VH-RODA 18–22 November 2019, ESRIN, Frascati

On-orbit star-based radiometric and spatial calibration of PLEIADES HR optical sensors

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* THALES

OVERVIEW OF PLEIADES HR MISSION & SATELLITE

MISSION

Spatial resolution:
- Panchromatic : 0.70 m
- XS (B, G, R, NIR) : 2.80 m

Simultaneous PA + XS acquisition

Swath: 20 km

Mode	Band	Spectral characteristics
Multi spectral	1	430 – 550 nm
	2	490 – 610 nm
	3	600 – 720 nm
	4	750 – 950 nm
Panchromatic	P	480 – 830 nm

SATELLITE

- Mass : < 1 T
- Power : Lithium-ion batteries

Rigid AsGa solar panels

- AOCS : 4 powerful CMG

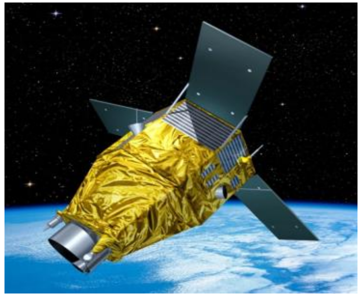
(Control Moment Gyros) actuators

☞ agility (roll and pitch): 60° in 25 seconds

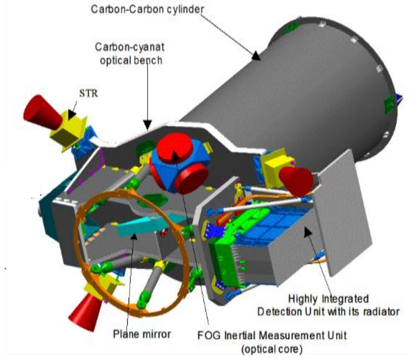
3 star trackers

4 optical fiber gyros

- Image telemetry at 600 Mbps
- 600-Gbit mass memory



INSTRUMENT



- Korsch camera
- Focal length 12.90m
- Diameter 0.65m

- PA retina : TDI detector
- XS retina : four color CCD

- 12 bit quantization
- On-board detectors normalization
- Wavelet compression:
  from 1.4 to 3.33 bits/pixel

