

International Conference on Space Optics—ICSO 2008

Toulouse, France

14–17 October 2008

Edited by Josiane Costeraste, Errico Armandillo, and Nikos Karafolas



The high resolution optical instruments for the Pleiades HR Earth observation satellites

Catherine Gaudin-Delrieu

Jean-Luc Lamard

Philippe Cheroutre

Bruno Bailly

et al.



International Conference on Space Optics — ICSO 2008, edited by Josiane Costeraste, Errico Armandillo,
Nikos Karafolas, Proc. of SPIE Vol. 10566, 105660C · © 2008 ESA and CNES
CCC code: 0277-786X/17/\$18 · doi: 10.1117/12.2308258

THE HIGH RESOLUTION OPTICAL INSTRUMENTS FOR THE PLEIADES HR EARTH OBSERVATION SATELLITES

Catherine GAUDIN-DELRIEU⁽¹⁾, Jean-Luc LAMARD⁽¹⁾, Philippe CHEROUTRE⁽¹⁾, Bruno BAILLY⁽¹⁾, Pierre DHUICQ⁽¹⁾, Olivier PUIG⁽²⁾

⁽¹⁾Thales Alenia Space, 100 Bd. Du Midi, 06156 Cannes la Bocca – France, E-mail: , catherine.gaudin-delrieu@thalesaleniaspace.com, jean-luc.lamard@thalesaleniaspace.com, bruno.bailly@thalesaleniaspace.com, philippe.cheroutre@thalesaleniaspace.com, pierre.dhuicq@thalesaleniaspace.com

⁽²⁾CNES, Centre de Toulouse, 18 Avenue E. Belin, 31401 Toulouse Cedex 4 – France, E-mail: olivier.puig@cnes.fr

1 ABSTRACT

Coming after the SPOT satellites series, PLEIADES-HR is a CNES optical high resolution satellite dedicated to Earth observation, part of a larger optical and radar multi-sensors system, ORFEO, which is developed in cooperation between France and Italy for dual Civilian and Defense use. The development of the two PLEIADES-HR cameras was entrusted by CNES to Thales Alenia Space. This new generation of instrument represents a breakthrough in comparison with the previous SPOT instruments owing to a significant step in on-ground resolution, which approaches the capabilities of aerial photography.

The PLEIADES-HR instrument program benefits from Thales Alenia Space long and successful heritage in Earth observation from space. The proposed solution benefits from an extensive use of existing products, Cannes Space Optics Centre facilities, unique in Europe, dedicated to High Resolution instruments.

The optical camera provides wide field panchromatic images supplemented by 4 multispectral channels with narrow spectral bands. The optical concept is based on a four mirrors Korsch telescope.

Crucial improvements in detector technology, optical fabrication and electronics make it possible for the PLEIADES-HR instrument to achieve the image quality requirements while respecting the drastic limitations of mass and volume imposed by the satellite agility needs and small launchers compatibility.

The two flight telescopes were integrated, aligned and tested. After the integration phase, the alignment, mainly based on interferometric measurements in vacuum chamber, was successfully achieved within high accuracy requirements. The wave front measurements show outstanding performances, confirmed, after the integration of the PFM Detection Unit, by MTF measurements on the Proto-Flight Model Instrument.

Delivery of the proto flight model occurred mi-2008. The FM2 Instrument delivery is planned Q2-2009.

The first optical satellite launch of the PLEIADES-HR constellation is foreseen beginning-2010, the second will follow beginning-2011.

2 INTRODUCTION

Following the SPOT satellites family, within the future Franco Italian ORFEO system dedicated to optical and radar Earth observation, CNES, who is in charge of the optical component, imagined a system whose performances are significantly enhanced compared to the SPOT series and achieve a range of operational missions widened to defense and civil safety domains. It is composed of two satellites equipped with optical high resolution cameras. The agility of the satellites allows a great capacity of daily image acquisitions. The so called PLEIADES-HR satellites, will deliver panchromatic images with broad field and 70cm ground sample distance at nadir. The panchromatic acquisition (Pan) is supplemented by four multispectral channels (MS) with narrow spectral bands and 2.8m ground sample distance at nadir.

