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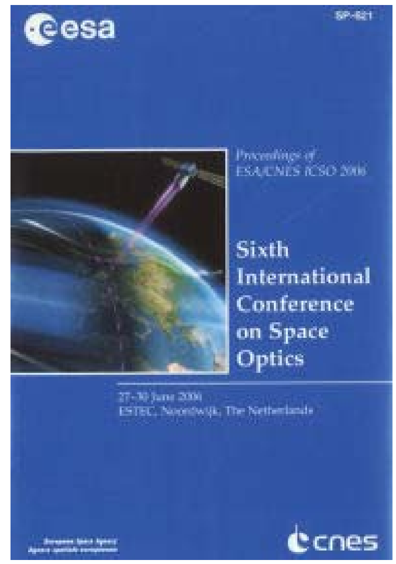

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FOCAL PLANE AIT SEQUENCE: EVOLUTION FROM HRG-SPOT 5 TO PLEIADES HR

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ABSTRACT

Optical and geometrical image qualities of Focal Planes, for "push-broom" high resolution remote sensing satellites, require the implementation of specific means and methods for the AIT sequence. Indeed the geometric performances of the focal plane mainly axial focusing and transverse registration, are duly obtained on the basis of adjustment, setting and measurement of optical and CCD components with an accuracy of a few microns. Since the end of the 1970s, EADS-SODERN has developed a series of detection units for earth observation instruments like SPOT and Helios. And EADS-SODERN is now responsible for the development of the Pleiades High Resolution Focal Plane assembly.

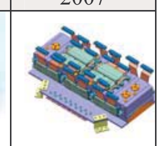
This paper presents the AIT sequences. We introduce all the efforts, innovative solutions and improvements made on the assembly facilities to match the technical evolutions and breakthrough of the Pleiades HR FP concept in comparison with the previous High Resolution Geometric SPOT 5 Focal Plane. The main evolution drivers are the implementation of strip filters and the realization of 400 mm continuous retinas. For Pleiades HR AIT sequence, three specific integration and measuring benches, corresponding with the different assembly stages, are used: a 3-D non-contact measurement machine for the assembly of detection module, a 3-D measurement machine for mirror integration on the main Focal Plane SiC structure, and a 3-D geometric coordinates control bench to focus detection module lines and to ensure they are well registered together.

1. PRESENTATION OF THE HIGH RESOLUTION MAPPING FOCAL PLANE

EADS-SODERN started in 1980s the development of civil space-borne Earth surface mapping focal plane assemblies with the SPOT1 push-broom satellite of CNES. Afterwards EADS-SODERN has developed a series of focal planes, which have been progressively adapted to match the technical evolution of satellites in the programmes SPOT and then Pleiades. This development policy has resulted in equipment with remarkable operating reliability and with technical design which continues to use the best space-rated technology.

Table 1 shows the most striking features and the trend of resolution improvement (the decrease of ground sampling distance GSD) from 10 m to better than 3 m for the SPOT 5 satellite and better than 0.7 m for the Pleiades HR satellite Panchromatic (PAN) spectral band.

Table. 1. Typical features (GSD and swath width)

1980	1990	2000	2007
			
SPOT 1, 2, 3	SPOT 4	SPOT 5	Pleiades HR
--- B1 : 20 m / 60 km B2 : 20 m / 60 km B3 : 20 m / 60 km PAN: 10 m / 60 km ---	--- B1 : 20 m / 60 km B2 : 10 m / 60 km B3 : 20 m / 60 km --- SWIR: 20 m/ 60 km	--- B1 : 10 m / 60 km B2 : 10 m / 60 km B3 : 10 m / 60 km PAN : 3 m / 60 km SWIR: 20 m/ 60 km	B0 : 2.8 m / 20 km B1 : 2.8 m / 20 km B2 : 2.8 m / 20 km B3 : 2.8 m / 20 km PAN: 0.7 m / 20 km ---

Of course, this list of features is not complete and doe not show all the technological improvements made in such various fields as optics with spectral separators, mechanics and materials and monolithic line detectors.