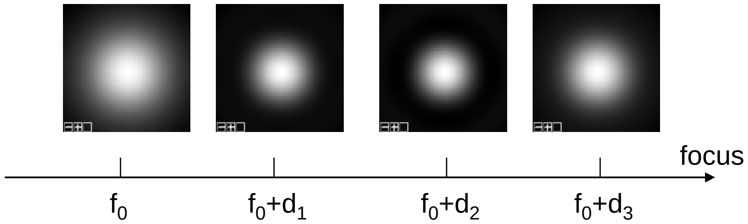
PHR-1A launch: December 17, 2011

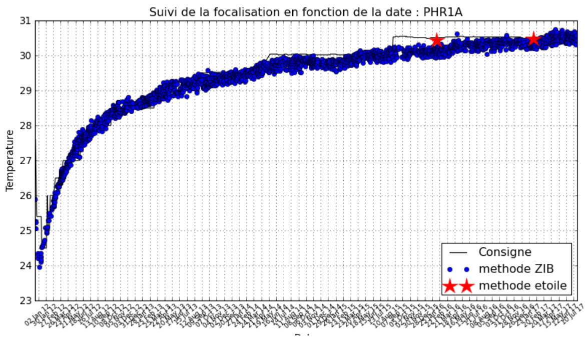
PHR-1B launch: December 2, 2012

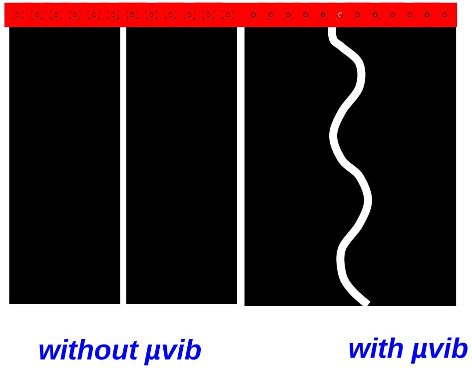

D:\DONNEES\JMD_SIQI\PLEIADES\VIDEO\RIO\VIDEO_PHR_3_8_1080x1920_2500_4000\TMP\P_AV26b

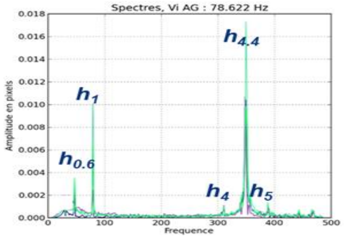
STARS USED AS A REFERENCE FOR ON ORBIT CALIBRATION

- **Spatial calibration based on stars: MTF or LOS stability assessment for PLEIADES satellites**
- **Radiometric calibration:**
  - **The spectral irradiance of some stars is known with a very high accuracy**
  - **No atmosphere to manage…**
  - **They are regularly used by astrophysicists to calibrate their instruments**



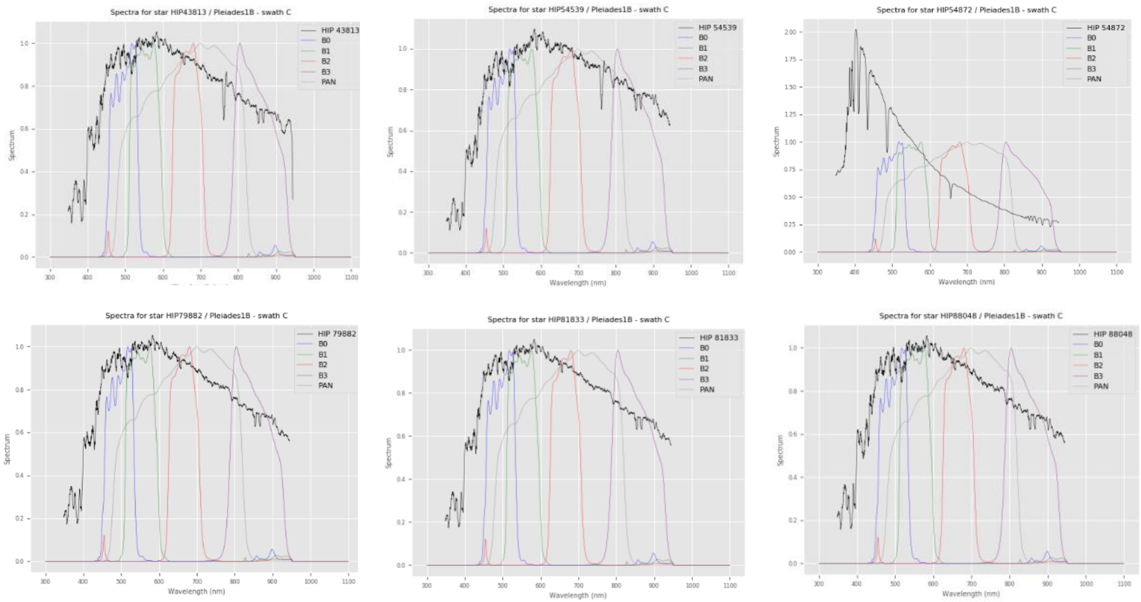


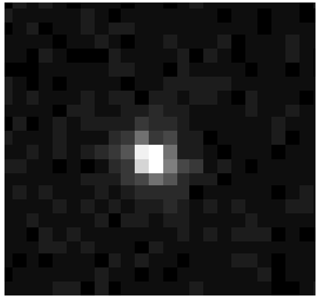




SELECTED STARS : SPECTRAL IRRADIANCE

☞ **Use of INDO-US library**





HIP 54872 seen by PHR-1B (B0)