Thales Alenia Space, in charge of designing, building and testing the optical instrument, has recently successfully completed the development of the Proto-Flight Model with outstanding image quality performances.

3 REQUIREMENTS

The PLEIADES-HR camera achieves all the image quality requirements (field of view, ground sample distance (GSD), modulation transfer function (MTF), signal to noise ratio (SNR)) while respecting the drastic restrictions of mass and volume imposed by satellite accommodation and performance. The main requirements that have led to the camera design choices are summarized hereafter:

Mass	<215kg
volume	L<1900mm Diameter<1200mm

	PAN	MS-B0	MS-B1	MS-B2	MS-B3
Spectral band	480nm 820nm	450nm 530nm	510nm 590nm	620nm 700nm	775nm 915nm
Field of view	20km				
GSD at nadir	0.7m	2.8m			

	PAN	MS-B0	MS-B1	MS-B2	MS-B3
MTF	> 0.073(*) at $1/2 \times 0.7 \text{ m}^{-1}$	0.2 at $1/2 \times 2.8 \text{ m}^{-1}$			
SNR @L2 radiance	> 90	> 90			
L2 W/m ² /sr/μm	97	130	115	100	100
MTF*SNR	>7,3				
distortion	<2%				

(*) : The MTF performance on final images is 0.2 after image restoration.

4 TELESCOPE OPTICAL DESIGN

The optical architecture of the telescope results from the optimization of radiometric performances compatible with volume restrictions, respect to the broad field of view and spectral range required. The four mirrors Korsch telescope, including a folding mirror, appears to be the best choice. The following figures recall the optical principle of the telescope (Fig.1 and Fig.2):

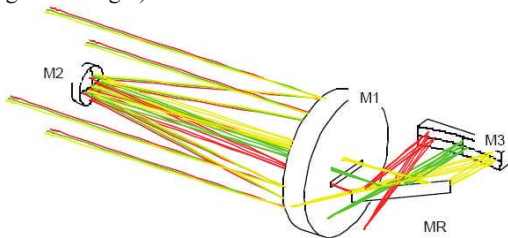


Fig.1 : CodeV 3D view of PLEIADES-HR telescope

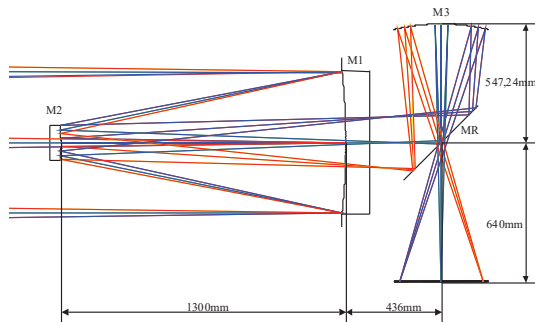


Fig.2 : CodeV 2D view of PLEIADES-HR

The front cavity is a light collector constituted by two centered mirrors. The primary mirror (M1) is a conic surface not far from a parabola. The secondary mirror (M2) is aspherical. The entrance pupil is located on the primary mirror. In the back cavity, behind M1, is located an intermediate image plane where the beams converge then diverge and are folded up by a long rectangular folding plane mirror (MR) towards the tertiary aspherical mirror (M3) which gives a corrected image at the focal plane (PF).

The beams are folded up along the field of view so as to locate the focal plane on a cold side of the satellite, due to thermal control constraint.

As for the beams coming from M3 towards the focal plane not being blocked by MR, the field of view is slightly shifted perpendicular to the image line. Thus, MR is shifted from the M1-M2 optical axis and M3 is off-axis as shown on Fig.1.

The real exit pupil of the telescope is located between M3 and the focal plane in the same plane than MR.

Both M1 and M2 are centered and circular mirrors. On the contrary, MR and M3 are very long “field” mirrors. M3 is off-axis with a low aperture number. Its use by sub-pupils along the field, makes it more difficult to manufacture as the wave front flatness must be guaranteed on every elementary zone while strictly restricting tilt and focus variations between them so as to control distortion effects at the focal plane. Therefore, this mirror is the main polishing difficulty, achieving the accuracy of traditional polishing technique. MR is subject to the same type of constraints, but as it is plane, its realization is less critical.

