THE PLEIADES SYSTEM : HIGH RESOLUTION CAPABILITY SUITED TO USERS NEEDS

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Résumé

Le lancement réussi de Pléïades 1A dans la nuit du 16 au 17 décembre 2011 est un évènement clé, longtemps attendu, pour les utilisateurs d'imagerie satellitaire. Ce satellite d'observation de la Terre fournit des images optiques à haute résolution avec pour double objectif principal de satisfaire les nouveaux besoins des organismes de défense et des usagers civils (institutions, scientifiques, etc.). La mission consiste en l'observation optique de la Terre avec une résolution au nadir de 0,7 m en panchromatique, et de 2,8 m pour les quatre canaux multi-spectraux. La fauchée d'une image est d'environ 20 km. Le système est fondé sur l'utilisation d'un ensemble de technologies européennes nouvellement développées, qui composent le satellite. Grâce à la très grande agilité du satellite, le système optique fournit instantanément des images stéréoscopiques, avec différentes configurations possibles, ainsi que des mosaïques.
La phase de recette du système s'est déroulée du lancement au mois de mars 2012. Elle a permis de vérifier séparemment chaque pièce et chaque fonction du satellite, afin de caractériser, régler et calibrer tous les modèles nécessaires pour obtenir les comportements et performances attendues. La validation thématique de Pléïades a été préparée depuis 2007 dans le cadre du programme d'accompagnement ORFEO, ce qui a permis le regroupement de nombreux organismes (IGN, BRGM, INRA, CNRS, Cemagref, CIRAD) et de prestataires de service (Astrium Geo-Information Services, ACRI, SERTIT).

Mots clés : Satellite, haute résolution, positionnement, agilité.

Abstract

The successful launch of Pleiades 1A on the night of 16th to 17th December 2011 is a long-awaited milestone for the users of satellite images. This satellite is operated in a dual-purpose Earth observation system providing high resolution optical images to satisfy the new mission requirements of both defence users and civilian stakeholders (institutions, scientists, etc.). 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. The system is based on the use of a set of newly developed European technologies to feature the satellite. Thanks to the huge satellite agility obtained with control momentum gyros as actuators, the optical system also delivers instantaneous stereo images, under different stereoscopic conditions, and mosaic images, issued from along the track thus enlarging the field of view.
The system commissioning phase that ran from the launch until march 2012 was dedicated to checking every single piece of equipment in the satellite and every system function, in order to characterize, tune and calibrate all the models that are required to assess the expected behaviour and performances. The thematic assessment of Pleiades data had been prepared since 2007 in the framework of the ORFEO program, gathering many user organisations (IGN, BRGM, INRA, CNRS, Cemagref, CIRAD) and service providers (Astrium Geo-Information Services, ACRI, SERTIT).

Keywords : *Satellite, high resolution, location, agility.*

1. Introduction

Pleiades follows on from a tradition of Earth observation initiated by CNES with the first SPOT satellite in 1986. With its expertise and experience gained in the civil field, CNES then became a key partner of the French Ministry of Defence and the Defence Procurement Authority (DGA). Pleiades brings the two worlds together while meeting the stringent requirements of each. CNES is the owner and architect of the Pleiades system.
The Pleiades project was undertaken 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 29th January 2001 in Turin, the agreement makes particular provision for the building of a dual-purpose observation system, ORFEO, with metre resolution, including an optical component developed in France and a radar component, Cosmo-SkyMed, developed in Italy. Cooperation agreements relating to Pleiades have also been signed with Austria, Belgium, Spain and Sweden.

Compared to the SPOT system, the Pleiades system is expected to supplement provision by offering users, whether civilian or military, access to a greater range of images. Pleiades will provide images of a smaller area than SPOT 5 (20 km field of view compared with 60 km). However, they are more precise, as the satellite acquires the images at a resolution of 70 cm.

Figure 1 : Pleiades 1A image of New York, Unites States of America ©CNES 2012.

The Pleiades system is served by a constellation of two optical satellites each weighing about a ton, designed for the visible and near-infrared range and positioned on a sun-synchronous orbit 694 km from the Earth, at a local hour at descending node of 10:30 am. Pleiades 1A was successfully launched on 17th December 2011 from French Guiana and the second satellite will be launched about one year later.

