades. Pléiades is a dual system, this means that it is intended to fulfill an extended panel of both civilian and Defense user's needs. The first Pléiades satellite was launched on December 17th 2011 while the second satellite, Pléiades 1B, has been placed in orbit less than one year after on December 2nd 2012. This paper reports the status of the satellite 1B after its launch and the in orbit commissioning. It describes the main mission characteristics and performances status. It exposes how the system, satellite and ground segment have been designed in order to be compliant with a dual exploitation between civilian and defense partners. Pléiades delivers optical high resolution products consisting in a Panchromatic image, into which is merged a four multispectral bands image, orthorectified on a Digital Terrain Model (DTM). The system is based on the use of a set of newly European developed technologies to feature the satellite. In order to maximize the agility of the satellite, weight and inertia have been reduced using a compact hexagonal shape for the satellite bus. The optical mission consists in Earth optical observation composed of 0.7 m nadir resolution for the panchromatic band and 2.8 m nadir resolution for the four multi-spectral bands. The image swath is about 20 km. Thanks to the huge satellite agility obtained with control momentum gyros as actuators, the optical system delivers as well instantaneous stereo images, under different stereoscopic conditions and mosaic images, issued from along the track thus enlarging the field of view. The ground segment is composed of a dual ground center located in CNES Toulouse premises in charge of preparing the dual mission command plan and of the real time contacts with the satellite through a control center. The dual ground center interfaces with several mission centers : one center is built for each Defense partner (France, Spain …), one center is set up for the Civilian Operator. Each mission center is in charge of managing the programming requests, then, receiving the mission telemetry, processing the data to feed a catalog and an archive, to generate the system products and distribute them to the final user. System reactivity has been optimized with a chronology based on three mission planning activations per day. The mission plan is uploaded to the satellite just before flyby over East Asia , Europe and North America. In addition a Direct Tasking mode is available for commercial Image Receiving Stations.

Keywords. : Pléiades, earth observation, optical, satellite, agility, performances.

1. Introduction

1.1. Pléiades mission overview

The Pleiades project was undertaken, under the leadership of the French Space Agency (CNES), as part of an intergovernmental agreement setting out the objectives and general principles of cooperation between France and Italy in the field of Earth observation. Signed on 29 January 2001 in Turin, the agreement makes particular provision for the building of a dual-purpose observation system, ORFEO, with submetric resolution, including an optical component, Pleiades, developed by France and a radar component, Cosmo-SkyMed, developed by Italy.

Cooperation agreements relating to Pleiades have also been signed with Austria, Belgium, Spain and Sweden. In return, they have been granted a right to programming requests and access to the system archive, proportional to their contribution to development according to schemes similar to those used for the Spot family.

The Pléiades system is a truly dual-purpose optical observation system. As a complement to the French military space observation system Helios 2 and the Spot satellites, it has been designed to meet the needs of both Defense and civilian users, institutional and also commercial.

The purpose of Pléiades is to deliver optical images of sub-metric resolution to these two categories of customers, while meeting the stringent requirements of each one: those of Defense in terms of priority (50 high priority images are allocated each day) and confidentiality of requests, and those of civilian users in terms of acquisition capability and coverage. The Dual System is specified to fulfill a broad spectrum of applications, in the field of cartography, agriculture and forestry, geology and hydrology, marine applications, Earth science, resource management, land use, law enforcement and risk management according to scientific, institutional and commercial customers

Given the dual nature of this system, two types of access are defined to schedule the satellites' tasks:

- The Defense channel used by Ministry of Defense beneficiaries for High Priority Defense programming requests.
- The Civil channel used by civilian users. It is operated by a civilian Operator.

The civilian data distribution is delegated to Astrium Geo-Information Services (ex Spot Image) through a Public Service Delegation: 40% of the resources of the system are reserved for institutional users of the cooperative countries for non commercial activities. CNES has granted an exclusive license to the Civilian Operator allowing him to process, distribute and commercialize the data and products on the worldwide market.

