PLEIADES HIGH RESOLUTION OPTICAL SENSORS CALIBRATION BASED ON STARS

A. Meygret, G. Blanchet, C. Latry,
L. Gross-Colzy*, S. Colzy*, A. Kelbert**

**

*

STARS USED AS AN ABSOLUTE REFERENCE FOR ON ORBIT 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

- IVOS 28-29: We have shown that stars can be used for the on orbit calibration of high resolution optical sensors using PLEIADES 1A

OVERVIEW OF PLEIADES HR MISSION & SATELLITE

MISSION

Spatial resolution:
Panchromatic : 70 cm
XS (B, G, R, NIR) : 2.80 m
Simultaneous PA + XS acquisition
Swath: 20 km

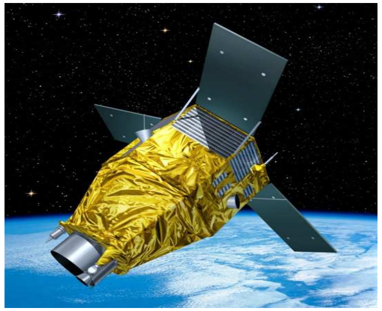
Mode	Band	Spectral characteristics
Multi spectral	1	430 – 550 nm
	2	490 – 610 nm
	3	600 – 720 nm
	4	750 – 950 nm
Panchromatic	P	480 – 830 nm

SATELLITE

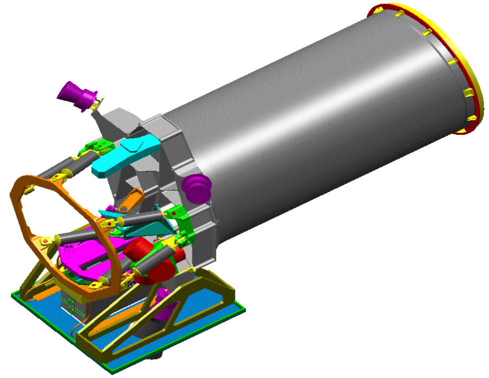
- Mass : < 1 T
- Power : Lithium-ion batteries
Rigid AsGa solar panels

- 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



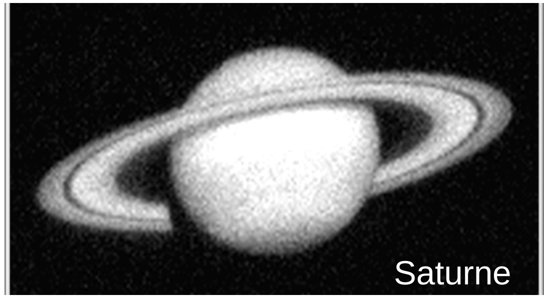
- Korsch camera
- Focal length 12.90m
- Diameter 0.65m

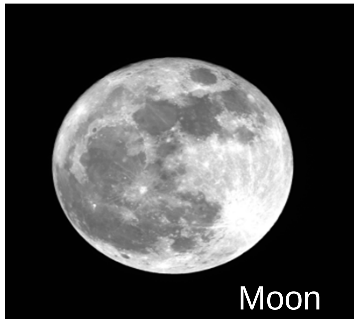
- PA retina : TDI detector
- XS retina : four color CCD

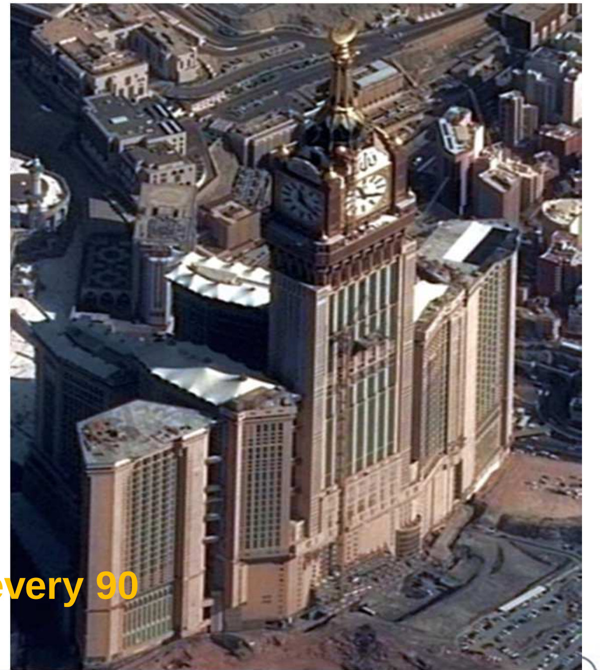
- 12 bit quantization
- On-board detectors normalization
- Wavelet compression:
from 1.4 to 3.33 bits/pixel

