THE PLEIADES-HR MOSAIC SYSTEM PRODUCT

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ABSTRACT:

Pleiades is the highest resolution civilian earth observing system ever developed in Europe. This imagery program is conducted by the French National Space Agency, CNES. It will operate in 2009-2010 two agile satellites designed to provide optical images to civilian and defense users. Images will be simultaneously acquired in Panchromatic (PA) and multispectral (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. Imaging capabilities have been highly optimized in order to acquire along-track stereo pairs and triplets, multi-targets and mosaics.

The automatic orthomosaic product is the most ambitious innovation of the PHR ground image processing.

Starting from an overview of the system characteristics enabling acquisition suitable for mosaic, this paper presents the geometric, radiometric and topological issues of the automatic ortho-mosaic and then focuses on the processing flow. It details the different steps: strategy, bundle adjustment, DEM refining, radiometric adjustment, seam line computation, a helped and quick image quality check and finally mosaic rectification. The process capabilities are illustrated with different sensor images. And finally the ortho-mosaic product content is described.

1 PLEIADES SYSTEM OVERVIEW : SATELLITE ACQUISITION AND PRODUCTS

The Pleiades system, of which the first platform of the constellation shall be ready for launch in early 2009, is the new generation of high resolution optical sensor satellites , developed by CNES in the framework of the joint French-Italian Orfeo system.

The Pleiades satellites will benefit from technology improvements in various fields which will allow achieving, at an affordable price, performances previously reserved to ambitious military spacecrafts.

The main characteristics of PHR satellite are agility, geolocation accuracy and image quality.

The mission of the Pleiades system is to meet an ambitious dual civilian/defense order book in terms of number of images, supplying 20 km wide Earth images of a resolution equal to 0.70 m (under nadir viewing conditions) in panchromatic band and 2.80 m in colour (blue, green, red, near infrared). The Pleiades satellites will be compact (about 1 ton weight) and agile, meaning that the whole spacecraft body can be tilted to achieve off-nadir viewing (less than 30° with performance specifications compliance and up to 47°). Covering must be almost world-wide with a revisit interval of 24 h for 2 satellites.

Agility allows the satellite to access rapidly to off-nadir targets within a large flight corridor, this leading to a sequence of numerous images. This agility meets several user requirements :

- Lateral multiband covering: a 100x100 km^2 zone can be acquired by the satellite from the same orbit.
- Stereoscopic capacity in a single pass: 3 images from the same zone can be acquired in a single pass with a B/H ratio ranging between 0.1 and 0.5.

The geolocation accuracy is ensured by 3 Star Trackers, and 4 control moment gyroscopes.

Aside from technology breakthrough, a key factor is a proper dimensioning of the instrument. Taking into account image processing techniques from the very beginning has allowed to define a much smaller instrument than the one that should have had to bear the whole set of system performances.

The range of PHR single strip products is composed of 3 levels:

- the Raw product, a complex set of 25 images, mainly for in-flight system commissioning and calibration, without geometric modification,
- The Sensor product, resulting from correction of on-board systematic distortions and attitude variations; specially dedicated to photogrammetric use (de Lussy, 2005).
- The Ortho-image level, resulting from terrain distortion correction with DTM, and geocoding.

A Pleiades HR mosaic has to be realized to meet the following needs :

- The interest area cannot be covered with only one 20km width strip.
- The end-user wants to have at his disposal a continuous image layout with both geometric and radiometric consistency

Then we have to connect the different strip units with each other, after a one by one ortho rectification. Thanks to the high agility and the precise pointing capability of the platform, several adjacent strips can be acquired within a unique pass of the satellite over the targeted area. According to the length of the neighbouring strips and the tolerated B/H ratio between them (see figure 1), the covered area may reach up to 10000 km² and even more,. If a larger area is needed,, a set of several single pass acquisitions must be tasked, thus building a multi pass block.