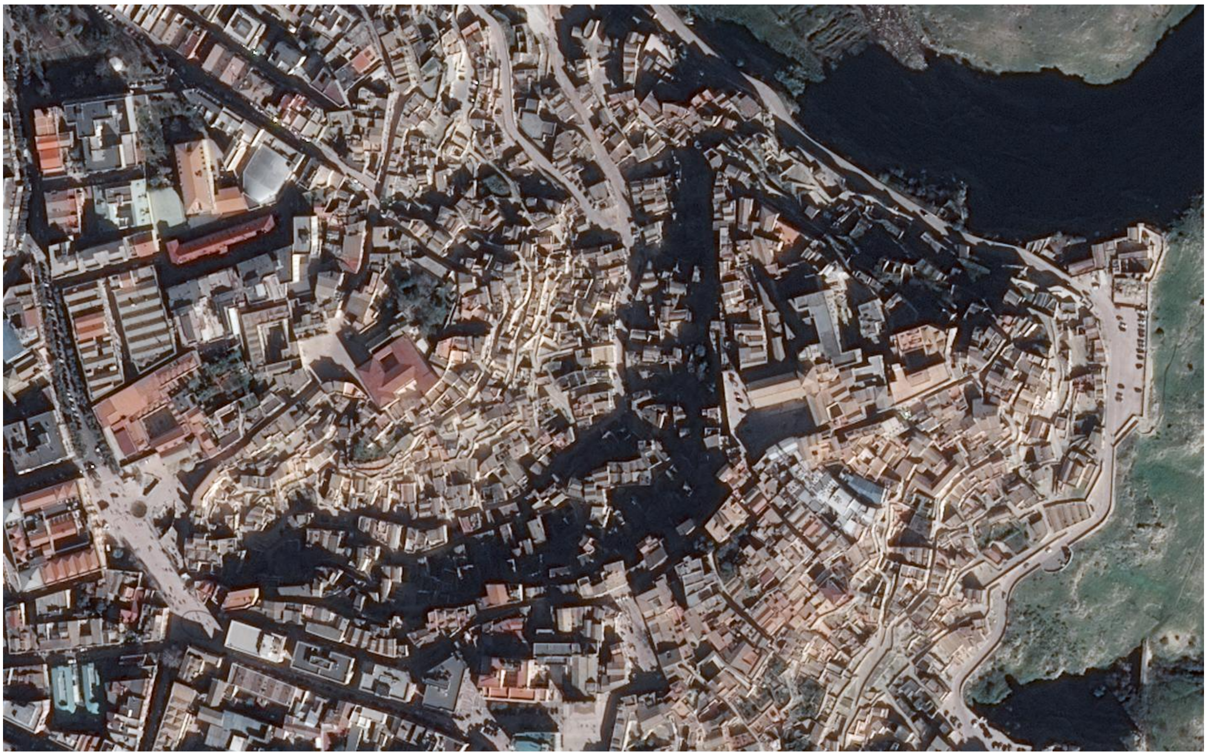


Figure 1. Pléiades 1B image of Matera Sassi acquired during commissioning © Copyright CNES 2013.

1.2. Key mission performances

The Pléiades system consists of a constellation of two optical satellites (visible and near-infrared range) each weighing a ton, positioned on a quasi-circular, Sun-synchronous orbit of 695 km altitude, at a local hour at descending node of 10:30 am.

The first Pleiades satellite was launched by a Soyuz rocket on the 17th December 2011, from the European spaceport at Kourou in French Guiana. The second satellite was launched less than one year later on December 2nd 2012.

Worldwide coverage and a daily accessibility to any point on the globe are requested, and fulfilled by the use of both satellites simultaneously in orbit and 180° phase shifted. This concept is necessary for two reasons:

- To ensure the accessibility and prompt imaging required by Defense and Civil Security missions.
- To ensure the coverage capability required for mapping and land planning needs.

The Pleiades system offers:

- daily access to any point on the globe (with its two satellites)
- a panchromatic channel with a 70 cm vertical viewing resolution.
- four spectral bands (blue, green, red and near-infrared) with a 2.8 m resolution.
- field of view of 20 km in vertical viewing.
- acquisition capacity, in a single pass, of mosaic of images.
- virtually instantaneous acquisition capacity for stereoscopic pairs (and even triplets).
- cloud-free image coverage of 2,500,000 km² per year.

In addition it offers very precise image location enabling optimal use of data in Geographic Information Systems (GISs).

2. Satellite description

CNES entrusted the building of the two satellites to EADS Astrium (satellite prime contractor) and Thales Alenia Space (high-resolution instrument prime contractor).

Figure 2. Pleiades 1A a few days before launch

2.1. Architecture

Pléiades' agility is a key factor enabling it to provide the service expected by users.

The satellite is able to off-point rapidly around its axis (yaw, pitch, roll). This high agility is made possible by a very compact design, achieved by: (Fig 3)

- Fixed, rigid solar panels.

- Equipment built into the satellite to reduce the vessel’s inertia.
- The high-resolution instrument partly embedded inside the bus.

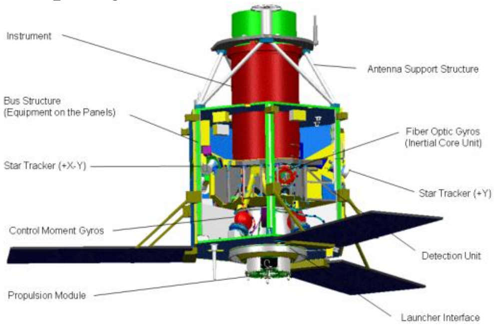


Figure 3. satellite architecture

- A sophisticated control mechanism thanks to a new generation of control moment gyros. (Fig 4)

Figure 4. 15 Nms CMG actuator

The attitude control system uses 4 fiber-optic gyroscopes and 3 star trackers to provide attitude accuracy compatible with the system location specification of the products. The orbit navigation is performed by an autonomous navigator using the DORIS system.

The Pléiades satellites have been designed for a theoretical lifetime of 5 years. However, propellant and other consumables have been sized for more than 7 years and the example of the Spot and Helios satellites shows that this period may well be exceeded in orbit: ten years or more are expected.