Name	HIP code	B0	B1	B2	B3	PAN
				L(W/m²/sr/µm)		
HD76294	43813	110.61	117.32	111.20	84.54	1730.54
HD150997	81833	79.25	84.05	79.63	60.64	1243.67
HD146791	79882	99.64	105.68	100.17	76.23	1563.53
HD96833	54539	121.64	132.02	133.21	107.09	2052.07
HD163917	88048	90.81	96.36	91.51	69.51	1426.67
HD97603	54872	256.09	205.10	127.86	68.89	2255.54

Selection criteria:

- Equivalent radiance
- Type of star
- Radiometric stability
- Accessibility

STARS USED FOR RADIOMETRIC CALIBRATION

- **INDO-US libraries provides normalized irradiance spectrum (1273 stars)**

$$E(\lambda) = \frac{E_{norm}(\lambda) \cdot E(5556Å)}{E_{norm}(5556Å)}$$

With:

$$E(5556Å) = 10^{log(E_{VEGA}(5556Å)*2.5112^{-M})-0.006+0.018*(B-V)}$$

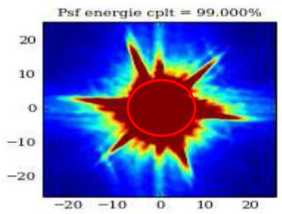
- **Taking into account the difference between the effective wavelength of band V in Johnson system (λ=5480Å) and the wavelength of definition of the magnitude M in Vega system (λ=5556Å)**
- **B-V: color index**
- **E_{VEGA}(5556Å)= 3.56 *10^{-12} W/m²/Å**

Absolute calibration coefficient A_k for band k :

$$A_k = \left(\frac{dx}{f}\right)^2 \cdot \frac{\sum_p Z_k(p)}{E_k}$$

where :

- $Z_k(p)$ is the signal of pixel p after radiometric correction
- f is the focal length
- dx is the pixel size
- E_k is the star equivalent irradiance



→ Integration of the signal over a circular area corresponding to 98% of the PSF

⇒ Requires the PSF knowledge
⇒ New approach: simultaneous MTF and absolute calibration retrieval
☞ Continuity of S. Fourest* work

* Fourest S. & Lebègue, L. (2009). Star-Based Calibration Techniques for PLEIADES-HR Satellites. *18th Annual CALCON Technical Conference.* Logan, Utah, USA.

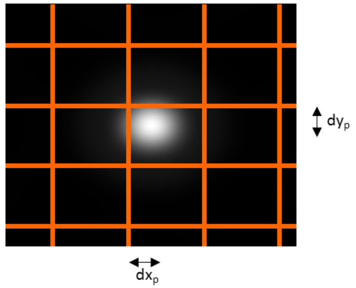
THE RADIOMETRIC MODEL

For each star p, the radiometric model, after normalization, in the Fourier domain can be written as:

$$FT^{p}_{l,m} = \sum_{u=0}^{s-1} \sum_{v=0}^{s-1} A_k \cdot L_k \cdot MTF_{l+u\cdot s, m+v\cdot s} \cdot ramp(dx_p, dy_p)_{l+u\cdot s, m+v\cdot s}$$

where:

- FT is the Fourier transform of p star image
- the aliasing contributions to the signal are summed
- MTF is the Modulation Transfer Function, which is normalized
- l,m are space frequencies along- and across-track
- s is the oversampling factor with regard to the Nyquist frequency
- ramp(dxp,dyp) is the phase ramp in Fourier space corresponding to a shift (dx_p,dy_p) for star p with regard to the sampling grid
  ⇒ pre-processing to determine (dx_p,dy_p) assuming that the MTF is real
- A_k is the absolute calibration coefficient
- L_k is the star’s equivalent radiance



Star slightly shifted with regard to the sampling grid

MATHEMATICAL FORMULATION

For nb_star stars we build a system of nb_star + s^2 equations:

$$\left(\begin{bmatrix} ramp^{1}_{alias_0} & \cdots & ramp^{1}_{alias_{(s^2-1)}} \\ \vdots & \ddots & \vdots \\ ramp^{nb\_star}_{alias_0} & \cdots & ramp^{nb\_star}_{alias_{(s^2-1)}} \end{bmatrix} \atop \begin{bmatrix} 0 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & r \end{bmatrix}\right) \cdot \begin{pmatrix} A_k.MTF(l,m)_{alias_0} \\ \vdots \\ A_k.MTF(l,m)_{alias_{(s^2-1)}} \end{pmatrix} = \begin{pmatrix} \frac{FT^{1}_{l,m}}{L^{1}_{k}} \\ \vdots \\ \frac{FT^{nb\_star}_{l,m}}{L^{nb\_star}_{k}} \\ 0 \\ \vdots \\ 0 \end{pmatrix}$$