2. COMPARAISON SPOT5 / PLEIADES HR

The Pleiades FP (Focal Plane) new generation of instrument represents a breakthrough in comparison with the previous SPOT5 instruments as a significant step in GSD is made. And contrary to SPOT5 dioptric telescope which is optimised with a significant glass thickness in the focal plane allowing spectral separation and optical image division by prisms, the Pleiades FP takes into account the catoptric telescope design that excludes optical corrector. The comparison of the spectral separator architecture is summarized in table 2.

The SPOT5 spectral separator consists of elementary prisms. The angles of these prisms and the dichroic coating deposited on the surfaces are calculated in such a way that each interface between prisms acts as a long-pass filter i.e. transmits longer wavelengths and reflects shorter wavelengths. The beam, which is of

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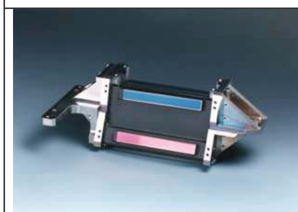
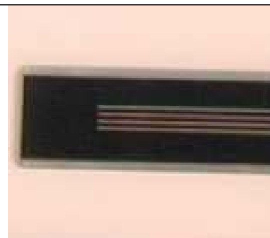
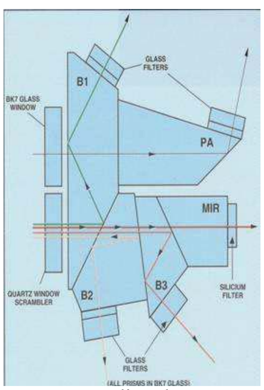
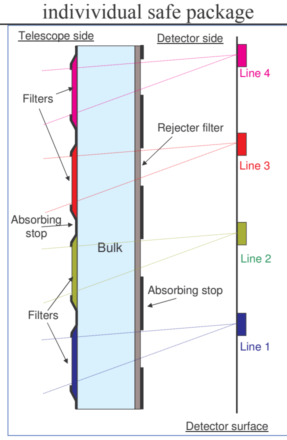
polychromatic light at the input, is progressively filtered in channels B1, B2 and so on. Beams derived by total reflection are filtered at the specified bandwidth thanks to low-pass filters placed at the outputs of the beam splitter.

Table. 2. Spectral function fulfilling
(Comparison SPOT 5 HRG / Pleiades HR)

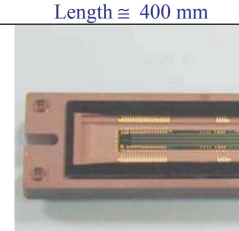
SPOT 5	Pleiades HR
Multipectral channels B1, B2, B3 and SWIR Panchromatic channel	Multipectral channels B0, B1, B2, B3 Panchromatic channel
One spectral separator per Focal Plane	One patterned filter per detector
 Beam splitter overview	 Image of patterned filter in indivividual safe package
 Beam splitter layout	 Patterned filter layout

The Pleiades instrument concept authorises only very limited glass thickness in the optical path, therefore optical glass thickness is less than few millimetres. This imposes to discard the beam splitter concept in favour of a new approach with a small patterned filter, cast in one piece, mounted on the detector. As depicted in table 2 the beam, which is polychromatic at the input, is filtered by coatings with multi-layer dielectric structures on the front and rear sides of the filter.

Besides the spectral separator aspect, the XS and PAN lines of sight are approximately few mrad apart, i.e. few cm in the focal plane of the telescope. Indeed in push-broom mode, the separation of the PAN from the XS CCD-lines, i.e. the in-field angular separation PAN/XS, causes a time delay of the colour images. Studies have been performed to minimize this time delay taking into account the design of the line features and the detector package size. However with the increasing of the focal length the PAN-sharpened images (merging of high resolution panchromatic and lower resolution multispectral images to a high resolution colour image) of Pleiades FP are more accurate even if the FP widths are similar (table 3).