2.2. Payload

The instrument (Fig 5) is based on a design concept with very high dimensional stability combining a carbon/carbon structure with Zerodur® mirrors. For optimal in-flight performance, the instrument includes an innovative thermal refocusing device which avoids the need for a complex mechanism. (Fig 6)

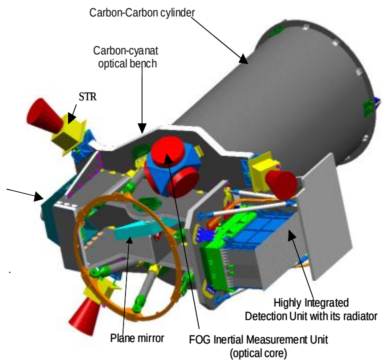


Figure 5. Instrument Configuration

Optical Architecture

The optical solution chosen for the telescope is a Korsch type combination, with a primary mirror size of 650 mm diameter and a focal length of 13 m. (Fig 6)

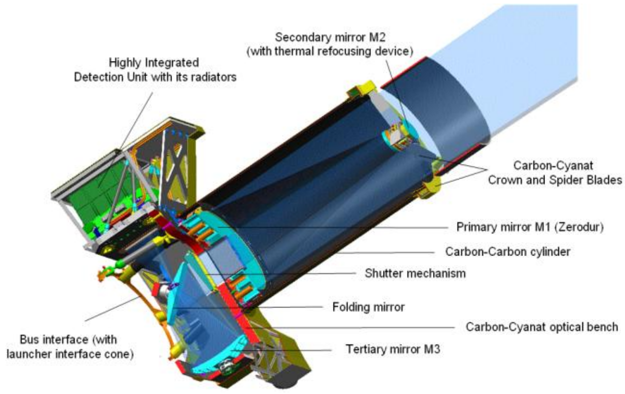


Figure 6. Optical architecture

This multi-spectral, high-resolution (70 cm) and large-field (20 km) optical instrument, weighting 200 kg, produces images in the visible and near-infrared ranges

Detection

Back-thinned TDI CCD image sensors (Fig 7) are used for panchromatic detection channel, with a maximum of 20 integration lines. They can be used thanks to an optimized guidance strategy of the satellite line of sight, micro-vibrations levels minimization, specific geometrical accommodation of detector lines in the focal plane and telescope optical distortion minimization.

These devices are back-illuminated for high quantum efficiency and sensitivity. Their TDI format enables them to capture high resolution images without slowing down the satellite. They offer 6,000 active pixels per line and a pixel size and pitch of 13µm square. An architecture with anti-blooming structure in each pixel ensures that image outputs are not jeopardized (smeared) by specular reflections.

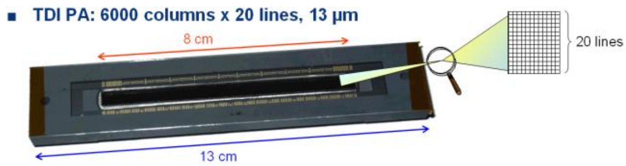


Figure 7. panchromatic TDI sensor

The multi-spectral detection channel is realized with 5 sensors of 1500 pixels per line each, with a pixel size of 52 µm (Fig 8). Each sensor consists in a four lines assembly, enabling four colors imaging (blue, green, red, near infrared). Interferometric filters directly stuck down on the detector glass window provide coloring of these four channels.

Figure 8. multi-spectral sensor

Five sensors of each kind are used simultaneously to obtain a wide field of view (about 20 km). (Fig 9)

Image reconstruction at the level of the inter-array areas is one of the tasks of the ground segment. [1]

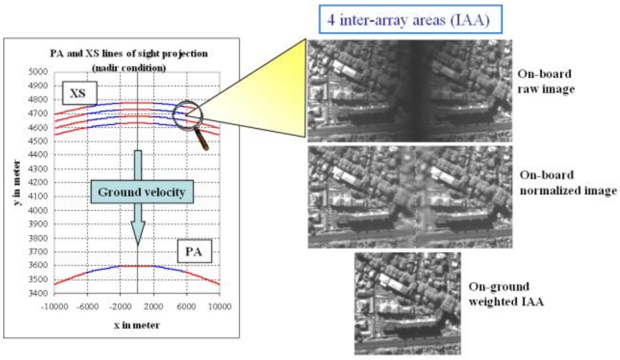


Figure 9. image reconstruction

Image chain

The video data are compressed on-board thanks to the Payload Data Compression Unit and then transmitted to the ground with a 4.5 Gbits/s output rate. A wavelet transform algorithm is used, enabling compression rates at 2.8 bits per pixel.

The compressed data are then memorized in the Solid State Mass Memory. This memory has a storage capacity of 600 Gbits at the end of life.

The data are then encrypted and coded following a trellis-coded scheme in 8-PSK type modulators coupled to Traveling Waves Tube power Amplifiers (TWTA). They are multiplexed and down-linked with an omni-directional 64° aperture horn antenna. The output rate is nominally of 465 Mbits/s, on three individual channels of 155 Mbits/s each.

3. main mission characteristics

3.1. Agility, Acquisition capabilities and revisit time

Agility

Due to its high agility and high performance of the guidance algorithms, the satellite is capable of targeting image along any ground direction within 47° of vertical viewing position, and even more, with very low maneuvers durations between two consecutive images.