PHR-1A launch: December 17, 2011
PHR-1B launch: December 2, 2012

EXAMPLE OF PLEIADES AGILITY



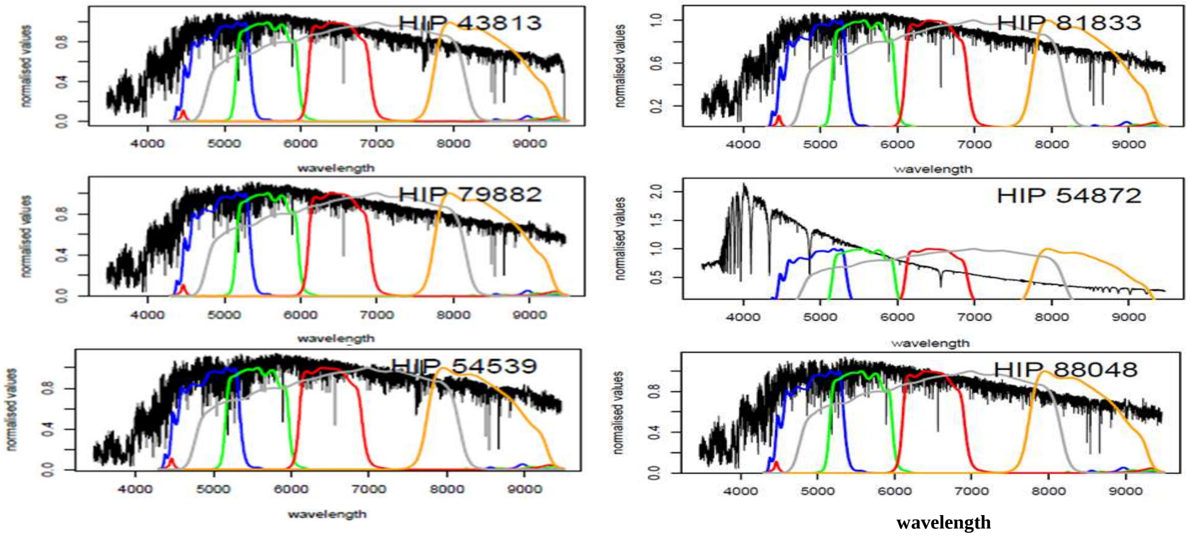




Mecca "tower clock" viewed by PLEIADES 1B every 90 sec in a single pass

SELECTED STARS : SPECTRAL IRRADIANCE

☞ Use of INDO-US library



HIP 54872 seen by PLHR-1A (B0)

Selection criteria:

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

Library	Names	Library file	Hip code	B0	B1	B2	B3	PAN
					L(W/m2/sr/µm)			
INDOUS	HD97603	97603.fits	54872	261,07	202,44	134,40	70,60	2303,26
INDOUS	HD96833	96833.fits	54539	122,27	134,23	135,04	108,84	2073,08
INDOUS	HD76294	76294.fits	43813	111,33	118,94	113,23	86,08	1750,53
INDOUS	HD146791	146791.fits	79882	100,29	107,14	101,99	77,64	1581,39
INDOUS	HD163917	163917.fits	88048	91,41	97,66	93,14	70,80	1442,96
INDOUS	HD150997	150997.fits	81833	79,75	85,22	81,08	61,76	1257,87

STARS USED FOR RADIOMETRIC CALIBRATION

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

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

With:

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

- **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/m^2/Å**

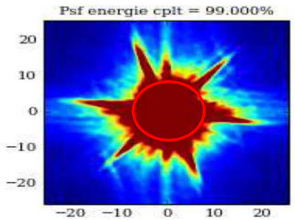
CALIBRATION PRINCIPLE

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 **(importance of the offset 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 absolute calibration and MTF 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.