The telescope field of view allows the simultaneous imaging of a panchromatic line and four multispectral lines with a slight field separation compliant to mission requirements.

The main optical characteristics and sensitivities are given below:

Entrance pupil diameter	650mm
Focal length	12905mm
Numerical aperture	f/20
Field of view	1.6°
Maximum registration	PAN-MS 1.6mrd MS-MS 0.5mrd
M1 M2 distance	1300mm
M2 magnification	67
M3 magnification	3.4
Maximum optical distortion	PAN 1.82 % MS 1.97 %

Because of the high axial magnification of M2, the front cavity needs a very accurate control of the M1-M2 distance within a few microns obtained thanks to a carbon-carbon composite cylinder. A thermal refocusing device, linked to M2, is also implemented in order to compensate offsets and long term drifts.

The back cavity is not particularly sensitive to misalignments. Its design results from a compromise between compactness and distortion that is all the more high as M3 gets closer to the image plane.

The mechanical architecture is shown on the following CAD-slice view.

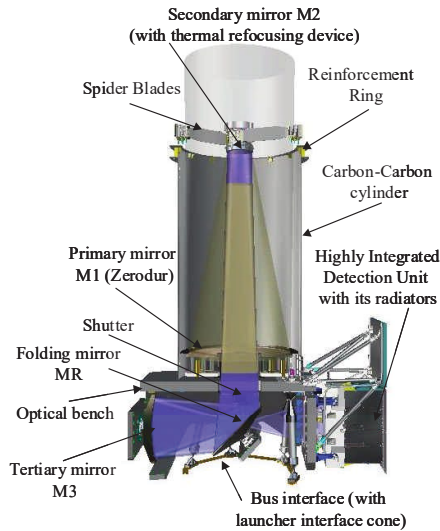


Fig.3 : CAD view of the mechanical architecture of PLEIADES-HR camera

5 TELESCOPE ASSEMBLY

The most critical integration phase consists in a careful pre-assembly of the mirrors in the mechanical structure. All the mirrors, equipped with their mechanical fixation devices (MFD), were designed, manufactured and coated by the SESO Company in Aix-en-Provence. The mirror fixation devices (MFD) are designed to minimize the deformation of the mirrors by filtering small displacements and local flatness irregularity at interface.

As to respect the drastic cleanliness constraints required, all the integration and test phases are carried on in the class100 clean room.

5.1 Primary mirror assembly

The primary mirror is maintained on the mechanical structure of the camera in three points, 120° spaced, using filtering MFD. Whatever, relative displacements of the fixation points have a major impact on wave-front deformation. Accordingly, particular caution has been taken when integrating the mirror in the flight structure, using an original dedicated tool. This tool is an invar ring divided in three sectors aimed to prevent the three fixation points from relative displacements during the transfer of the mirror from its handling interface to the flight structure. This original tool made it possible to perform a non deforming integration of the mirror with no need of optical control. The efficiency of the operation has been proved through the final optical measurements which showed that wave-front deformation is lower than the budgeted allocation. This performance has been successfully

achieved on the two telescope models.

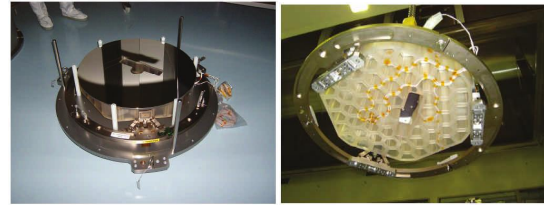


Fig.4: M1 on its transport interface with transfer tool

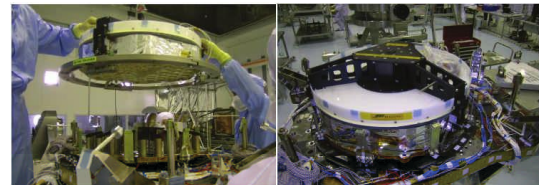


Fig.5: M1 with its protection cover being integrated on the base-plate structure

5.2 Secondary mirror assembly

The assembly of the M2 sub-system includes the mirror itself equipped with its mechanical fixation device, its baffle to prevent straylight, the thermal refocusing device with its radiator and the spider blades as shown on the following pictures.