This high agility permits:

- to ensure a good reactivity of the system in order to satisfy the urgent needs of the defense or the civil securities
- to minimize scheduling conflicts within the dual use framework, and therefore better meet the simultaneous needs of all users
- to acquire image in any direction which will allow, for example, coastlines or river routes to be monitored, which could be very useful for optimizing programming in a crisis case (flooding, tsunami, etc.).
- to enlarge the swath by taking in the same pass adjacent stripes. Mosaic images ranging from 60x200 km² (3 strips) to 120x65 km² (6 strips) with 20° access authorized, and from 60x340 km² (3 strips) to 140x105 km² (6 strips) with 30° access authorized, can be acquired.
- to acquire in the same pass stereoscopic pairs or tri stereoscopic triplets even with low base over height ratio, a very important improvement in order to avoid hidden objects in urban area (occlusions). Figure 10 shows the maximum length of stereoscopic coverage acquired from the same orbit with several B/H, either for stereo pairs or for triplets.

b/H	Stereo length	Tri-stereo length
0.1	25 km	-
0.2	80 km	25 km
0.4	195 km	80 km
0.6	315 km	135 km
0.8	350 km	201 km
1	350 km	260 km

Figure 10. Maximum length of stereo coverage

- To perform calibrations on stars or moon images or using “exotics” guidance methods.[2], .[4], .[5], .[7].

During a single overpass of an area of 1000x1000 km², each Pleiades satellite acquires about 20 targets with metric resolution (fig 11). In a smaller theatre of operations (100x200 km²), 16 targets may be acquired.

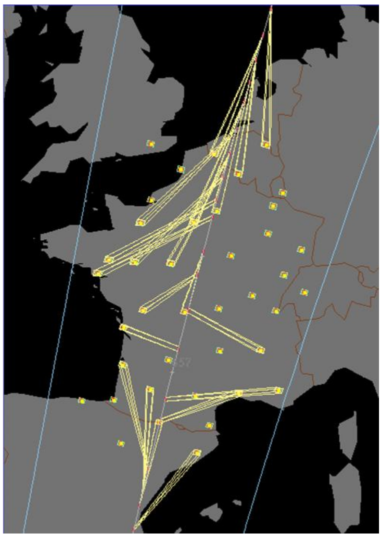


Figure 11. 20 targets on a 1000x1000 km² area

This amazing agility has been fully demonstrated during the first year of in orbit activities of Pléiades 1A. More than 600 images are acquired daily by each satellite. Figure 12 shows an example of single pass mosaic acquired over Shanghai area in January.

Figure 12. 20 images acquired on Shanghai on January 1rst 2013

In addition to stereoscopic acquisitions, during commissioning, Pleiades agility has been pushed to its limits in order to acquire more than 30 images in a single pass to produce a sequence of animated images allowing to highlight human activities on the targeted area.(Fig 13)

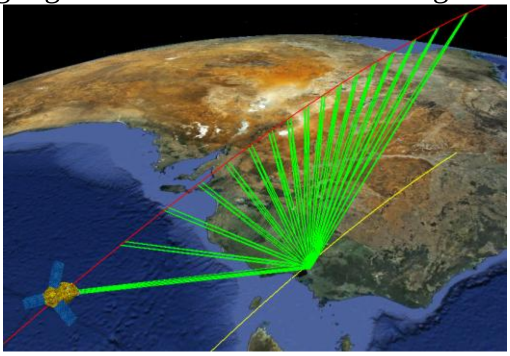


Figure 13. example of video acquisition mode over Melbourne

Revisit time

This high acquisition capability is accompanied by a revisit interval of less than 24 hours to meet both civil and military requirements

The orbit has been selected in order to minimize the revisit time with either one or two satellites in orbit. A one-satellite system needs a viewing angle of 47° to access to any location on the globe in 2 days, whereas with 2 satellites in orbit, Pléiades needs a viewing angle of only 43° to access everywhere daily. The revisit time for different viewing angles is given hereafter:

Viewing angle	1 satellite	2 satellites
5°	26 days	13 days
20°	7 days	5 days
30°	5 days	4 days

Figure 14. revisit time

3.2. System chronology and reactivity

Routine chronology

The system chronology has been adapted in order to optimize reactivity. Three mission plans are computed per day and uplinked to each satellite:

- **Morning plan (~6:00 UTC):** Optimization over Europe Africa. Uplink is performed over the Kerguelen station
- **Afternoon plan (~13:00 UTC):** Optimization over America. Uplink is performed over the Kiruna station
- **Evening plan (~23:00 UTC):** Optimization over Asia. Uplink is performed on the ascending part of the orbit using Toulouse station.

The ground segment is able to take into account last-minute customer request up to 2 hours before the satellite pass over the ground station and to tune the mission plan according to the most recent weather forecast.

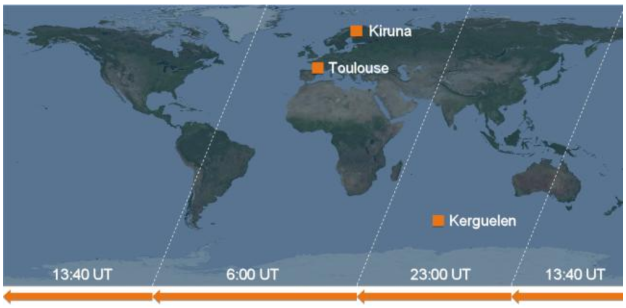


Figure 15. System chronology

This feature greatly increases the overall efficiency of Pléiades mission planning. After one year of intensive exploitation, Pléiades has demonstrated its capability to acquire cloud-free images very quickly (more than 50% of the images have a cloud cover better than 10%). As an example (fig 16) 94% of Burundi have been acquired and validated within 4 weeks and 3 segments of 90km have been acquired cloud-free over Amazonia on a single pass…