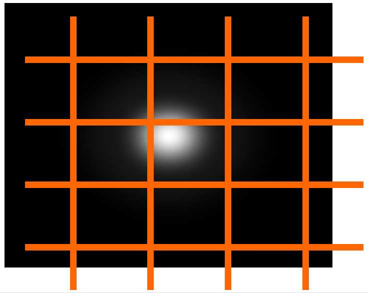
THE RADIOMETRIC MODEL

For each star p, the radiometric model 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
- MTF=FT(PSF), normalized
- l,m are spatial frequencies
- s is the oversampling factor
- ramp(dx_p,dy_p) is the phase ramp corresponding to a shift (dx_p,dy_p) for star p
  $\Rightarrow$ 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 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 equation system

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

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

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

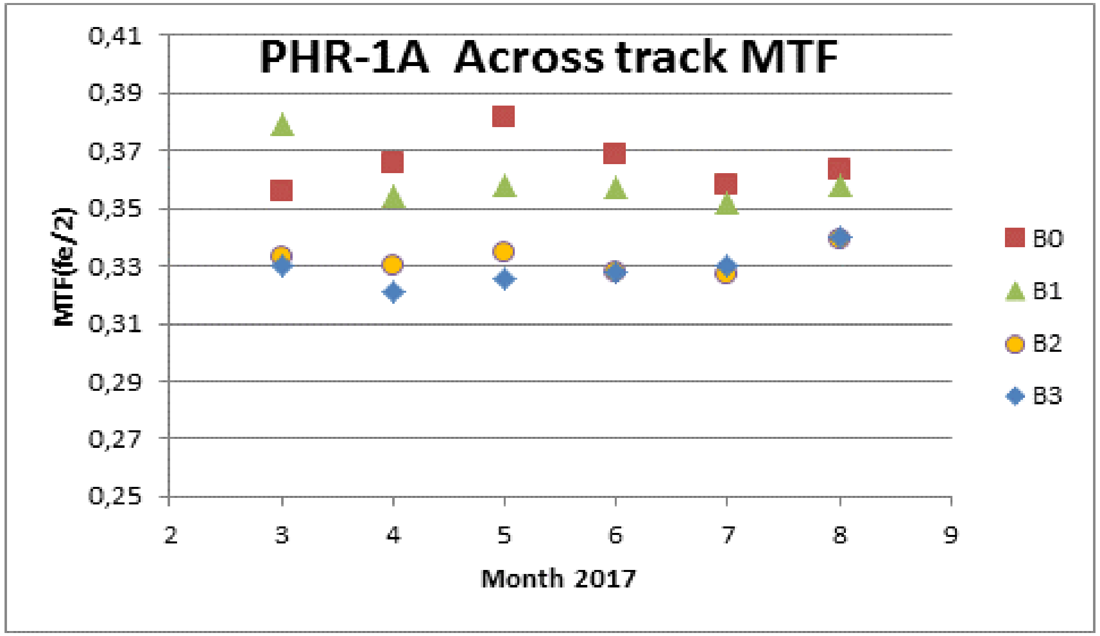
with:

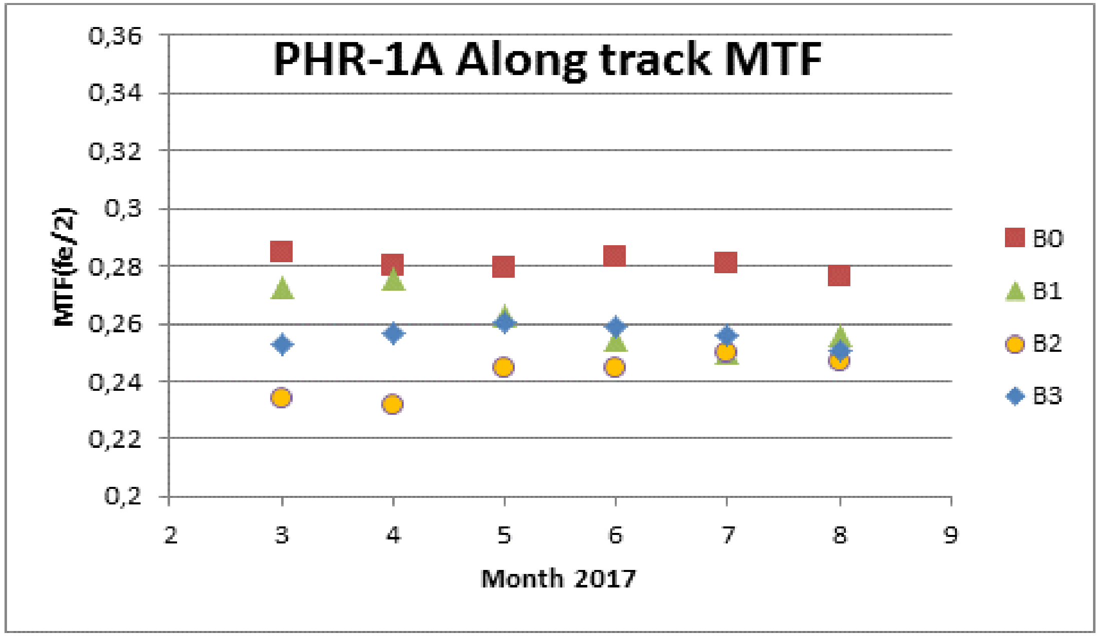
- **W the weight matrix: W(p,p)=L(p) ∀p=1,… nb_star**
- **W(p,p)=1, ∀p>nb_star**