Moreover the size of the focal plane is also linked to the size of the pixel. The architecture of Pleiades HR is based on a TDI (Time Delay Integration) mode CCD array for the PAN band to improve the radiometric performances of the instrument. The available TDI technology allows a pixel size of about 13 µm square. Thus for the PAN channel, this aspect and the required Swath / GSD ratio lead to replace the SPOT5 monolithic detector with 2 staggered linear arrays of 12 000 photodiodes by 5 TDI detectors with 6 000 columns. The resulting lengths of the focal planes are compared in table 3.

Table. 3. Size of image plane
Comparison SPOT 5 HRG / Pleiades HR

SPOT 5	Pleiades HR
PAN pitch ≅ 3.25 µm Ratio swatch/GSD ≅ 20 000 1 CCD [2 staggered lines of 12 000 pixels to reduce the GSD] Length ≅ 75 mm	PAN pitch ≅ 13 µm (TDI) Ratio swatch/GSD ≅ 30 000 5 CCDs [6 000 pixels] Length ≅ 400 mm
 Detectors (CCD and SWIR)	 XS Detector (with crosshair graticles during geometrical assessments)
PAN / XS angular separation: 18.5 mrad Width ≅ 20 mm	PAN / XS angular separation: 1.5 mrd Width ≅ 20 mm

3. PLEIADES HR CONSIDERATIONS

The main driving parameter on the optical architecture of Pleiades FP is the realization of 400 mm length continuous retinas. First of all the angular separation between PAN and XS lines is based on the use of a SiC central mirror of approximately 400 mm length. As depicted in [1] and figure 1 the continuous line is obtained by so-called optical butting technique on each spectral channel PAN and XS. Two optical splitting plane mirrors (~ 80 mm length) per retina reflect the light rays towards two detectors when three detectors are illuminated in direct path for each channel.

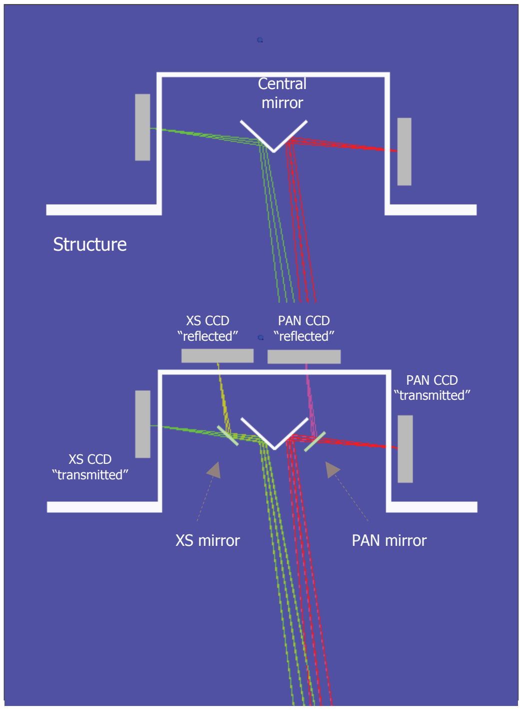


Fig. 1. Pleiades HR optical architecture

Arrangement of CCD lines in the focal plane is depicted in figure 2. The TDI PAN detector are slightly tilted in the focal plane in order to minimize the mismatch between the charges transfer rows and the image motion direction across the array due to telescope distortion.

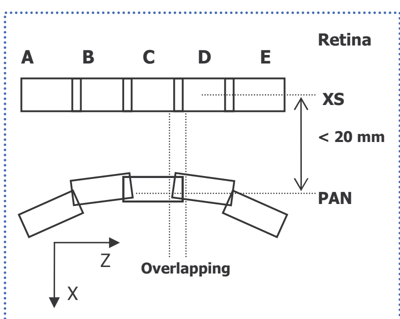


Fig. 2. Pleiades HR pixel layout

A specific feature which has a great impact on the FP AIT approach is related to the telescope optical interface that offers significant incident angles of the light paths. As illustrated figure 3, the relative positions of each splitting mirror and the dedicated detectors have to be accurately controlled with reference to the exit pupil centre O. This aspect is still more complex due to the arrangement of CCD lines as explained above and the performances of the telescope including the pupil change locations corresponding with the different image positions in the FOV, the accuracy of the paraxial approximation and so on.