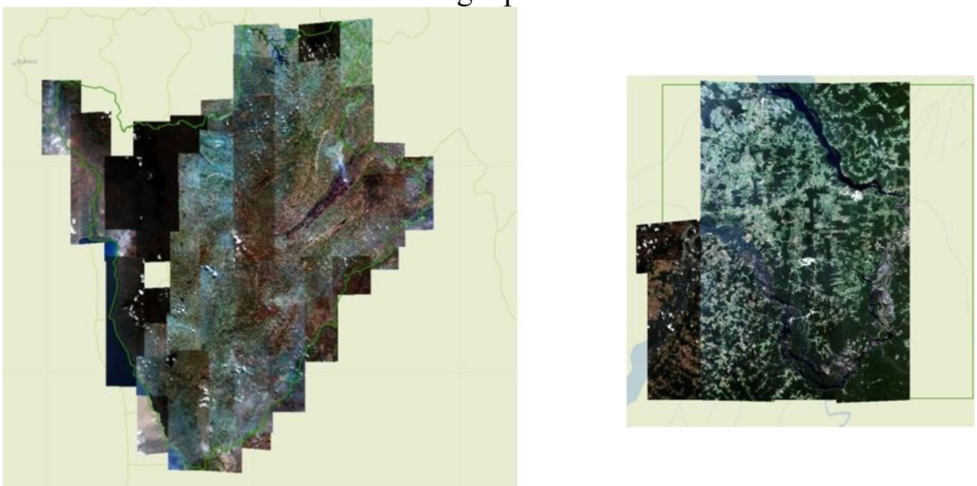


Figure 16. Burundi (left) Amazonia (right)

Direct Tasking

In parallel to this routine chronology, Pleiades system offers a Direct Tasking mode to dedicated regional receiving stations equipped with S and X bands capabilities.

This mode offers the best reactivity from collection planning to mission ready data, to support ultimate near-real time applications. Direct tasking process follows the hereafter sequence of events: (Fig 17)

- an orbit slot is booked up to 24 hours before the satellite pass.

- the customer’s collection plan is prepared and validated. It can be refined and optimized up to 30 minutes before acquisition (considering the latest weather conditions or urgent requests).

- the tasking plan is compiled into commands plan, then ciphered and uploaded.

- the satellite acquires and downloads simultaneously the image data to the Direct tasking station, guarantying a near-real time service.

- the data is automatically produced : 30 minutes from reception to usable information.

Figure 17. Direct tasking

3.3. System products

System Image product levels based on data collected by Pleiades satellites include: [1]

- **Raw image**: 5 strips panchromatic and multi spectral images, this product will remain internal to the system and is not distributed
- **Perfect sensor product**: this product is a raw image taken by a perfect sensor with the following characteristics
  - Straight (no distortion) and regularly sampled PA/XS lines of sight
  - Perfectly registered PA and XS retina
  - System-level MTF for PA
  - Polynomial attitude fitting the mean estimated attitude
  - Estimated actual orbital ephemeris and perfect time stamping

this product is intended to be used for value added processing which can be performed with simplified interfaces

- **Ortho images**: image with PANCHROMATIC and B0,B1,B2,B3 re-sampled in mapped ground geometry and system geometrical model corrections (standard geometrically corrected product). Corrections coming from global existing DTM (SPOT5 HRS instrument 10 m accuracy DTM for example) are applied.
- **Mosaic products**: in the case of lateral multi-band mode acquisition, the system will supply all the orthoimages acquired in a georeferenced common geometry stitched together to generate a single product.

Endogenous high precision DTM (around 1.5 m accuracy) can be extracted from the Pleiades stereo pairs or triplet. [9] This product is foreseen as a future extension of the system but is not available in the first release of the ground segment.

For levels Perfect sensor, Ortho images, and Mosaic products, true and false colors pan-sharpened multispectral images are available. These products are resampled at 0.5m in order to preserve all the frequential information acquired by the instrument and to make the products robust to further ground processing.

4. ground segment overview

The ground segments were entrusted to CapGemini and CS-SI (programming system), Thales services (image system) and a consortium involving EADS Astrium, Cap Gemini, CS-SI and Thales services (integration of user centers), while INDRA has been given responsibility for the Spanish Defense mission center. The receiving stations have been developed by Zodiac.

4.1. architecture

While CNES is prime contractor for the ground segment, its various components are located at different sites and managed by different operators. (Fig 18)

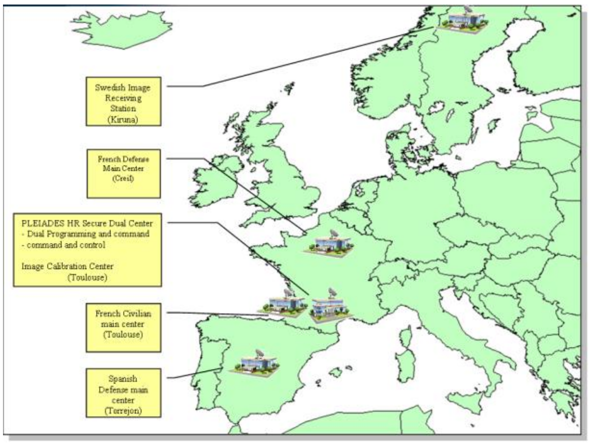


Figure 18. ground centers locations

• **The dual control center** is being hosted by CNES in Toulouse. Its role is to:

- schedule all programming requests, by gathering them from civil channel and Defense channel users,
- manage the satellites on a daily basis, receiving telemetry for verifying its good health, and uploading all the commands enabling it to fulfill its mission,
- calibrate the satellites and their instruments, for the benefit of all users. The Image calibration Center is in charge of computing and distributing the image processing parameters obtained during instrument calibration operations.