STAR BASED CALIBRATION: MTF RESULTS

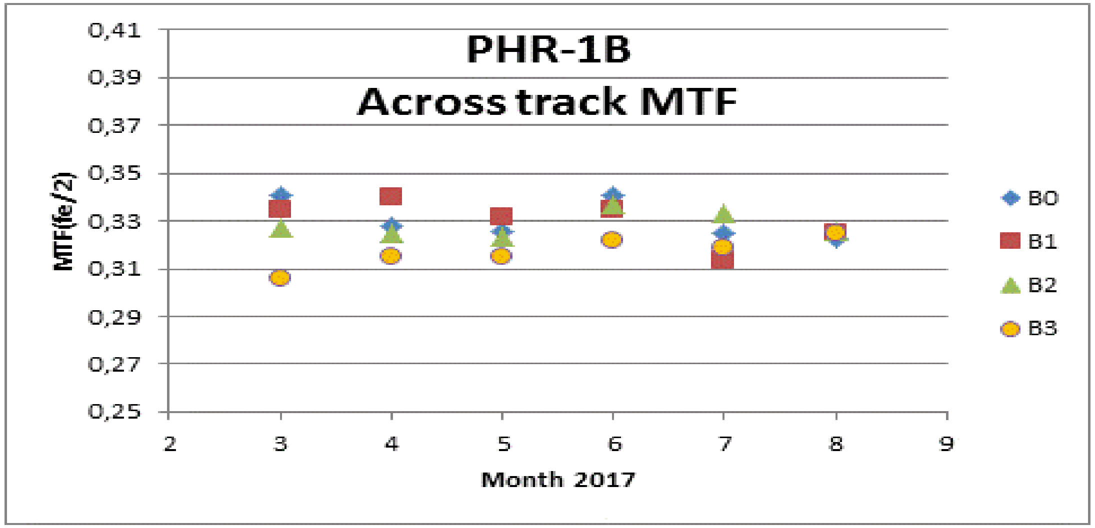
PLEIADES 1A and 1B data acquired between february 2017 and september 2017 for 6 stars: 12 to 18 images per month and satellite

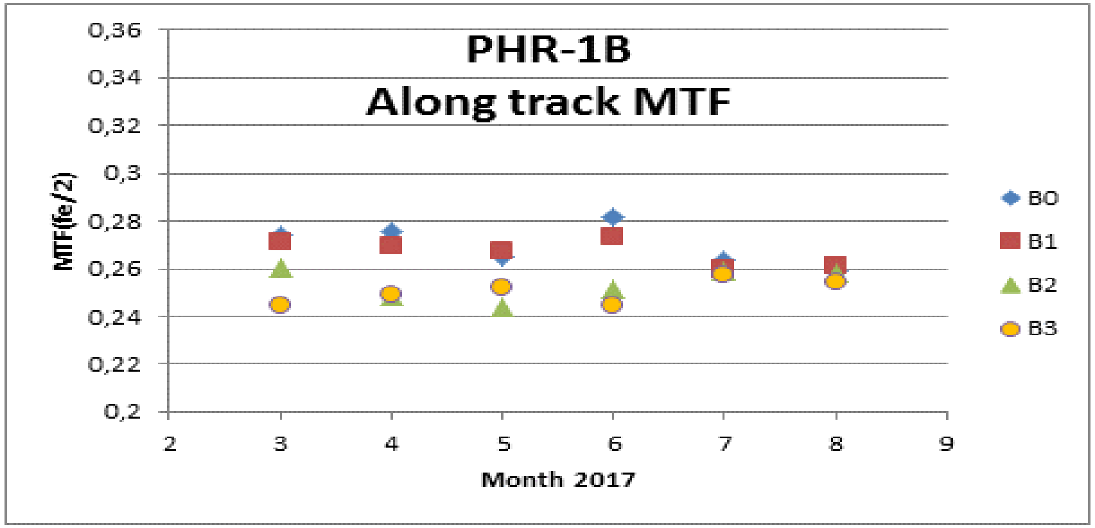
- **42 to 51 mesureaments for each equation system considering a shifting window of 3 months**
- **Oversampling factor = 3**