Fig.6: integration of the M2 sub-system: mirror, baffle, refocusing device, radiator and spider

The M2 sub-system is accurately pre-aligned in front of the primary mirror using laser tracker and three dimensional measurements.

5.3 Tertiary and folding mirror assembly

The tertiary mirror and the plane folding mirror are transferred from their transport interface to the back cavity.



Fig.7: (left) M3 on its panel, (right) MR on its transport interface and cover



Fig.8: back cavity mechanical structure ready for mirrors integration

5.4 Telescope alignment

As Thales Alenia Space owns a space optics centre unique in Europe, the PLEIADES-HR camera benefits from vast clean rooms, vacuum chambers equipped with optical benches, one of them being the largest in Europe, fast interferometers, collimators and large flat mirrors for optical alignment.

The first optical alignment phase consists in orienting the tertiary mirror, in order to centre the beams on the diaphragm located at the exit pupil. In that purpose, the camera is lighted over its entrance pupil with a collimated beam using the collimator.

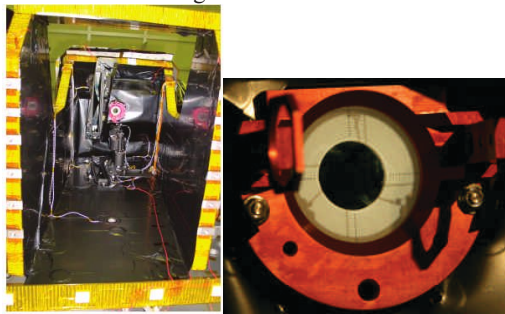


Fig.9: (left) MR in the back cavity and exit pupil reticule (right) trace of the beam on the reticule

Although the secondary mirror is not aligned yet, thanks to the high accuracy of the mechanical assembly of the telescope, the beam is focused on the image plane through the optical path. Its decentering is observed on a reticule at the exit pupil location. Tilting the tertiary mirror causes the beam to be recentered if necessary. On both telescope models, the beam centering target ($\pm 1\text{mm}$) has been easily reached.

The second alignment phase consists in tilting and decentering the secondary mirror in order to optimize the wave front error performance over the total field of view of the camera. This is done thanks to computer aid, based on interferometric measurements and using CodeV© alignment skill. Low frequency aberrations such as astigmatism, coma and focus can be reduced to an optimum by moving the M2 mirror using a 5

degrees of freedom tool whose resolution is $1\mu\text{m}$ for decentering and 1 arcs for tilt.



Fig.10: M2 maintained on the alignment tool prealigned in front of the telescope

Given the astigmatism and coma values measured for 3 to 5 field points and the optical model, the ALI option of the CodeV© software, returns the set of displacements of the mirror to be done to optimize the WFE over the entire field. The mirror is moved according to the calculation and another series of measurements is done. After pre-alignment loops under atmospheric pressure, in order to reach the best accuracy, the camera is put in a vacuum chamber with an accurate thermal control. The convergence of the alignment process was then reached in one iteration under vacuum. The perfect convergence between measurements and predictions, validates the quality of the interferometric measurements and the compliance of the specimen to the optical model. The sensitivity of wave front errors to M2 displacements is perfectly compliant to the theoretical model.

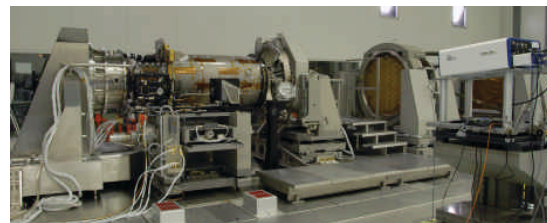


Fig.11: interferometric configuration for M2 alignment – vacuum chamber opened

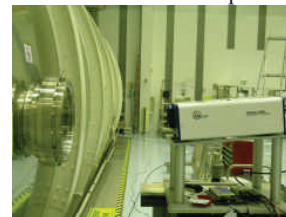


Fig.12: interferometric configuration for M2 alignment - vacuum chamber closed

5.5 Telescope optical performances

So as to accurately characterize the final optical

performance of the aligned telescope, wave front errors and focus measurements are achieved in many field points, under vacuum and accurate thermal control, as close as possible to flight conditions.