- **Where alias represents the aliasing contribution and r a regularisation factor to force the MTF to be equal to 0 for higher frequencies than the cutoff frequency**
- **This system of equations with 2*s^2 +1 unknown is solved by a linear least squares method:**

Res(l,m) = A_k.MTF(l,m)

A_k=Re[Res(0,0)]

MTF(l,m)=Res(l,m)/A_k

WEIGHTED LEAST SQUARES TO MANAGE THE STARS IRRADIANCE

Objective: to give a higher weight to brighter stars in the resolution of the system of equations

$$A = \begin{pmatrix} \begin{bmatrix} ramp^{1}_{alias_0} & \cdots & ramp^{1}_{alias_{(s^2-1)}} \\ \vdots & \ddots & \vdots \\ ramp^{nb\_star}_{alias_0} & \cdots & ramp^{nb\_star}_{alias_{(s^2-1)}} \end{bmatrix} \\ \begin{bmatrix} 0 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & r \end{bmatrix} \end{pmatrix}$$

$$y = \begin{pmatrix} \frac{FT^{1}_{l,m}}{L^{1}_{k}} \\ \vdots \\ \frac{FT^{nb\_star}_{l,m}}{L^{nb\_star}_{k}} \\ 0 \\ \vdots \\ 0 \end{pmatrix}$$

$$Res(l,m) = \begin{pmatrix} A_k.MTF(l,m)_{alias_0} \\ \vdots \\ A_k.MTF(l,m)_{alias_{(s^2-1)}} \end{pmatrix}$$

Res(l,m)=$(A^TWA)^{-1}A^TWy$

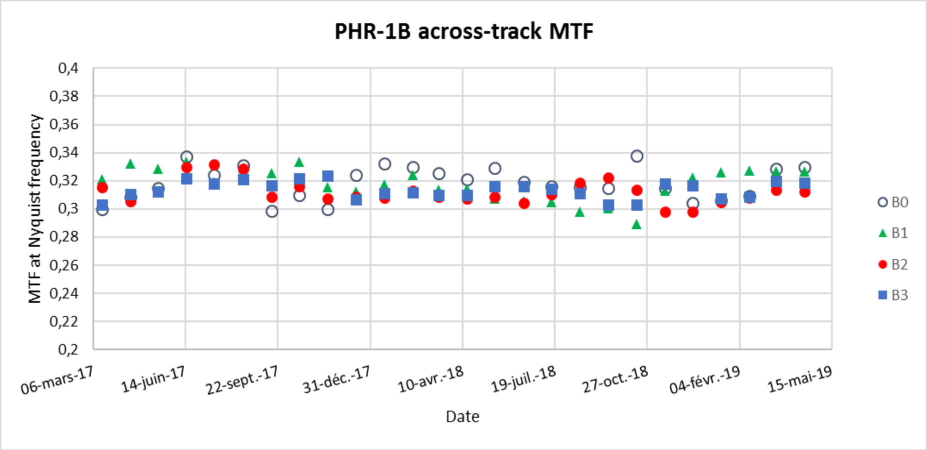
with:

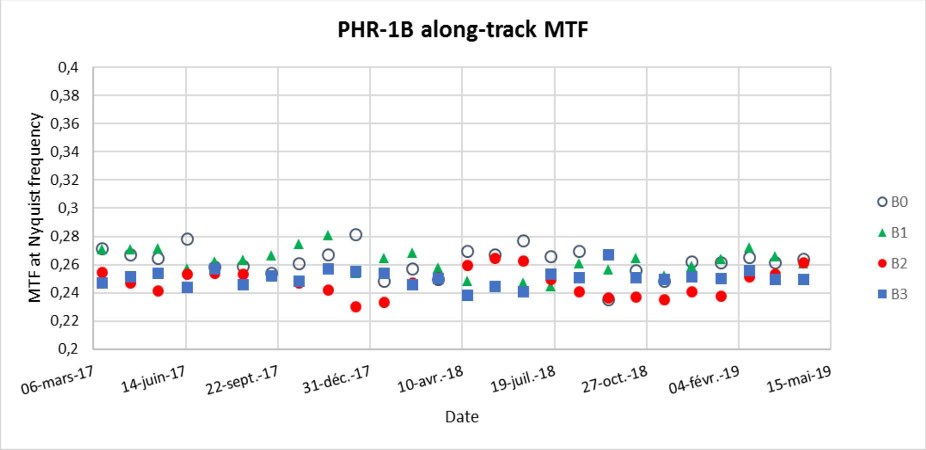
- **W the weight matrix: W(p,p)=√L(p) ∀p=1,… nb_stars**
- **W(p,p)=1, ∀p>nb_stars**

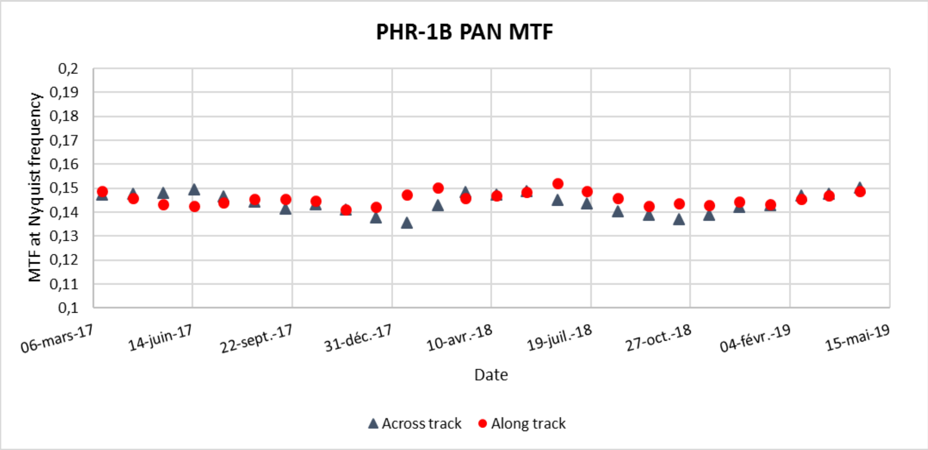
STAR BASED CALIBRATION: MTF RESULTS

PLEIADES 1B data acquired between february 2017 and may 2019 for 6 stars: 12 to 18 images per month

- 42 to 54 mesureaments for each equation system considering a shifting window of 3 months
- More than 500 Pan +XS images processed
- Oversampling factor = 3 for XS bands and 2 for PAN band



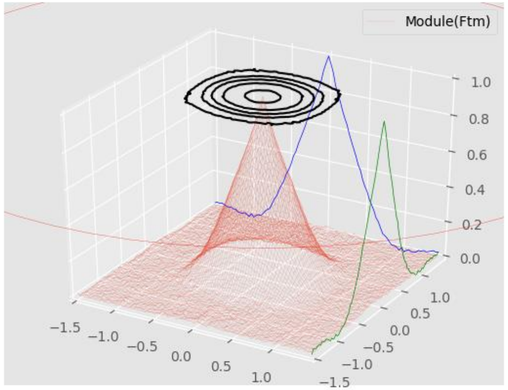




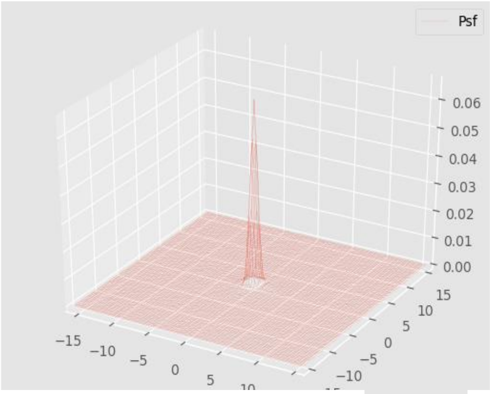
- Good stability of the MTF measurements