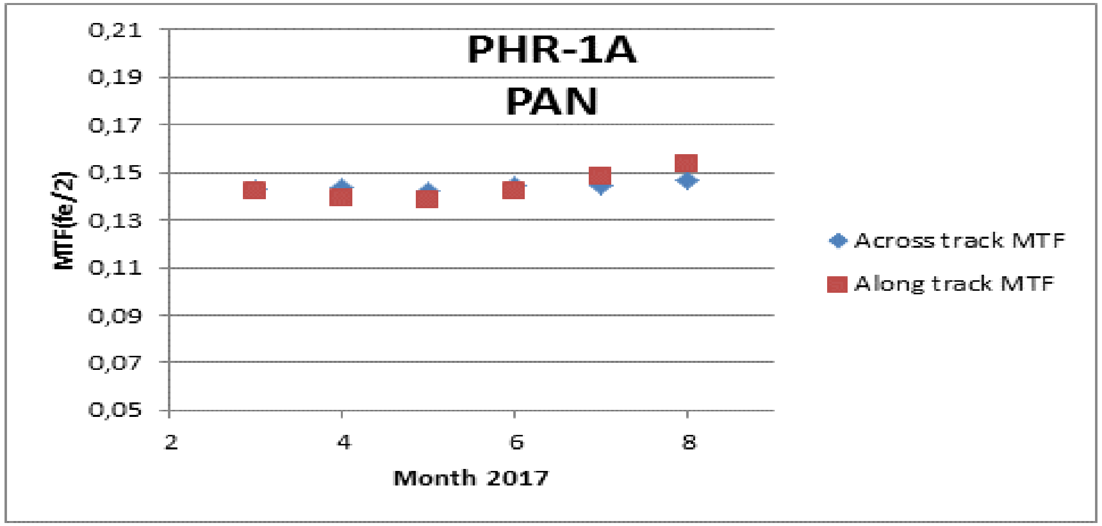


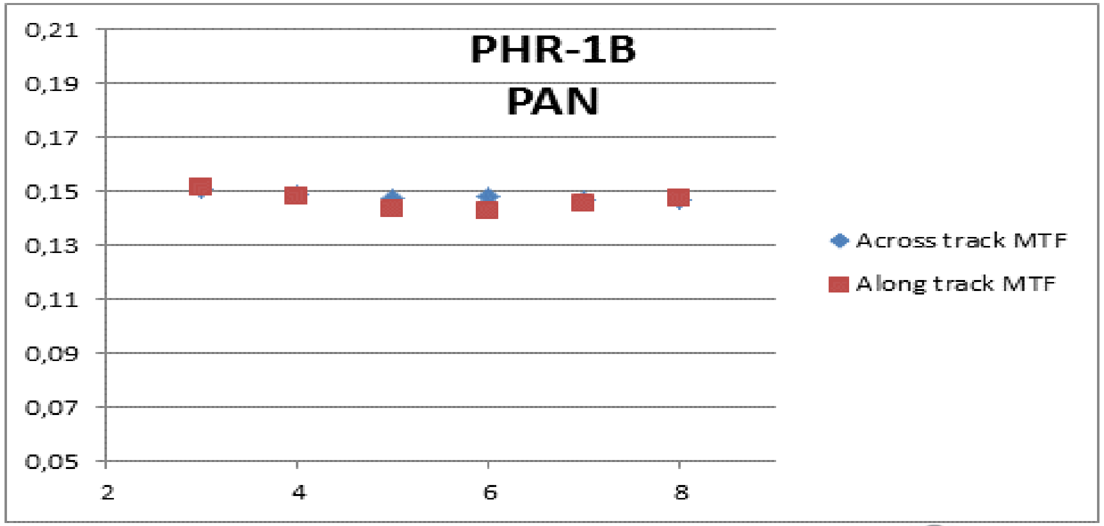


STAR BASED CALIBRATION: MTF RESULTS

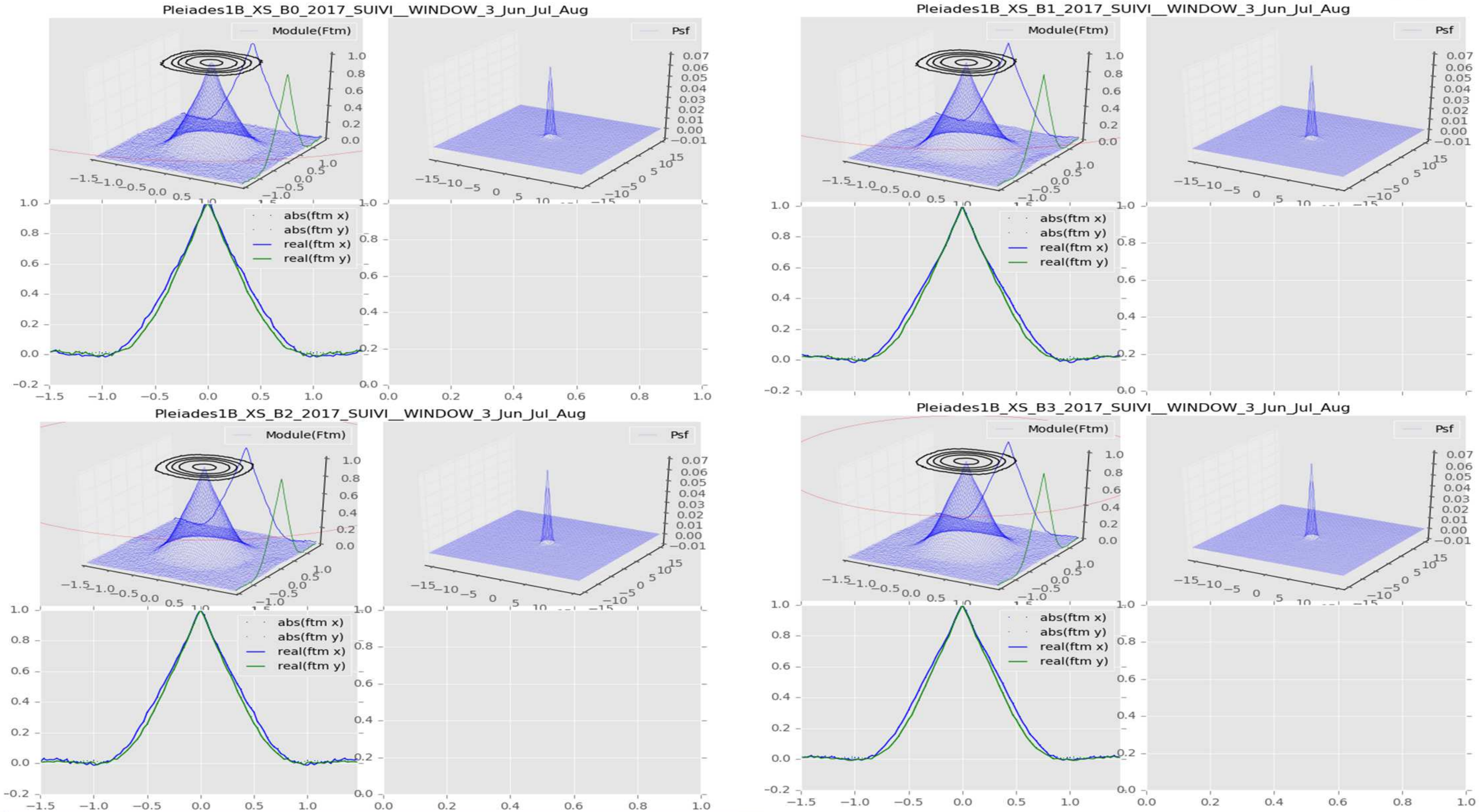




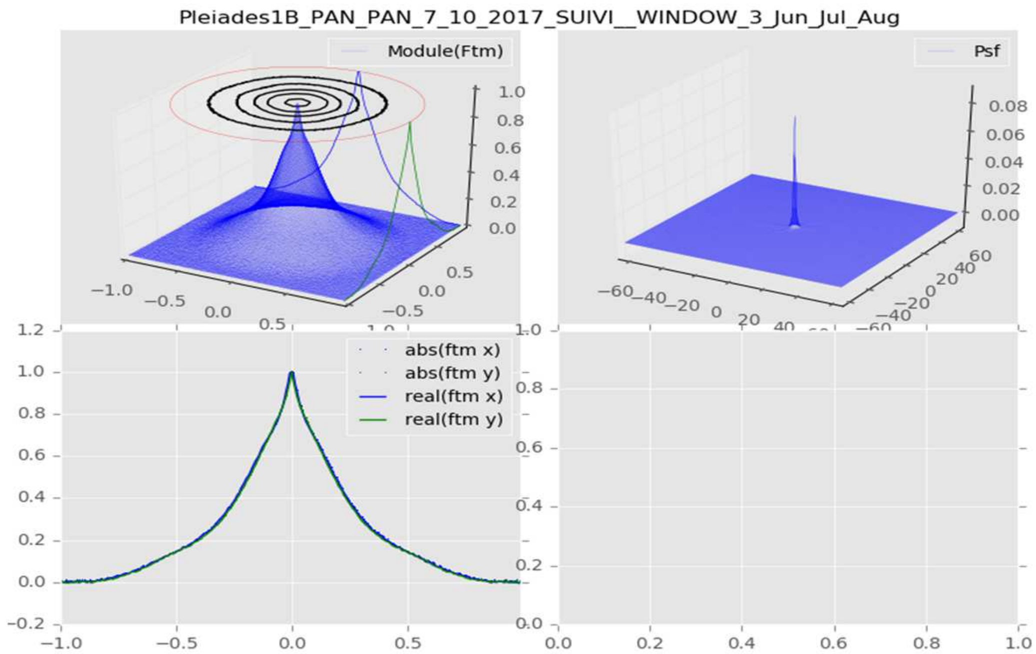