Moreover for the assessment of the total geometric image plane quality on each axis, the summary budget combines the three-dimensional tolerancing contributions of each component, structure, mirror and detection module.

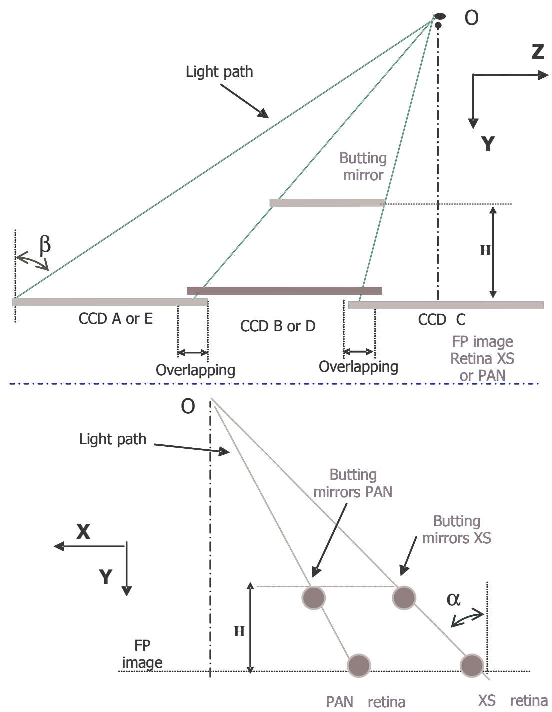


Fig. 3. Pleiades light paths (paraxial approximation)

The depth of focus δ of an optical system is expressed as the axial displacement that the image may experience before the resultant image blur becomes excessive. According to the classical theory of diffraction:

$$\delta = \frac{\lambda}{NA^2} \tag{1}$$

Decreasing the numerical aperture (NA) on Pleiades FP is thus particularly attractive. But due to significant incident angles and the implementation of TDI detectors, lateral shifts become unacceptable more rapidly than blurring. Therefore, depth of focus tolerancing, i.e. retinas flatness, remain critical in Pleiades FP.

In addition to those previous considerations, the reduction of the numerical aperture and the implementation of opaque diaphragms for straylight purpose inside the focal plane reduce the CCD dies visual accessibility during AIT sequences. Sensitivity to particulate contamination is also increased by the reduction of the numerical aperture.

4. AIT SEQUENCE

The assembly chronology is presented in the flow chart figure 4. Three stages are critical:

- the manufacturing of detection modules,
- the manufacturing of the equipped structure,
- the final assembly of the focal plane with the geometric setting of the detection modules on the equipped structure.

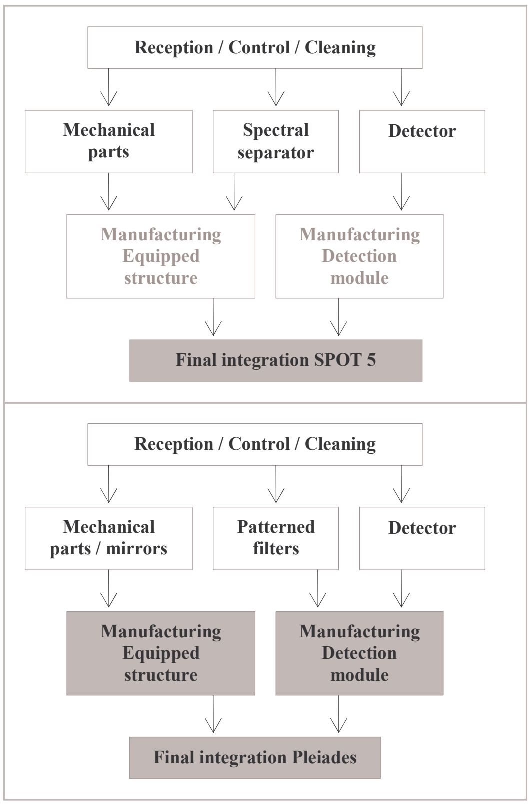


Fig. 4. Principle of FP flow chart

Manufacturing of detection module

The detection module (figure 5) constitutes the whole detection. They consist of:

- one CCD (panchromatic or multispectral),
- the mechanical frame glued o the opposite rear of the detector package (This mechanical frame screwed on the structure, ensure an isostatic mounting on the structure and evacuate the thermal heating.),
- the associated front-end analogue electronics,
- the associated filter placed in front of and close to the CCD window (only for Pleiades FP).