STAR BASED CALIBRATION: MTF RESULTS

Pleiades1B_XS_B2_SUIVI__WINDOW_3_012018_022018_032018



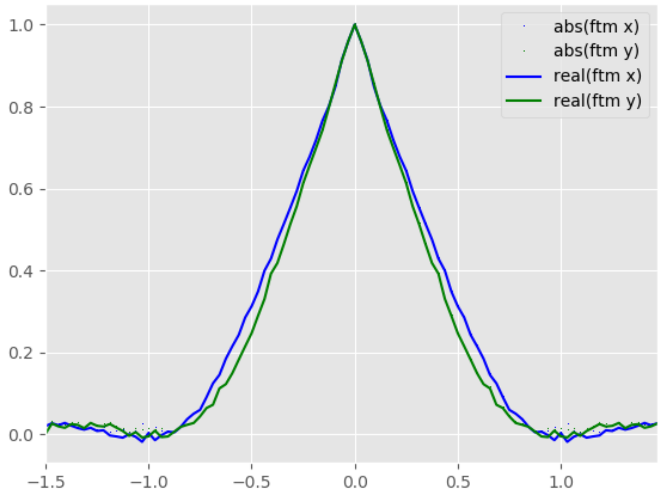
Pleiades1B_XS_B2_SUIVI__WINDOW_3_012018_022018_032018



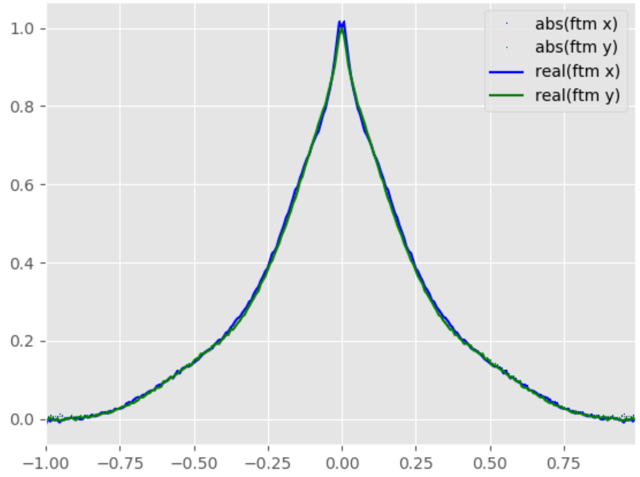
☺ **Very weak noise on the retrieved MTF**