The Pleiades system offers:

- 2-days access to any point on the globe (daily access with two satellites);
- Native 0.70 m panchromatic imagery and 2.80 m RBG+Near-Infrared (NIR) color imagery used to deliver coloured image products at 70 cm;
- Field of view of 20 km in vertical viewing;
- Acquisition capacity, in a single pass, of a 100 km by 100 km mosaic of images;
- Virtually instantaneous acquisition capacity for stereoscopic pairs (and even triplets) of 20 km up to 300 km
- Cloud-free image coverage of 2,500,000 km^2 per year.

In addition if offers very precise image location (12 m CE90) enabling optimal use of data in Geographic Information Systems (GIS).

The Pleiades system is the first truly dual-purpose optical observation system (Gleyzes et al., 2012). As a complement to the French military space observation system Helios 2 and the SPOT satellites, it delivers optical images to defence and civilian users, while meeting the stringent requirements of each one. Defence requests deal with priority (50 high-priority images will be allocated each day) and confidentiality, whereas civilian users have wills 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.

2. System design and commissioning

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

2.1. Satellite architecture

Location performance, image resolution and agility were taken into consideration very early as a key factor for the design. It means not only making the satellite very agile around its three axes (yaw, pitch, roll), but also ensuring high stability of the line of sight after each attitude maneuver, which is very challenging. Pleiades satellite has a compact design, achieved by fixed and rigid solar panels, equipment built into the satellite to reduce the vessel's inertia, and the high-resolution instrument which is partly embedded in the bus. The attitude control system uses a new generation of control moment gyros that can make the whole satellite off-point very quickly. The orbit navigation is performed by an autonomous navigator using the DORIS system.
The attitude estimation system uses four fiber-optic gyroscopes and three star trackers to provide attitude accuracy compatible with the system location specification of the products. The attitude sensors are closely linked to the instrument structure in order to minimize any relative motion with respect to the line of sight.
The Pleiades satellites have been designed for a theoretical lifetime of five years. However, propellant and other consumables have been sized for more than seven years and the examples of the SPOT and Helios satellites show that this period might well be exceeded in orbit.

The Pleiades satellites benefit from technology improvements in various fields allowing to achieve performances which were exclusive to ambitious military spacecraft. All these new technologies were just emerging in Europe when the project was launched. Aside from technology breakthrough, a key factor in achieving this goal is a proper dimensioning of the instrument. Considering from the start, image processing techniques have enabled to define an instrument much smaller

Figure 2 : Pleiades 1A a few days before launch.

than would have been required if it had to support the system performances by itself. The multi-spectral, high-resolution (70 cm) and large-field (20 km) optical instrument, weighing 200 kg, will produce images in the visible and near-infrared ranges. It incorporates major technological innovations to reduce its bulk compared to the previous generation of satellites. These innovations are a significant advance in terms of both miniaturization and performance in the video electronics field.
The instrument 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 that avoids the need for a complex mechanism.

Detection is performed thanks to new detectors. The panchromatic line is composed of five Back-thinned TDI CCD image sensors (Figure 7) with a maximum of 20 integration lines.

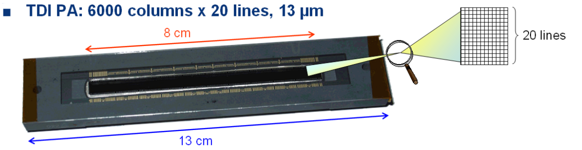

Figure 3 : PA TDI detector.

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

Figure 4 : XS 4-lines CCD detector.

During the development, all the system design and the on-board/on-ground trade-off were carried out in order to match the users' needs, taking into consideration the ground processing capabilities to relax some expensive satellite requirements. For example, the XS and PA retina are geometrically registered by ground image processing that compensate for any static misalignment between raw images.