One of the key features of detection module is the choice of the material that insures stiffness and thermal stability with a reasonable mass, i.e. SiC on Pleiades FP. As depicted in the previous chapter, we also implement patterned filter on Pleiades detection module. Both aspects lead to a very critical AIT sequence.

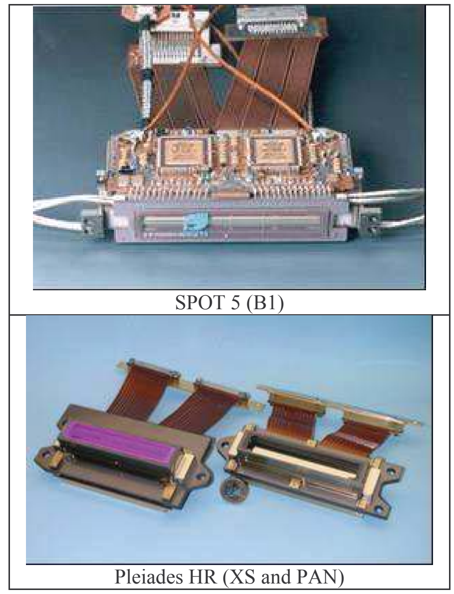


Fig. 5. Detection modules

Manufacturing of equipped structure

The manufacturing of equipped structure is a specific phase on Pleiades FP programme because of the implementation of the two different kinds of mirrors (figure 6).

During this sequence the mirrors but also the mechanical interface of the focal plane are set with a few ten micrometers tolerancing. The adjustment goals are defined at any stage of the process by a realistic optical modelling.

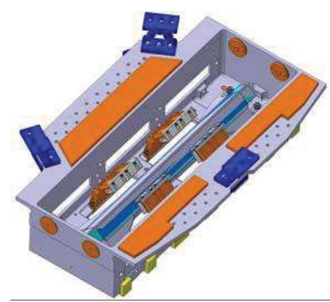


Fig. 6. Pleiades equipped structure

Final assembly

The final assembly is dedicated to the integration of detection module on the structure and the control of the geometry quality. During this phase, the detector lines are adjusted in focus and in transverse registration. The process consists in an optical measurement of pixel physical positions with respect to the mechanical interface reference of the focal plane.

In the case of SPOT 5 or analogue FP, due to the concept of spectral separator and limited number of detectors, this phase consists mainly in a control of the geometrical position of few homologous pixels, i.e. spectral images from the same part of terrain seen by the telescope can be entirely super-imposed.

The case of PLEIADS is much more critical because of FP size increase and because absolute location geometry of elementary pixels is not sufficient. In fact, inter CCDs-retina and Pan/XS relative alignment shall be well known in order to supply superimposed Pan/XS satellite data.

The next chapter deals with the measurement benches for the Pleiades AIT sequences. It is important to understand that the model accuracy requirement dedicated to FP internal geometry knowledge is the major constraint.

5. GROUND SUPPORT EQUIPMENT

The facilities described here are extremely rigid structures with granite reference planes. They consist of two basic functional parts:

- The assembly platform of three motorized linear stages along X, Y ad Z-axis, (We refer to the X and Z axis as being horizontal)
- a measuring instrument specific to each facility i.e. an optical and processing instrument or a probing device.

For Pleiades HR AIT sequence, three specific integration and measuring benches, corresponding with the different assembly and realization stages, are used:

- A 3-dimensional non-contact measurement machine called BMV for the assembly of detection modules with micro positioning tools for patterned filter integration,
- A 3-dimensional measurement machine with micro positioning tools for mirror integration on the main FP SiC structure,
- The 3-dimensional geometric coordinates control bench called BCR12 which is used to focus detection module lines and to ensure they are well registered together.