Across-track MTF
Along-track MTF

Pleiades1B_XS_B2_SUIVI__WINDOW_3_012018_022018_032018



Pleiades1B_PAN_PAN_7_10_SUIVI__WINDOW_3_012018_022018_032018



STAR BASED CALIBRATION: MTF RESULTS

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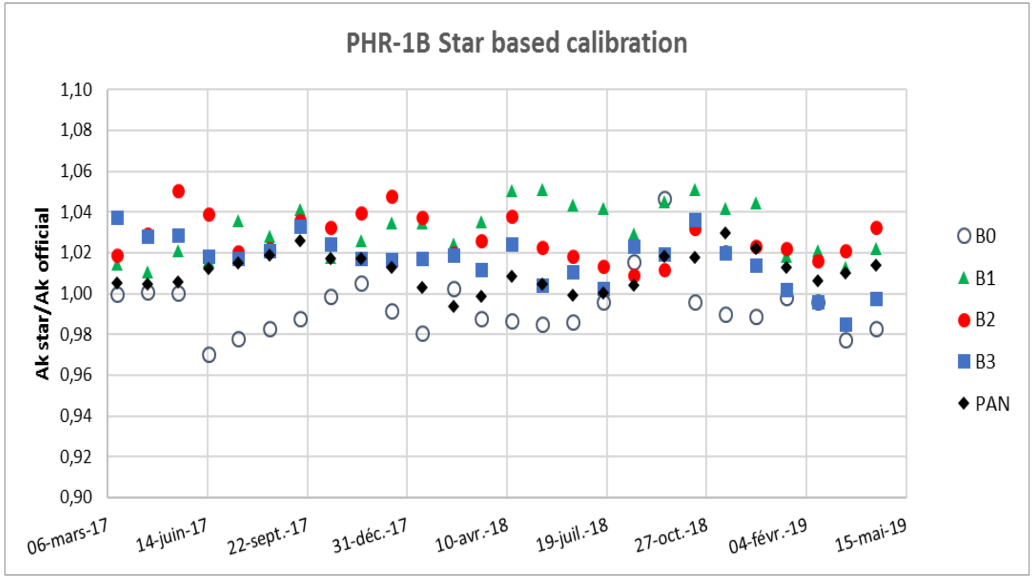
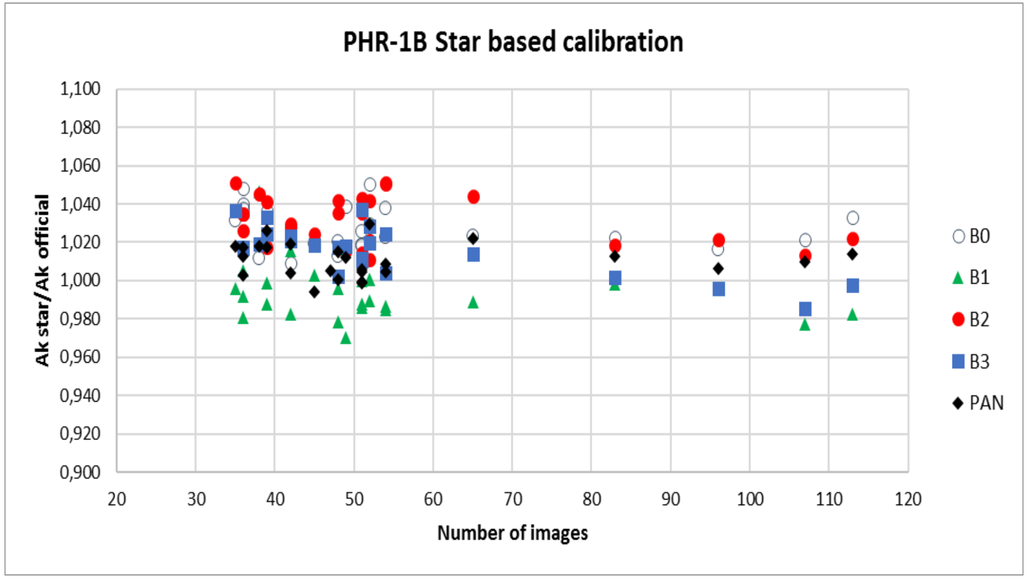
Synthesis for the period february 2017 – may 2019

PHR-1B MTF (fe/2)	MTF across-track	MTF along-track	Requirement (>)	MTF across-track official	MTF along-track official
PAN	0.15	0.15	0.08	0.15	0.16
B0	0.32	0.26	0.2	0.31	0.26
B1	0.32	0.26	0.2	0.30	0.27
B2	0.31	0.25	0.2	0.31	0.27
B3	0.31	0.25	0.2	0.31	0.26

⇒ **Good consistency with the official MTF**

STAR BASED CALIBRATION RESULTS





⇒ **Good stability of PHR-1B calibration measurements over more than 2 years**

⇒ **Lower deviation as the number of processed images increases**

STAR BASED CALIBRATION RESULTS

PHR-1B	B0	B1	B2	B3	PAN
Ak star / Ak official	0.994	1.031	1.027	1.016	1.011
Standard deviation	0.014	0.012	0.011	0.012	0.009