2.2. The ground segment

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

- The dual control centre is hosted by CNES in Toulouse. Its role is to:
  - Schedule all programming requests, by gathering them from Civil channel and Defence channel users;
  - Manage the satellites on a daily basis, receiving telemetry for verifying its good health, and uploading all the commands enabling it to fulfil its mission;
  - Calibrate the satellites and their instruments for the benefit of all users.
- The mission centre of the civilian operator, Astrium Geo-Information Services (e.g., SPOT Image), satisfies all the demands of institutional users from partner countries as well as commercial ones. Its role will be to :
  - Accept and manage user requests;
  - Generate the requested work plan and send it to the dual control centre three times a day;
  - Receive, archive and process image telemetry;
  - Manage a catalogue of images.
- The French and Spanish defence mission centres (located respectively at Creil in the Oise department and Torrejón near Madrid) serve each country's defence users. Their basic functions are similar to those of the civilian operator's centre, with some differences relating to interfaces and security.

2.3. First results of the commissioning

Pleiades amazing viewing capabilities were fully demonstrated during the in-flight commissioning phase. Three days after launching, the first orbit over Western Europe delivered stereo pairs and off-nadir scenes. Five days after launching, the control momentum gyros were used up to their full range, allowing the satellite to perform attitude maneuvers at 3.4^o/sec between two data captures (Figure 5).

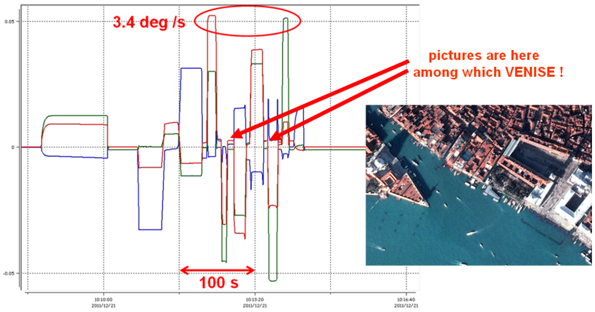

Figure 5 : Satellite attitude rate.

This huge agility provides a very good stereo-viewing capability from the same overpass: the system is able to deliver stereo pairs and triplets without any significant limitation of the satellite use. In addition, the off-nadir viewing capability delivers amazing pictures that reveal the entire relief (Figure 6).

Figure 6 : Pleiades 1A image of Le Mont St Michel, France ©CNES 2012.

Meanwhile, all camera parameters were thoroughly estimated thanks to dedicated methods (Lebegue et al., 2012; Lacherade et al., 2012; Fourest et al., 2012; Blanchet et al., 2012; Greslou et al., 2012; de Lussy et al., 2012). These calibration activities were performed over multiple sources of data acquired by Pleiades, including classical scenes on the Earth, but also innovative acquisitions with dedicated guidance profiles suited to stellar and planets observation (Fourest et al., 2012). For instance, MTF and refocusing assessment were dramatically simplified thanks to images of stars that provide the point-spread function of the camera directly. The Moon was also pictured in order to monitor the absolute calibration performance (Figure 7).

Figure 7 : Moon details viewed by Pleiades ©CNES 2012.

Geometrical calibration also benefits from the satellite agility since a couple of images of the same flat target can be acquired to estimate both the focal plane cartography and the attitude residuals without any ground reference (Delvit et al., 2012) (Figure 8).

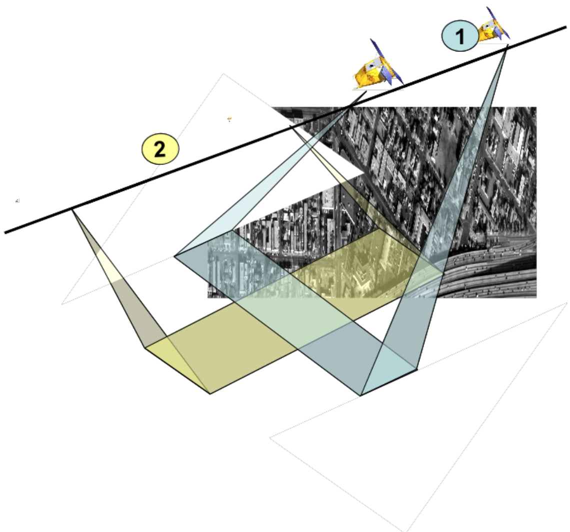

Figure 8 : Innovative Autocalibration mode.