The average WFE performance of both telescopes is in line with the aimed objective. The telescope associated with the PFM instrument shows outstanding performance, average WFE performance in the whole field of view being 32nm rms, ie $\lambda/20$ at 633nm.

Focus measurements along the field show a field curvature very close to theory.



Fig.13: aligned telescope ready for detection unit integration

6 DETECTION UNIT

The focal plane (Fig.14) is the heart of the highly integrated detection subassembly (Fig.15). The size of the observed image is close to 400mm and is analyzed in 30,000 samples in Pan and 7,500 samples in MS.

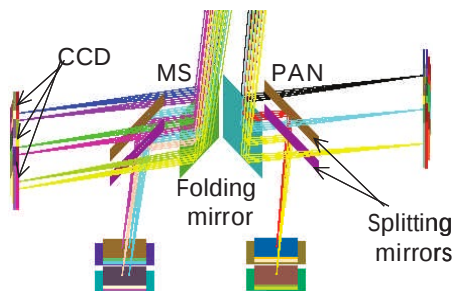


Fig.14: Focal plane concept

The Pan band is constituted of 5 back-thinned TDI mode CCD arrays, whose pixels are PhotoMOS type with lateral anti-blooming structure. The image section has 6000 columns of active square pixels, each $13 \times 13 \mu\text{m}^2$.

The colored bands (MS) are constituted of 5 CCD four linear arrays. The spacing between the centres of two consecutive line is 936 μm . Each line of pixels has

1,500 photo-elements on a 52 μm pitch and the size of each photo-element is $52 \times 52 \mu\text{m}^2$.

The spectral selection is made by optical filters placed very close in front of the detectors. Pan filters and MS stripe-line filters are space qualified multi-layer coatings deposited on glass substrates. An absorbing material deposited between the MS filters isolates each band from the others to avoid inter-band straylight.

A SiC main structure ensures accurate positioning and thermal dissipation of the equipped detectors.

For an easy high level image products ground processing, optical butting with splitting zerodur® mirrors provides the continuity of the detection lines (Pan/Pan and MS/MS in the field registration) and folding with long roof SiC mirror separates Pan and MS image.

The link between the Focal Plane and the Video Electronics is made with flexible circuits optimized to operate at frequency close to 7 MHz.

Radiometric performances are optimized thanks to video processing entirely integrated on the focal plane.

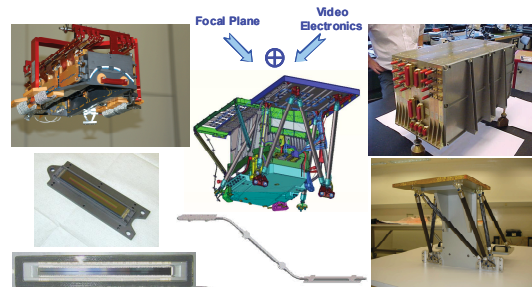


Fig.15: Detection Unit

7 CAMERA INTEGRATION AND TESTS

After electrical integration and radiometric performance verification, the PFM Detection Unit is mounted on the telescope for final qualification test campaign.

The first step consists in MTF measurements along the Pan line. This is done via a contrast evaluation method, using a collimator that lights the camera over the full entrance pupil.



Fig.16: PFM undergoing optical measurement (MTF)

The MTF performance is deduced from the acquisition of images of a square wave pattern whose spatial frequency is close to the Nyquist frequency of the Pan pixel, located at the image plane of the collimator.

The MTF performance measured at that step confirmed the high level image quality expected at telescope step and authorized the instrument to go through the qualification mechanical tests.

Due to the mechanical configuration of the instrument inside the platform, the quasi-static and sine levels tests cover the loads induced by acoustic, shock and thermal environments.

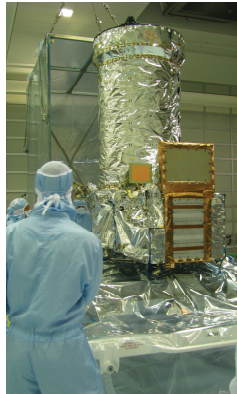


Fig.17: PFM camera ready for mechanical tests

All simulation levels have been passed in record time with no performance degradation.

The comparison between measurements (MTF and geometrical tests) before and after mechanical tests prove the perfect stability of the instrument.