- Very good consistency with regard to the official calibration
- Weak standard deviation

STAR BASED CALIBRATION AND MTF RETRIEVAL: ERROR BUDGET ELEMENTS

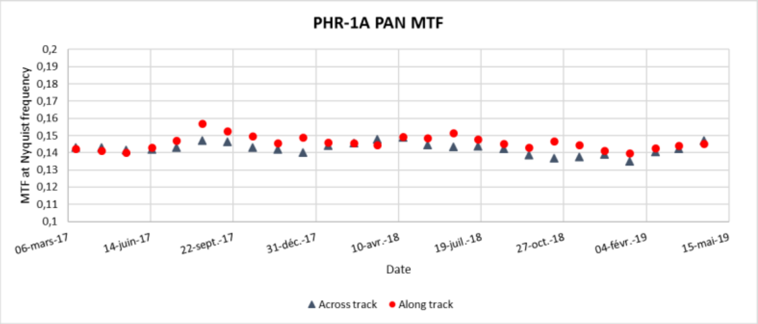
- **The calibration error depends on:**
  - **- the residual offset correction**
  - **- the instrument noise**
  - **- the spectral response non uniformity in the field of view: $\Delta\lambda=\pm2.5nm \Rightarrow \Delta L<1\%$ for B0**
  - **- the MTF variation in the field of view (lower than 0.02 at Nyquist frequency)**
  - **- the knowledge of the centering of the star image with regards to the sampling grid**
  - **- the residual non linearity**
  - **- the size of the window for the extraction of the star in the image**
  - **- the error on the reference spectrum (INDO-US): $\Delta M=0.1 \Rightarrow \Delta L=\pm2\%$**
- **The mean residue of the linear least squares method for MTF and calibration retrieval is representative of most of the above errors and includes the method error**

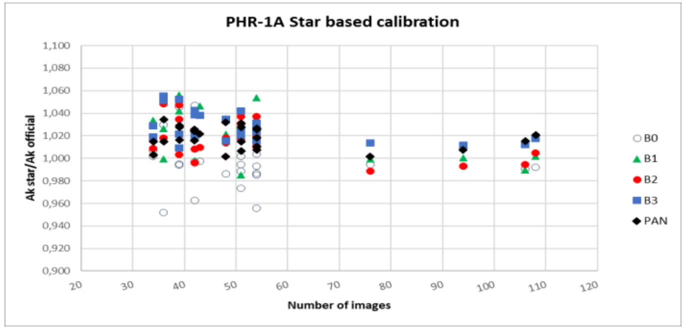
Mean residue (%)	B0	B1	B2	B3	PAN
PHR-1B	5,0	3.8	4.2	4,0	4,9

For PHR-1B B0 calibration, the uncertainty on the measurement is typically 5%, while the difference with regards to the official calibration is lower than 1%.
For the MTF, this table tells us that the maximum error is lower than 0.016, obtained for PHR-1B B0.

CONCLUSION

- **We are able to simultaneously assess the MTF and the radiometric calibration of an optical sensor using stars***
- **Very good calibration and MTF results for PLEIADES 1B**
- **Operational at CNES for high resolution optical sensors: similar results for PLEIADES 1A**





- **The quality of the results strongly depends on the number of observations because of the aliasing that needs to be solved**
  $\Rightarrow$ next step: using a physical model for the MTF
- **The method is not limited to PLEIADES class high resolution sensors. It can also be applied to sensors like SENTINEL-2 MSI instrument using for example Vega which radiance would be close to 220 W.m^{-2}.sr^{-1}.μm^{-1} in the 10 m resolution green band**

Meygret A., Blanchet, G., Latry, C., Kelbert, A., Gross-Colzy, L., "On-Orbit Star-Based Calibration and Modulation Transfer Function Measurements for PLEIADES High Resolution Optical Sensors", IEEE Transactions on Geoscience and Remote Sensing, 10.1109/TGRS.2019.2900026

THEIA L2A production… SENTINEL-2

SENTINEL-2 monthly synthesis: September 2019

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