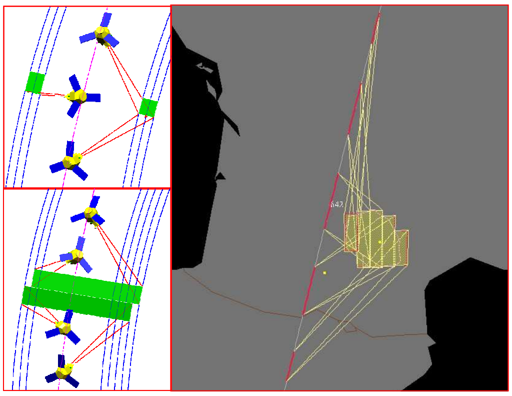

Figure 1 : illustration of Pleiades agility

In dense urban areas, where the ground may be hidden by high buildings, the mosaic process might fail or lead to no satisfying results ; the programming of the satellite may prevent from this risk, by centering the strips over those areas.
Hereafter, we present the geometric, radiometric and topological issues of the automatic generation of orthomosaics and then focus on the processing flow. We detail the different steps: strategy, bundle adjustment, DEM refining, radiometric adjustment, seam line computation, a helped and quick image quality check and finally mosaic rectification. The process capabilities are illustrated with different sensor images. Finally the orthomosaic product content is described.

2 MAIN ISSUES OF AN AUTOMATIC MOSAIC PROCESSING

The Pleiades mosaic building process, named SIGMA (Integrated, Generic and Automated Mosaic System) **can be described in four steps matching the four obstacles we have to overcome.**
At first, the geometrical colocalization of the input images has to be controlled, since we have to ensure a good connection quality. The geometrical colocalization performance depends on two factors :

- The accuracy of geometric models , as data giving the acquisition conditions
- The accuracy of DTM used for image orthorectification

So the refining of geometric models and DTM are the first challenges. After that, the colocalization between overlapping images will be better but it could not be perfect.
To obtain a nice-looking mosaic, two obstacles remain to overcome :

- **To harmonize the radiometry of images** by minimizing local and global discrepancies.
- **To optimize the tracing of the seam lines** in order to avoid areas where too obvious geometrical or radiometrical gaps remain.

2.1 Effect of the relief on the mosaic quality

The Pleiades mosaic processing shall use the most accurate available DTM: Reference3D © or DTED1 SRTM or a DTM supplied by the customer in DTED format (if no DTM is available, no mosaic can be made).
The intrinsic accuracy of Reference3D ©, better than 10m in elevation, should be sufficient in a single pass context where small B/H occur between adjacent strips : refining the DTM on image overlaps is then unuseful. We are less confident in the DTED 1 SRTM accuracy in this respect : DTM refining shall be necessary.
Let us notice finally that the ortho mosaic, as all the Pleiades system ortho images, are not corrected from the effects due to features raising above the ground (buildings, vegetation, etc…): in order to eliminate hidden parts of the landscape a great amount of images should be necessarily acquired. So the absolute and relative location accuracy (and the intrinsic geometric coherence) requirements shall be met on the ground surface. The mosaic quality will depend upon an accurate appraisal of ground elevation data.

2.2 Mosaic framework illustrated with pictures

On the North East side of the image shown in figure 2 hereafter, we can notice a great North/South shearing at the channel bridge. All along the seam line, we can detect some out of joint objects. The seam line search algorithm cannot overcome such image to image mismatch , unless a geometric model refining is applied beforehand.

Figure 2 : Attempt of joint before geometric models refining

On figure 3, we can see that the South West part of the image is much less contrasted than the North West part. The seam line search algorithm could overcome this discrepancy, despite of no radiometric harmonization,. Nevertheless such defects are unacceptable : they disturb image interpretation, particularly at the macroscopic scale
And finally, on figure 4, after having proceeded to geometrical refining, radiometric harmonization and seam line optimization, the result is definitely more presentable. Some small artefacts remain. They are in general due to residual errors on the digital model of ground or to above ground objects presence.

Figure 3 : Attempt after geometric refining but before radiometric harmonization

Figure 4 : Result after geometric refining and radiometric harmonization.

2.3 Expected image quality

In the case of a single pass cover, the weak angular differences and the almost simultaneity of strips guarantee the correct functioning of the algorithms. So image quality requirements are applicable :
The local coherence are the same as the ortho-image local coherence : jump of less than 0.2pixel for on-ground adjacent pixel, except on the seam lines where the jump will be less than 0.5pixels . The ortho-image multi-spectral superposability is not altered by the joint. The mosaics radiometric discontinuities, computed as the difference between the left and the right averaged radiometric value of 100x100 boxes located each side of the boundary between 2 contiguous scenes will have (line wise noise)/(column wise noise)< 2 for the same landscape.