8 FINAL PERFORMANCE TEST RESULTS

The main image quality parameter is the SNR.MTF product which determines the useful support of the MTF and hence image resolution. The performances apply for each spectral band, throughout the life of the satellite, excluding the compression effect and outside inter-array zones.

The PFM optical instrument shows outstanding image quality performance compared to the required level.

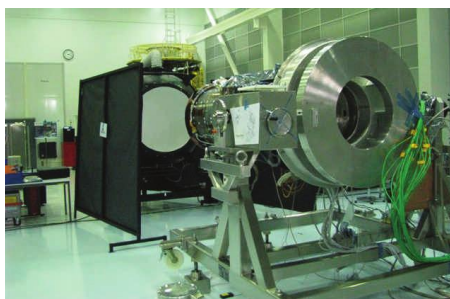


Fig.18: PFM undergoing radiometric measurement

8.1 Panchromatic band

The images acquired in Pan mode correspond to those for which resolution performances must be maximum. The following performance applies to the angular frequencies corresponding to the spatial frequencies, on ground, for nadir viewing, at the nominal altitude and with the theoretical focal length, less than the spatial frequency of interest on ground $f_o = 1/(2 \cdot \text{GSD}_{\text{pan}})$, irrespective of the image viewing direction. Raw MTF complies with the following conditions at instrument level with the hypothesis of 13 active TDI lines :

For any frequency f less than or equal to f_o we have:

- $\text{SNR.MTF}(f) > 20$ [requirement > 7.3] at L2 radiance;
- $\text{MTF}(f) > 0.13$ [requirement > 0.073] at worst case radiance (L1);
- $\text{SNR} > 147$ [requirement > 90] (where SNR designates column noise at L2 radiance).

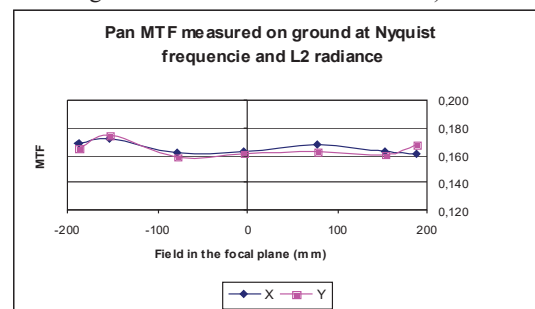


Fig.19: Pan MTF measurements based on contrast evaluation method

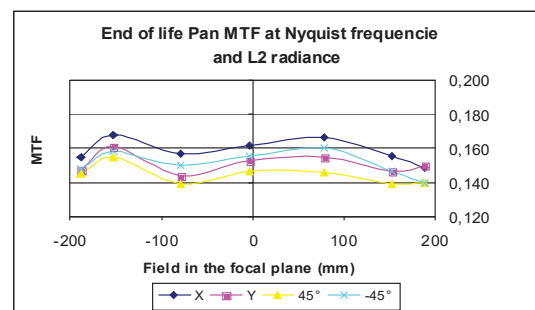


Fig.20: Predicted Pan EOL MTF based on ground measurements

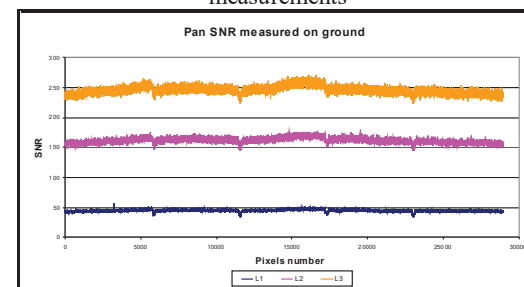


Fig.21: Pan SNR measured with 13 active TDI lines

8.2 Multi-Spectral bands

Performances apply to the angular frequencies, on ground and for nadir viewing, corresponding to the spatial frequencies specified below, irrespective of the image viewing direction.

For all module spatial frequencies less than or equal to spatial frequency of interest on ground $f_0 = 1/(2 \cdot \text{GSDms})$, we have the following for each MS band :

- **MTF > 0.25** [requirement > 0.2] along X and Y axes, at worst case radiance (L1);
- **SNR > 130** [requirement > 90] (where SNR designates column noise at radiance L2).