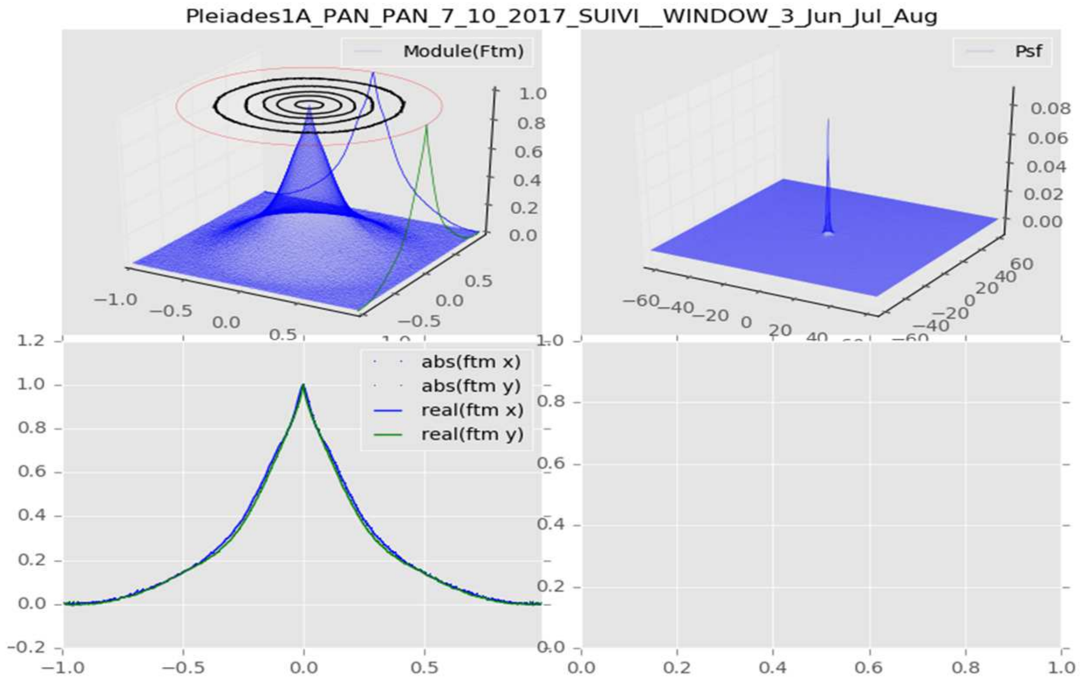


STAR BASED CALIBRATION: MTF RESULTS – PHR1B XS



STAR BASED CALIBRATION: MTF RESULTS – PHR-1A&1B PAN





☺ Very weak noise on the retrieved MTF

STAR BASED CALIBRATION: MTF RESULTS

PHR-1A MTF (fe/2)	MTF across track	MTF along track	Requirement (>)	MTF across track official	MTF along track official
PAN	0,14	0,14	0,08	0,16	0,16
B0	0,37	0,28	0,2	0,33	0,28
B1	0,36	0,26	0,2	0,32	0,28
B2	0,33	0,24	0,2	0,32	0,25
B3	0,33	0,26	0,2	0,32	0,26