These requirements were used to size the algorithms implemented in SIGMA.
In the case of multi-pass cover, the diachronism and the more or less angular differences can, according to the extent of the discrepancies, lead to more or less desperate situations with respect to image quality. The algorithms are designed not to fall in failure but no image quality commitment is expressed.

2.4 Automation, parallelization of the treatments and supervision

As mentioned above in the section "system overview", the chain of Pleiades mosaic aims to provide large images as great as possible and thus increase the Pleiades system value-added in terms of Field of view / Resolution ratio. In addition, we intend to provide a system product, generated from scratch within a short time and marketable according to a fixed cost per km^2. At last, since it is not a man made product, as known as free from any defect thanks to time consuming interactive corrections, we must of course ensure an acceptable level of quality for any mosaic.
All these constraints impose :

- A strong parallelization of the treatments and a great automation (control of deadlines and costs)
- A good robustness of the algorithms and a strategy for quality checking, including a controlled duration of the interactive phases (monitoring both product quality and production costs)

3 THE PLEIADES ORTHOMOSAIC PROCESSING

In this section, one will attempt to present the algorithmic choices made to answer the above described constraints. We will start by detailing the geometrical step of the process designed to guarantee the superimposition of the images and thus to help to find good connection lines. Then we will go on with the radiometric step of the process corresponding to the real seaming process. Afterwards we will connect on the inventory of the data selected for interactive control. Finally, we will explain the means of parallelization of the treatments implemented to fulfil the requirements in processing time.

3.1 First phase : to guarantee the geometry of the connections

This first data processing step consumes the best off-the-shelves available DTM and the raw geometrical models corresponding to best knowledge of acquisition conditions of each strip. To guarantee the quality of the connections, it is necessary that ** homologous viewing directions cut themselves on the DTM, except where above ground objects occur in images.. The main objective of this first data processing step is thus to provide a coherent unit of refined geometrical models and refined DTM.

A second objective could be to use the ortho image layer of Reference3D © to refine or control the absolute localization of the mosaic.
This first phase of the mosaicking process thus breaks up into two sub-functions : refining the geometrical models and refining the DTM, both actions being implemented sequentially.

3.1.1 Refinement of the geometrical models

This treatment is based on a process of correlation called POLLUX and developed in partnership between CNES and IGN (the French National Geographic Institute) designed to provide a scatter of tie points between two images. Its principle is to use an iterative hierarchical approach. The result of the N-1 iteration provides the location and required size of the exploration window for the iteration N correlation (to some pixel precision). By restricting the explored field one avoids thus false correlations. The use of tight (close) criteria to validate measurements still increases the robustness of the algorithm. One thus obtains a scattered distribution of homologous points with high accuracy.
These points are then injected into a process of block space triangulation called EUCLIDE and developped also in partnership between CNES and IGN. The implemented technique is based on a physical modelisation of the viewing segment (Gigord, 1999). Our fine knowledge of the Pleiades system imager enables us to optimize the adjustment of the space triangulation through a relevant choice of parameters and associated uncertainties to be refined.
After the in-flight calibration we think of getting a quasi-perfect determination of the inner orientation parameters (focal, distortion, inter-alignment of the retinas) (Greslou, 2006). Taking into account the weak awaited thermo elastic deformations, the inner orientation is stable in time and no refining is necessary. With regard to the external orientation, the performances of dating and orbitography are excellent and the only significant correction needed is the refining of the attitude : we hope that a linear correction, common to the strips composing a single pass acquisition will be enough. Six parameters per single pass acquisition would thus be enough to ensure refining. This limited number contributes to the robustness of the algorithm (Gigord, 1999).
POLLUX and EUCLIDE are used twice in the mosaic chain: once to determine the tie points necessary to the relative refining of the images and secondly to select the ground control points necessary to the absolute refining using Reference3D ©.