The mission center of the civilian operator, Astrium Geo-Information Services (ex Spot Image) in Toulouse, has the task to satisfy all the demands of institutional users from partner countries as well as commercial users. Its role is to:

- accept and manage user requests,
- generate the requested work plan and send it to the dual control center three times a day,
- receive, archive and process image telemetry,
- manage a catalogue of images.

A set of Regional Image Receiving Stations deployed under the responsibility of Astrium Geo, allows local reception and processing of Pléiades data all over the world. The first one is already installed in Sweden near Kiruna. Its polar location allows to get frequent contacts with the satellite to empty the content of the on board mass memory. Several other stations have been installed by Astrium geo in China, Japan, Canada …

• **The French and Spanish defense mission centers** (located in Creil near Paris and Torrejón near Madrid, respectively) serve each country's Defense users. Their basic functions are similar to those of the civilian operator's center, with some differences relating to interfaces and security.

5. Pléiades 1B satellite commissioning

5.1. Overall schedule and status

Two months and a half after launch, Pléiades 1B Technical Commissioning Review has been successfully held on 21srt february 2013.

Image Quality Commissioning Review is being held on 4th June 2013.

Pleiades 1B Satellite is fully validated:

- electrical and thermal sub-systems,
- AOCS with Control Momentum Gyros,
- Doris on board navigator (real time orbit knowledge < 70 cm),
- Instrument,
- image telemetry chain.

All the acquisition modes have been successfully exercised:

- Single scenes
- Strips
- Depointing angles from nadir up to 50 deg
- Stereoscopic acquisitions (bi and tri)
- Mosaics

5.2. *Agility, Acquisition capabilities and revisit time*

Pléiades 1B is as agile as his twin brother

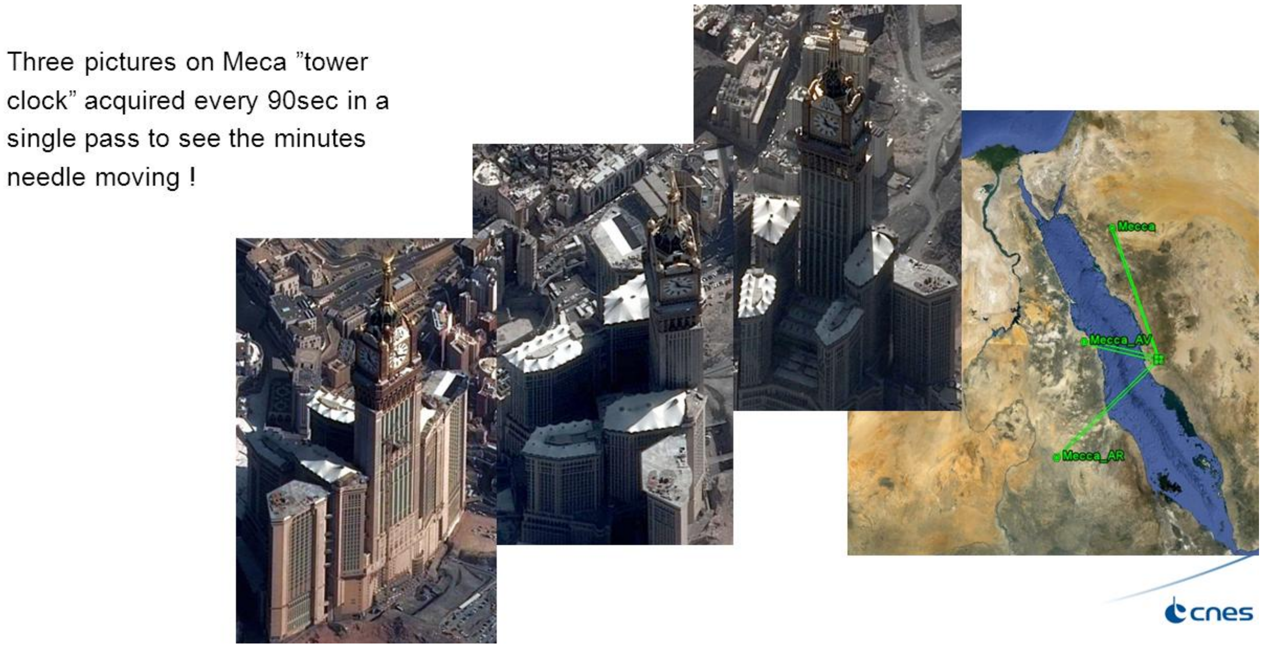


Figure 19. example of 3 acquisitions on Meca with the tower clock

5.3. *Image Radiometric performances*

Signal-to-noise ratio assessment

Using the lessons learned with Pleiades 1A, several brand new techniques were used to assess the instrumental signal-to-noise ratio. The major one benefits from a dedicated guidance called "slow-motion" [1]. The principle is to steer the satellite so that the projection of the scan-line on the ground remains constant along the image (figure 20).