4 months after the launch, Pleiades 1A has delivered more than 10000 images including many stereo pairs and triplets. It also opens the way to multiple views (more than 20) in a single satellite overpass, which will provide data of high interest for the photogrammetry community.

As mentioned in (Lebegue et al., 2012), the main performances assessed between the launch and April 5th,

Image Quality criteria	Status
Localization CE90	16 m
PAN/XS registration in XS pixels	0.25
XS/XS registration in XS pixels	0.15
Planimetry in PAN pixels	0.20
PAN MTF @ Nyquist frequency	0.16
PAN SNR @ radiance 100 W/m^2/μm/sr^{-1}	150
Absolute calibration accuracy	5%

Table 1 : Pleiades images performances status.

2012 is given in the table below and will be updated by the end of the image quality commissioning phase in June 2012 (Table 1).

Figure 9 : Pleiades image of Cannes, France, acquired on the 27th February 2012 ©CNES 2012.

3. ORFEO Pleiades preparatory program

ORFEO, the Pleiades Accompaniment Program, was set up by CNES to prepare, support, and promote the use and the exploitation of the images acquired by this very high resolution optical sensor, especially in public sector. It was initiated in 2004 and will last until the end of the first year of the Pleiades-1A satellite life.

The objectives of this program are two-fold:

1. Assess the thematic capability of the Pleiades system to produce the various services required by end-users for distinct domains (defence, risks, cartography, hydrology, forestry, agriculture. . .);
2. Develop efficient tools to facilitate image information extraction by end-users.

Pleiades imagery is available at Astrium GEO-Information Services (exclusive provider) with specific conditions and prices for European public service users, through a Public Service Delegation giving access to 40% of Pleiades resources. This was therefore a key issue in preparing the institutional community for this new data source.

3.1. ORFEO thematic activities

The Thematic part of the ORFEO accompaniment program covers a large range of applications, and aims at specifying and validating products and services required by users.

An in-depth work of user needs assessment in eight domains (sea and coastline, risks and humanitarian aid, cartography and urban planning, geophysical hazards, hydrology, forestry, agriculture and defence) gave rise to a large number of feasibility studies from 2006 to 2011. Since 2006, more than 40 studies have been led by scientists and thematic experts from French and Belgian institutions, in close collaboration with public end-users such as the Ministry of Internal Affairs, the Ministry of Ecology and Sustainable Development, the French Mapping Agency (IGN), etc. Such studies have been carried with imagery support provided by CNES both in the optical domain (WorldView-2, Formosat, QuickBird, Ikonos, GeoEye-1, Kompsat, aerial images) and in the radar domain (TerraSAR-X, COSMO-SkyMed, aerial images).

Pleiades-1A has been in orbit since December 2011. The third and last phase of the ORFEO program, the "Users Thematic Commissioning" (UTC) phase, started in March 2012. This phase is a direct follow-up to the ORFEO program objectives and philosophy, aiming at supporting and encouraging institutional use of Pleiades, performing research, Research and Development (R&D), and demonstration projects required by institutional actors. Free open source image handling and processing tools set up in the ORFEO methodological part will be provided, if needed, for easier access to data. Such activities are performed in synergy with Astrium GEO-Information Services marketing activities, aiming at developing Pleiades market among commercial users and setting up certified and qualified commercial services.

The most promising studies since 2006 are being assessed with Pleiades imagery, in the eight areas of interest. Several key issues such as response to crisis, urban planning, human pressure on coastlines, watershed cartography, forest management are being studied in depth.

The parameters taken into account for the selection of the thematic studies were:

- Projects ready for operational applications (e.g. monitoring large gathering/summits, updating databases. . .);
- Projects still in demonstration but very mature (e.g. coastline detection and characterization, scrubland detection for fire prevention. . .);

- Projects of interest for institutional actors whatever their technical maturity is: research, R&D, demonstration (e.g., Green and Blue corridors, biodiversity, roof reconstruction. . .);
- Projects for operational demonstration of acquisition capacity (e.g., IGN studies: department global coverage, Lidar-Digital Terrain Model assessment. . .).

Major disasters and emergency events will be covered with Pleiades imagery for Civil Protection needs.