3.1.2 To refine the system DTM

This treatment, still under development, is based upon bricks coming from CNES and perhaps from IGN R&D. It is aiming at refining the knowledge of the altitude of the ground to guarantee the good colocalization of the images in their overlapping zones.
It should be structured around the following steps :

- Construction of the endogenous DTM (stereoscopic Pleiades/Pleiades couples) by massive correlation on the overlaps. To fulfil the requirements of lead time a fast strategy of correlation (hierarchical strategy or by propagation : TBD) is under development.
- Filtering first ground / above ground features, then modulate middle frequency information of the DTM input using ground mask. These algorithms are under study.

3.2 Second phase: to carry out the junction

The junction phase has a double objective: **harmonize radiometry and optimize the choice of the seam lines**.

3.2.1 Hierarchical joint strategy with respect to multi-pass

We envisage a hierarchical strategy for the successive assembly:
For each single pass mosaic, Do :
> *Carry out the junction (Harmonize radiometry then choose the seam lines) between strips of this single pass*

End Do
Carry out the junction (Harmonize radiometry then choose the seam lines) between individual single-pass sets of the multi-pass block
The hierarchical treatment of the junctions offers many advantages :

- To adapt the adjustment (configuration parameters) to the treated case.
- To allow stopping the treatment flow at a partial mosaic: completed junctions of all single pass, partially completed multi_pass junctions.
- Lastly to allow treatment parallelization capabilities.

The figure 5 below illustrate the realization of a Pleiades mosaic composed of two strips acquired from single passes on a certain date (in red and blue), and from a third strip acquired on another date (in yellow).

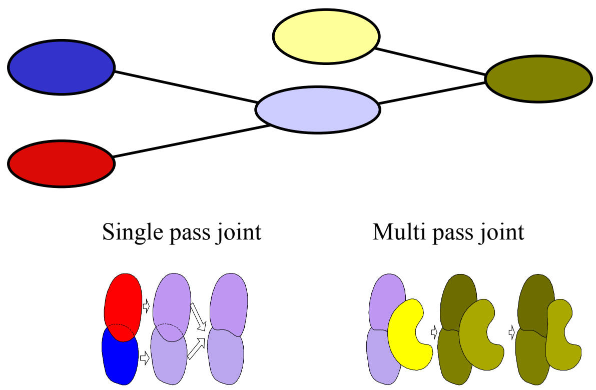

Figure 5 : hierarchical treatment of the joints

3.2.2 Harmonization of the radiometry

This function receives as input the ortho-images generated on the overlap zone. At this stage of the process, based on refined models and refined DTM, these ortho-images are superimposable as well as possible geometrically speaking.
The objective of the treatment is to build, for each strip, a radiometric correction model (in the shape of LUT grids), which guarantees the quality of the radiometric connections (continuity) without introducing undesired overall phenomena (waves: bright / dark, colorimetric drift, etc...).
Taking advantage of internal experiment of CNES and of IGN, we have developed a calculation algorithm for radiometric correction in two stages, a brief description follows :

- First stage : global radiometric balance by least square method involving the N images to be harmonized
    - Unknown for each image :
      NewRad = Polynomial_Ai(x,y) * OldRad + Polynomial_Bi(x,y)

- Measurements : radiometric variations are analyzed acoording to image tiles of each two by two overlap
- Constraints designed to ensure the unicity of the solution : the stability of the overall average and the stability of the dynamic

- Middle stage : application of the global models, calculation of the average image on the stacking of the N overlapping images
- Final stage of local harmonization : N independent least square for each image
  - Unknown for each image :
    NewRad = Aj(x,y) * OldRad + Bj(x,y)
    Aj et Bj are LUT grids
    each LUT is of type « A * Rad + B »
  - Measurements : radiometric variation analyze on image tiles between this image and the average image
  - Constraints designed to limit the artefacts (due for example to radiometric inversions): continuity of local LUT (from place to place)

For the treatment of the aerial images used into the BD Ortho © data base, IGN uses a quasi-physical model of global harmonization taking into account the hot-spot, the veil, etc... (Martinoty, 2004). Such a model is justified because of the great diversity of viewing angles in the image series. Moreover very big overlaps between image shots (60 % along-track and 20 % across-track) guarantee the system observability. On Pleiades, taking into account the relatively small field of view and the "parallelism" between the attitude profiles of the single pass strips, we await very little differential BRDF: a physical or quasi-physical model is not justified. This is why we chose polynomial models. The stage of local harmonization is not systematically present in IGN process, but it is essential in diachronism situation as in multi pass Pleiades.
The results presented on figures 2 to 4 correspond to the junction of a Quickbird image pair acquired with a several months gap. The global harmonization is carried out with constant polynomials. The local harmonization can face the presence of cloud, fog and radiometric inversions and provides an acceptable result.