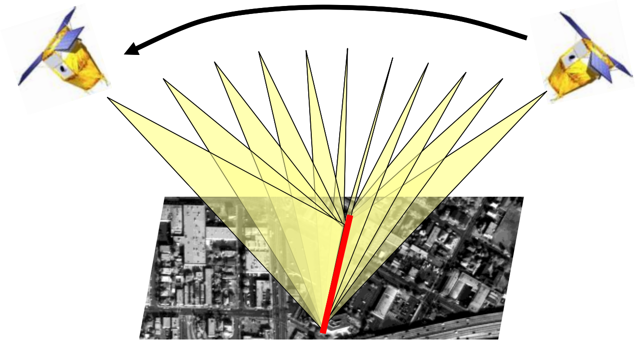


Figure 20. slow-motion acquisition principle

Therefore, each elementary detector views 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 on figure 21 where it becomes easy to compute the temporal evolution of each elementary detector response for a set of vicarious input radiance. In the end, we can assess the instrumental noise model and its contribution in the radiometric signal to noise ratio budget.

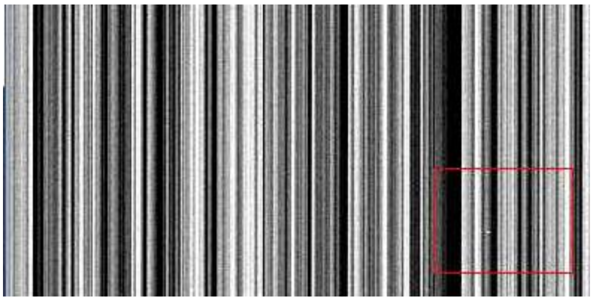


Figure 21. example of slow-motion image

Measured SNR ratio is very good (see table below).

PHR1B	PA	B0	B1	B2	B3
S/B(L1)	45	69	62	47	35
S/B(L2)	158	151	162	156	186
S/B(L3)	237	221	239	230	272

MTF assessment and refocusing operations

Refocusing operations have been conducted thanks to 3 methods. The main one, experienced on Pléiades 1A and operationally used for 1B uses stars [3] acquired for different adjustments of the refocusing system made of a thermal control of the telescope secondary mirror position. It allows to measure by the way a very accurate 2D assessment of the MTF, (figure 22) as the Point Spread Function (PSF) is the image of a punctual source of light as seen by the instrument. Thanks to this very efficient method, the instrument was refocused 5 days after launch.

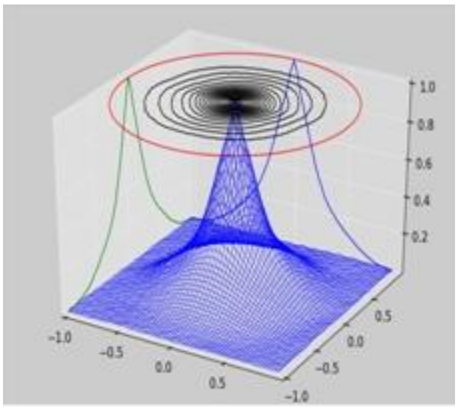


Figure 22. example of PAN MTF measured on stars

MTF results are well beyond instrument specifications (see table below), and very few image ground restoration (deconvolution) is necessary.

PHR1B	MTF @ Nyquist
PAN	**0.14**
B0,B1,B2,B3	**> 0.3**

5.4. *Image geometrical performances*

Line-of-sight dynamic stability

Several techniques were used to assess the line-of-sight stability such as inter XS band correlation [3], 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 the star, it will create a bright column in the image whose straightness depends on the line-wise behaviour of the potential micro-vibrations. A dedicated guidance law has been designed to fulfil these needs (figure 23).

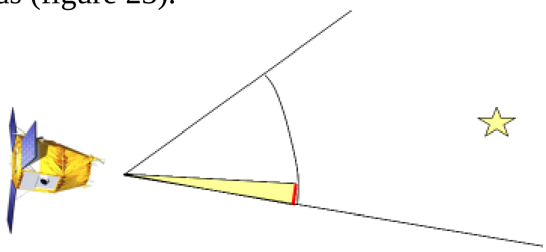


Figure 23. Star acquisition guidance principle

Thanks to this method, we were able to confirm 4 days after launch negligible level of micro-vibrations (magnitude < 0.1 PAN pixel) without any consequence on image quality (figure 24).

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.

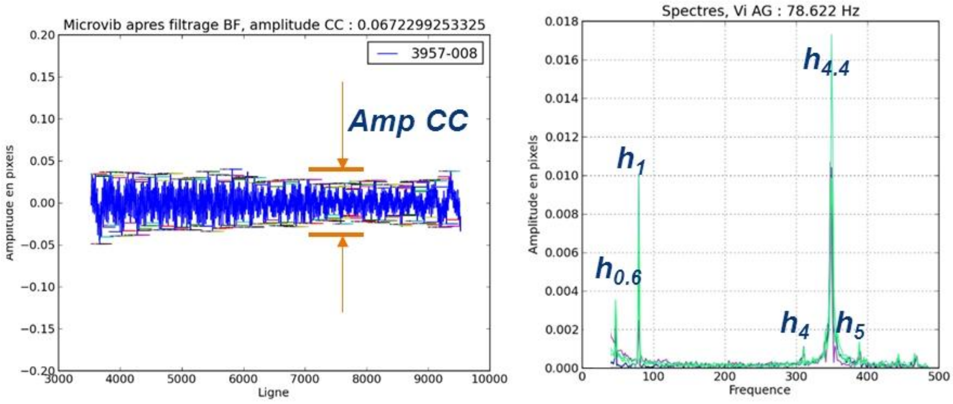


Figure 24. Star calibration method for micro-vibrations measurement

Focal plane cartography and 3D rendering

The absolute focal plane cartography, which means the assessment of the accurate viewing directions of every pixel in the instrumental frame, is achieved by correlation of PAN images with a reference supersite [3]. The cartography was accurately achieved within 2 months.