The UTC philosophy remains in the actual association of institutional users in the related projects. Indeed, selected studies answer the requirements of the Ministry of Ecology and Sustainable Development, specified in the "*Plan d'Applications Satellitaires*" but also meets the requirements of other Ministries (such as Internal Affairs). Collaborative work between the different thematic working groups has been encouraged in order to maximize the efficiency for the key thematic studies (i.e. Green and Blue Corridors) and to gather the data acquisition over multi-thematic sites.
About 45 geographical sites related to almost 75 thematic studies have been selected, with more than 500 Pleiades acquisitions requested. The first Pleiades images in the UTC context have already been acquired, on sites such as Cannes in France (Figure 9), Arcachon in France (Figure 10), Dakar in Senegal or Merguellil in Tunisia.

A specific seminar will be held in 2013 to present the results of this large panel of public sector driven studies. The main French ministries (Ecology, Internal Affairs, Agriculture and Forestry,. . .) and European bodies such as the GMES (Global Monitoring for Environment and Security) project will be involved.

Figure 10 : Pleiades image of Arcachon, France, acquired on the 3rd February 2012 ©CNES 2012.

3.2. ORFEO methodological activities

The methodological part of the ORFEO preparatory program aims at preparing the use and exploitation of Pleiades sub-metric images.

This preparation includes capitalising on image analysis R&D results and know-how, as well as assisting the work of the thematic group and, more widely, that of the future users by providing them with algorithms, methods and easily available tools to visualise and process the images for their needs. To achieve this, in 2005 CNES decided to develop and maintain, within the framework of the ORFEO accompaniment program, an open-source remote sensing image processing library: the Orfeo ToolBox (OTB).

3.2.1. The Orfeo ToolBox

The Orfeo ToolBox (Inglada and Christophe, 2009; Christophe and Inglada, 2009; CNES, 2012) is written in C++ on top of ITK (ITK, 2012), a medical image processing library, and interfaces seamlessly with other open-source image processing software such as GDAL (Gdal, 2012) or OSSIM (Ossim, 2012).

Orfeo ToolBox is released under the CeCILL Open source license (equivalent to GPL), and is available on multiple platforms (Windows, Linux and Mac OS X). OTB comes with a modular architecture and natural scalability to image size and number of bands of most algorithms, thanks to native parallel and on the flow processing.

The most straightforward way of using the Orfeo ToolBox is to write C++ processing chain on top of it, while being guided by the extensive developer-oriented documentation (OTB Development Team, 2011a).

However, there are other lesser-known means to use it, dedicated for non-developers.

The first one is to use the OTB Applications framework. It is a set of application plug-ins that can be accessed through command-line, standalone QT graphical user interface, higher-level coding languages such as Python for instance, and plug-ins for the QGIS software (QGIS, 2012). This framework can easily be extended in two ways. Firstly, one can very easily write new application plug-ins and access them through all the above mentioned means. Secondly, the application plug-in interface can be used easily to integrate all the available plug-ins into one's own software environment.

The second and most end-user oriented means of accessing OTB functionalities is to use Monteverdi (integrated software for everyday life image manipulation and analysis tasks), which gives access to some of the most popular functionalities in OTB. Originally intended as a support for remote sensing training courses and capacity building, Monteverdi has gained a lot of interest