3.2.3 The choice of seam lines

This function receives as input the ortho-images covering the overlapping zones. Starting from the refined image models and the refined DTM, and after radiometric harmonization, these ortho-images are thus at this stage superimposable as well as possible, both in geometry and in radiometry. This superimposition will not be perfect: there is no correction of the above ground feature distortions, only the ground features are made superimposable, a perfect radiometrical matching being impossible in many multi pass cases.
The objective of the treatment is to determine connection lines which as well as possible avoid areas of radiometric and geometrical dissimilarity: an optimum compromise is required in each overlap. The algorithm principle is to calculate a local performance index (with the radiometric variation and the linear correlation coefficient) then seek the line corresponding at the least cumulated cost (Le Men, 2000).
In order to be able to optimize the computing times, the algorithm offers an option with hierarchical implementation. The first step is carried out with under-sampled images. The seam line is sought on the overall overlap zone. The second step is carried out in full resolution mode. The seam line is calculated on a ribbon around the seam line calculated in under-sampled mode.
This treatment is based on a software library provided by IGN which will be integrated as such.

3.3 Informations selected for interactive checking

As said before, we choose to set up a checking strategy allowing to reach the expected quality while monitoring the duration of the interactive phases. To be clear, we chose a careful targeting of the information content delivered to the technician in charge of the checking operations and the interactive corrections:

- Checking geometrical models : histogram of the space triangulation residuals.
- Checking radiometric harmonization: overall mosaic of the various products displayed at low resolution.
- Checking and correcting the seam lines :
  - Ortho-images in full resolution, only displayed within the overlap areas (the whole mosaic would not easily highlight zones requiring corrections)
  - Useful area of the each various products, results of the seam lines calculation
  - Junction quality flags provided in localized form :
    - We can use as flag the cost index calculated before,
    - We study other indicators based on a a posteriori calculation : for example detection of shearings of roads or contours of buildings on the seam line
  - Zones to be avoided (such as masks of water or urban centres) for correction of their contours.

Concerning the geometry and the harmonization we have confidence in the robustness of the algorithms and we expect only a passive check. The only considered as interactive correction relates to the mosaic seam line : the operator will be guided to examine in priority the zones corresponding to a weak indicator of quality. Gained experience in this respect shows that a human intervention can often provide an improvement of decisive quality with lower cost than automation.

3.4 Treatment parallelization

In order to make it possible to exploit to the maximum the parallelization capabilities, the treatments are cut out in two types of tasks :

- The tasks known as « of planning » in charge to prepare the executions of the tasks « of realization » and to describe their hierarchical tree.
- The tasks known as « of realization » in charge to carry out independent treatments that can be run in parallelization on different processors

Thus the system will be operated according to successive stages. It starts by carrying out planning tasks, which then describe the next tasks (planning and realization) to be carried out ; some of them may be themselves a task of planning generating a new list, and so on until there are no more tasks to carry out.
As an illustration (figure 6), let us take the case of a single-pass mosaic 100 km by 100 km. It is made up of five strips: A, B, C, D and E. Four seam lines must be calculated.
Carried out in only one call, this calculation would take 68 minutes according to the current benchmark. The planning task will determine that there are four independent zones, and will prepare the execution of four calculations of seam line in parallel.