The BMV equipment

This equipment is specifically designed for applications such that high accuracy integration process. It also allows precise inspections in particular taking into account the glass thickness in case of die CCD and filters.

The system performance quality over the entire range of the BMV is summarized in table 4.

Table 4. BMV platform features

Axis	Translation capabilities	Resolution	Accuracy
X, Y and Z	200 mm	≤ 0.1 µm	≤ 2 µm

Fig. 7. BMV facility

The 3-dimensionnal measuring machine

A classical co-ordinate measuring machine (CMM) enables the geometric constitution of the equipped structure which is obtained on the basis of adjustment and metrology of mirrors localization with a rate accuracy of few microns in adjustment and in knowledge. During the assembly process the probing device scans successively the reference frame located on the structure and the mirrors.

The figure 8 shows the Pleiades FP and adjustment tools during the engineering model assembly

Fig. 8. Assembly of mirrors on the structure on Pleiades EM model

The ZEMAX optical software is used as support for this integration to determine the fine adjustment corrections of the optical components.

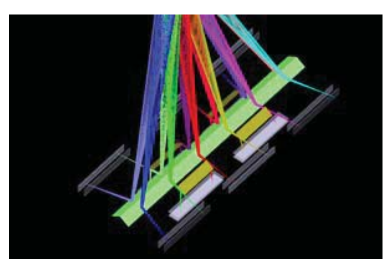


Fig. 9. Pleiades FP rays tracing

The BCR12 equipment

The BCR12 equipment, figure 10, is specifically designed and built for focal planes integration and control. The main element is a high precision platform, with three axes air bearing stages. This platform allows also immunity from vibration transmitted by the floor.

Fig. 10. BCR12 facility

The system performance quality over the entire range of the BCR12 is summarized in table 5.

Table 5. BCR12 platform features

Axis	Translation capabilities	Resolution	Accuracy
X	440 mm	≤ 0.1 µm	≤ 2 µm
Y (axial sighting)	9 mm	≤ 0.1 µm	≤ 2 µm
Z	140 mm	≤ 0.1 µm	≤ 2 µm

An optical bench is implemented on a long travel linear stage moving along the horizontal (X) axis. It is basically made with one integrating sphere light source, lenses, filter wheel, CCD camera and reference reticle. The measurement process with the motorized platform consists in:

- coarse superposition and adjustment of the reticle at the position of the pixel under inspection,
- analysis of the pattern on the camera,
- fine superposition and focalisation of both pixel and reticle.

Reticle and lenses are specifically designed for Pleiades FP assuming glass thickness and back focal length.

To guarantee the conformity of the test equipment, we designed a metrological standard, figure 11, with the same Pleiades FP mechanical interface and a glass window with multiple scale graticules etched on it.

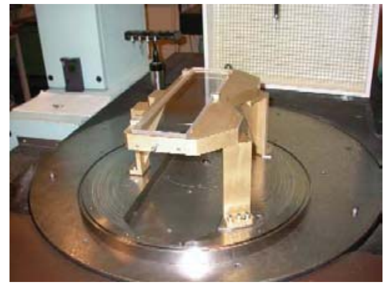


Fig. 11. Pleiades metrological standard

The assembly process of detection module on the structure is obtained on the basis of repeated phases of adjustment and metrology of pixel localization. This process is particularly achieved with a rate accuracy of few microns in adjustment for the TDI row orientations.

6. CONCLUSION

This paper aims at demonstrating how thanks to its extensive experience accumulated on the occasion of SPOT programme and on military programmes during thirty years, EADS-SODERN is able to propose solutions to the challenges linked with high performances focal planes integration.

In the frame of the French Pleiades programme, EADS-SODERN has developed dedicated integration and test facilities to fully manufacture and characterize the geometrical performances of focal plane. The first results obtained on breadboards and engineering model have demonstrated the high level of geometrical performances of the facilities and make us confident for the achievement of the programme.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

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