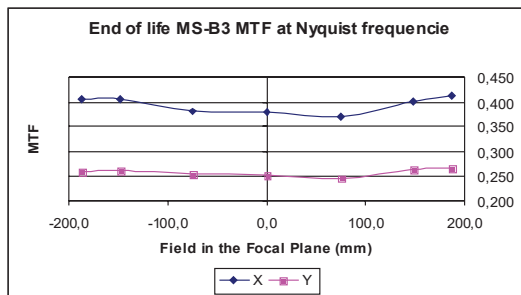


Fig.22: Predicted MS EOL MTF based on ground measurements

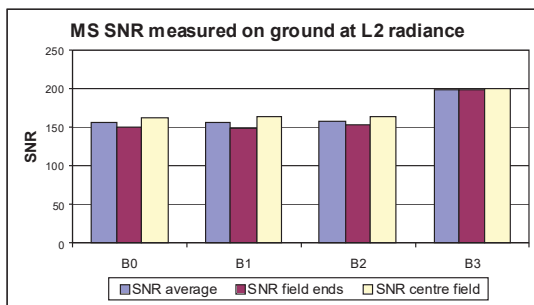


Fig.23: On ground MS SNR measurements synthesis

The displacement MTF, associated with the forward motion of the sensors (push-broom mode) for nominal integration times explains the difference between X and Y performances on MS band.

9 CONCLUSION

The optical architecture of the PLEIADES-HR camera, based on a light and compact Korsch telescope and a highly integrated detection unit, achieves the image quality requirements with margin. Instrument low mass and high compactness are major and mandatory contributors to the satellite agility performance.

Achieving these performances needs the use of advanced technologies and benefits from a highly

efficient thermal and mechanical architecture that ensures very high in-flight stability of the camera.

Through the development of the PLEIADES-HR camera, Thales Alenia Space has confirmed its successful experience in designing, building and testing high resolution optical instruments, with a special notice to the high performance optical facilities and skills available in Cannes for optical measurements and alignment.

PFM development has been successfully achieved. Outstanding MTF and SNR performances have been reached. The FM2 camera integration is in progress towards a delivery planned Q2-2009.

10 ACKNOWLEDGMENTS

This work was performed at Thales Alenia Space, under a contract from the Pleiades HR satellite prime EADS-Astrium (France), on behalf of CNES. Many thanks go to the many engineers at E2V Technologies, SAGEM, EADS-SODERN, SESO and SENER who participated in the development of the Pleiades-HR optical instruments. We also acknowledge the strong support given by the CNES teams.

11 REFERENCES

1. Lamard JL, Frécon L, Bailly B, Gaudin-Delrieu C, Kubik P, Laherrère JM, *The High Resolution Optical Instruments for the Pleiades-HR Earth Observation Satellites*, IAC 2008
2. Gaudin-Delrieu C., *Alignment and optical performance of the PLEIADES-HR Cameras*, OCS'08
3. Albouys V., Corberand P., Larue L., André S., Soler A., *PLEIADES HR Satellite - Mechanical and Thermal Architecture*, CEAS 2007
4. Fappani D., Ducollet H., *Manufacturing & Control of the aspherical mirrors for the telescope of the French satellite Pleiades*, SPIE Vol. 6687 (2007)
5. Materne A., Bardoux A., Geoffray H., Tournier T., Kubik P., Morris D., Wallace I., Renard C., *Backthinned TDI CCD image sensor design and performance for the Pleiades High Resolution Earth Observation Satellites*, ICSO 2006
6. Laubier D., Materne A., Lamard J.L., *The Pleiades-HR Instrument*, AAF-OPTRON 2005
7. Gaudin-Delrieu C., *Optical architecture of the Pleiades-HR Camera*, OCS 2005
8. Rosak A., Latry C., Pascal V., Laubier D., *From SPOT 5 to PLEIADES HR : evolution of the instrumental specifications*, ICSO 2004
9. Lamard J.L., Gaudin-Delrieu C., Valentini D., Renard C., Tournier T., Laherrère J.M., *Design of the High Resolution Instrument for the PLEIADES HR Earth Observation Satellites*, ICSO 2004