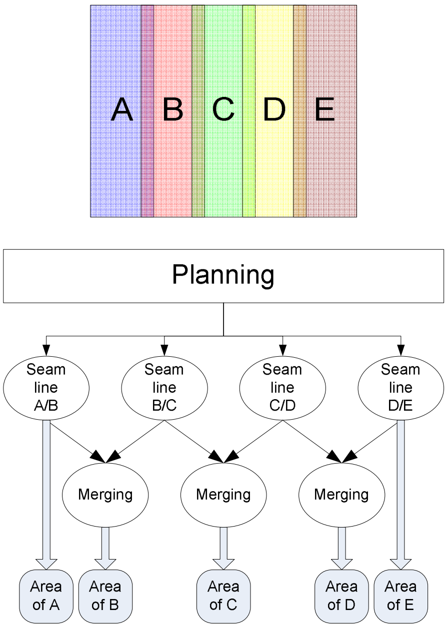

Figure 6 : illustration of parallelization

Each calculation of connection line being carried out in 17 minutes, and the planning and merging tasks over the useful zones being negligible, the advantage of this mechanism is to be noticed.

4 A GENERIC DATA PROCESSING

SIGMA is designed as a **multi-sensor** tool: At their introduction into a EUCLIDE building block, specialized libraries allow to translate the various products in a standard form independent from the native imagery. Thereafter, the image strips and geometrical models are seen in a completely generic form. The use of other imageries (aerial, Spot 5, Quickbird...) are essential to validate the algorithms at full scale... without awaiting launching.

SIGMA is developed in the form of a modular tool-kit in order to guarantee an evolutionarily and a maximum reusability.

Designed for the needs of the Pleiades mosaic**, SIGMA** naturally **covers the totality of the spectrum of a data processing sequence of value added images**:

- Refining of the geometrical models of an image set (multi-temporal stacking and/or swath enlargement)
- Generation of digital models of ground (within the Pleiades project framework, only some minimal functionalities are developed).
- Ortho-correction with large varieties of options (mosaic, carpet or stacking of ortho-images, with or without recombination of the spectral bands, with or without Pa+XS merging)

5 PLEIADES ORTHOMOSAIC PRODUCT CONTENTS

The product will be provided with complementary data, thus making it possible to know the full characteristics of the corrections made on each image and all the data necessary to the follow-up of the quality of the product.

In addition to information made available for checking purposes, the end-user will get :

- The refined system DTM.
- Refined geometrical models and synthesis on the quality of the refining of the models.
- For the whole set of the products, the mosaic of the visibility mask and the mosaic of the quality masks (the same as for ortho-image products : like clouds, defects, quality of the localization ortho (DTM and localization system).
- The entire orthomosaic image. Complementary studies about compression means are undertaken to reduce volumes of the provided image. A system of tiling will be set up.

6 CONCLUSION

The SIGMA system is under modellization and its development shall start at the beginning of summer 2006. Its multi-sensor design made it recognize and adopt like a basic tool by the CNES services of spatial image quality and processing. It meets the need paramount for the end-users of spaceborn and airborn images and so "reconcile the large field and the high resolution".

The range of PHR products is especially promising according to the satellite high agility, its accurate geolocation, the ground resolution, the high radiometric and geometric image quality and the care brought to process the products with high accuracy and the different types of products, well suited to user needs.

The automatic orthomosaic product thus supplements in a innovating way the PHR system product offer by respecting their quality standards. It is an ambitious and very useful innovation.

7 REFERENCES

Gigord P, Cantou JP, de Gaujac AC, Sempere JP, Rudowski V, Influence de la qualité de l'étalonnage géométrique sue la qualité des produits à valeur ajoutée, Revue Française de Photogrammétrie et de Télédétection, n°159 (2000-3), pp. 3-10.

De Lussy F, Kubik P, Greslou D, Pasacal V, Gigord P, Cantou JP, 2005. Pleiades HR-image system products and quality, Pleiades-HR image system products and geometric accuracy. ISPRS Hannover Workshop.

Greslou D, de Lussy F, 2006. Geometric calibration of Pleiades location model. ISPRS Marne la Vallée Workshop.

Le Men H., Boldo D., Mosaïque automatique d'orthophotographies, Actes du Congrès Reconnaissance des Formes et Intelligence Artificielle (RFIA) 2000, Paris, Février 2000

Martinoty G., Boldo D., Le Men H., Jacquemoud S., Effets radiométriques en milieu urbain à grande échelle et correction des ombres, Revue Française de Photogrammétrie et de Télédétection, n°176 (2004-4), pp. 54-66