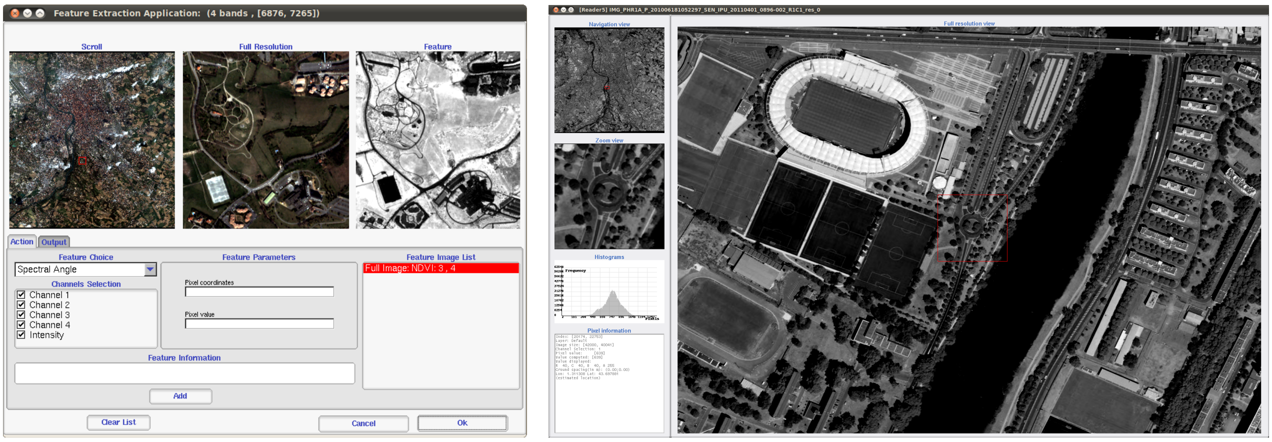

Figure 11 : Examples of Monteverdi software modules. **Left**: The feature extraction module, which allows to compute and preview a set of features. **Right**: The Monteverdi viewer, displaying a simulated Pleiades sample image distributed by Astrium GEO-Information Services.

from the end-user community as a complete FOSS tool. Figure 13(a) shows an example of a processing module available in Monteverdi. Both the application plug-ins and Monteverdi are thoroughly documented (OTB Development Team, 2011b).

3.2.2. What can be done with the Orfeo ToolBox ?

As a complete and modular algorithm library, it is difficult to make a complete list of available functionalities. This section will present the most popular and useful.

OTB can carry out all the basic image manipulation tasks: reading, writing, converting, rescaling, resampling, and extracting parts of remote sensing data... It can also perform basic pre-processing tasks i.e.: ortho-rectification, radiometric calibration or pan-sharpening.

But the richness of the Orfeo ToolBox lies in image processing: common processing tasks like thresholding, band-algebra, or Fourier and wavelet transforms, feature extraction and segmentation, vectorization, classification and change detection, gathering state-of-the-art algorithms in each domain. Advanced methodologies like Object Based Image Analysis or joint GIS-Image analysis are also available.

3.2.3. Support of Pleiades imagery

Supporting the new Pleiades imagery in the Open source world was a great challenge for the OTB team, since the JPEG2000 format in which images are delivered is not yet commonplace, and since they are uncommonly huge: a standard product is 20 by 20 kilometers, sampled at 50 centimeters, with four spectral bands.

To tackle this issue, CNES and the OTB team became involved in OpenJPEG (OpenJPEG, 2012), one of the most advanced JPEG2000 Open source alternatives. In cooperation with the OpenJPEG community, the software has been much improved and is now able to handle Pleiades imagery with reasonable performances. Additional contributions are to be made to OSSIM in order to share the support for Pleiades sensor modelling.

The result of all this work is that one can smoothly navigate in a Pleiades image through Monteverdi or the standalone OTB viewer, including access to the intermediate resolutions thanks to JPEG2000 features. The navigation experience on a decent computer should be rather friendly, as shown in Figure 12(b).

In addition to navigation, one can easily uncompress parts or the entire Pleiades image in reasonable time. Using Pleiades image as input to OTB or applications plug-ins processing chain, though on-the-flow, decompression might become time-consuming for some algorithms, in which case prior decompression to disk is advised.

4. Conclusion

The actual capabilities and performances of the Pleiades system are being intensively tested during the Users Thematic Commissioning phase.
The very promising results already obtained in the calibration phase show that images and system performances are of excellent quality.
Meanwhile, three other key challenges that are both thematical and methodological, remain to be tackled by the ORFEO team.
First, the large number of studies should demonstrate and concretely assess the benefit of sub-metric optical data for a large range of public sector users.
Secondly, the Orfeo Tool-Box Open source library, OTB applications and Monteverdi, should be of real benefit to a large number of users (from C++ developers to end-users), in order to use, manipulate and process these huge and incredibly rich images. Lastly, the ORFEO

program should significantly and practically demonstrate that Pleiades imagery is of great technical benefit for both the public and commercial sectors.

The final objective to achieve is to show that such imagery can be efficiently integrated into operational processes, so that decision makers include this new type of data into their usual tools.

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