Moreover, stereo and tri-stereo altimetric accuracy has been assessed. It is better than 1.8m max LE90% using a stereo pair and 1m max LE90% using a tri-stereo.

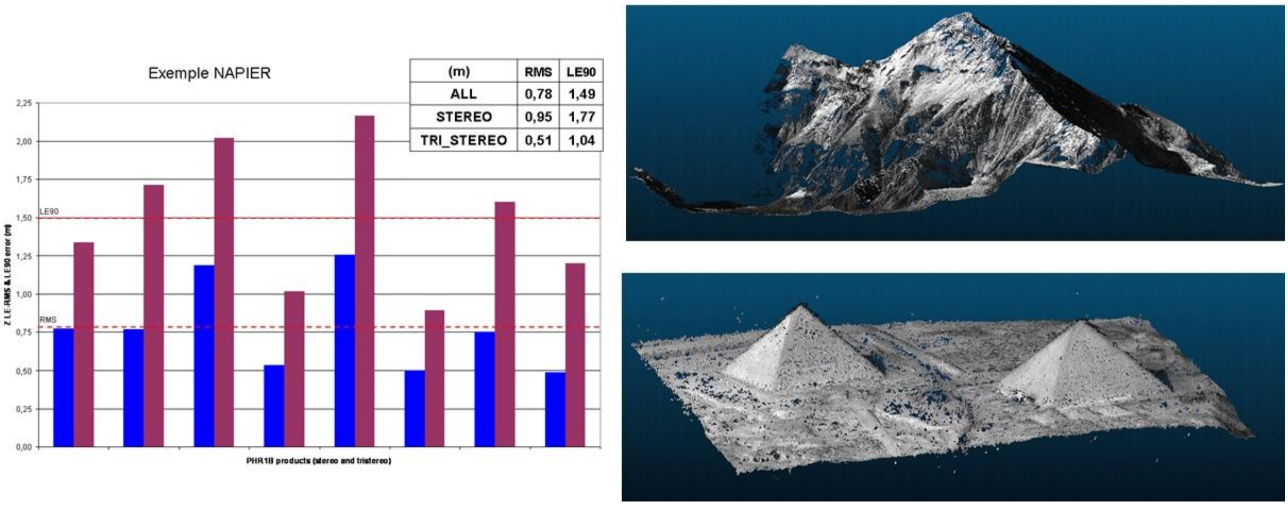
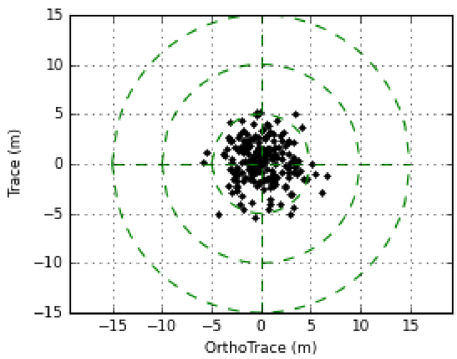


Figure 25. Pléiades 1B altimetric accuracy

Absolute localization performance

A fundamental user’s requirement concerns the image localization without using Ground Control Points (GCP). The assessment of this performance is based on the statistics of the difference between real and image-given localization of very accurate GPS GCP (figure 25). CNES use a large GCP database covering a wide range of latitude in order to observe orbital and seasonal phenomena.

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



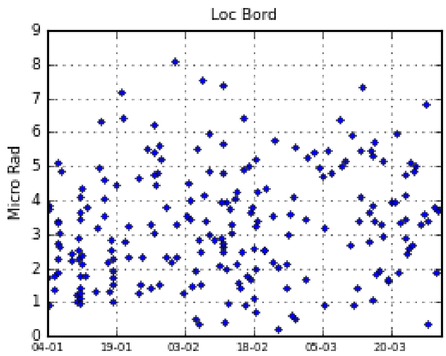


Figure 26. Pléiades 1B localization performance measured on the time period 2013 January to April.

Results are excellent as the performances are close to 4m max CE90% (see table below, statistical evaluation of 213 images taken within a cone of 30°)

On board real time attitudes	D+12h refined attitudes
4.65 m	4.05 m

6. Conclusions

One year and a half after the first satellite's launch, Pléiades system is in very good health and the two satellites are fully operational.

The availability is close to 100%. The main centers of the ground segment are fully deployed and operational too. The civilian center generates daily up to 350 pictures !

Regional image receiving stations have being installed (Japan, China, Canada) and Astrium Geo is shortlisted for some new stations…

The second satellite, launched end 2012, has completed the constellation and makes available to the users a daily revisit system with a huge acquisition capacity.

Commissioning of PHR1B has been completed successfully and the image quality performances have been assessed and appear to be very good.

Success of Pleiades is now in the hands of operational teams that will focus their energies to satisfy the users' needs and keep Pleiades in good health during several years!

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