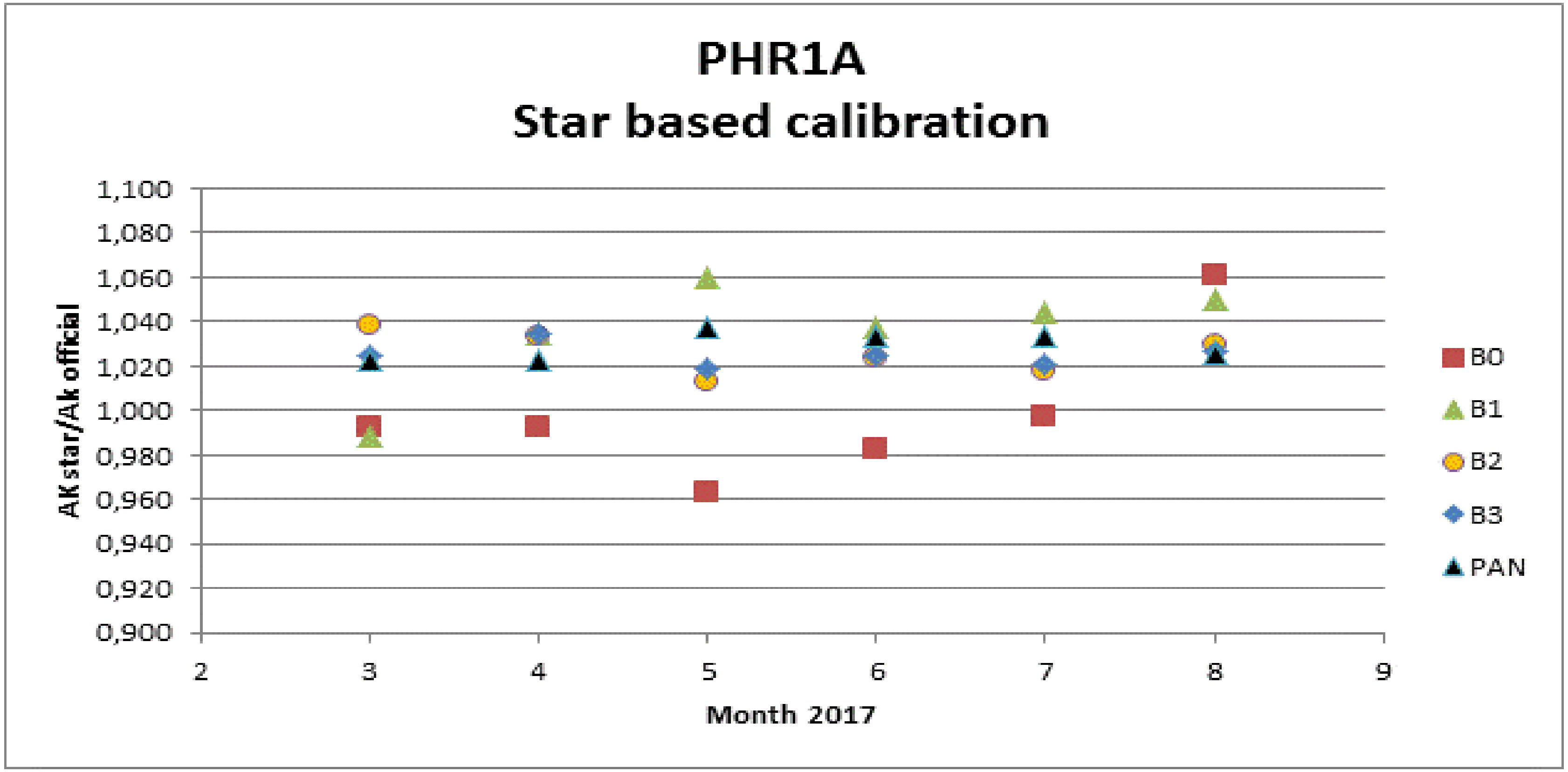
Synthesis for the period february 2017 - september 2017

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	0,15
B0	0,33	0,27	0,2	0,29	0,27
B1	0,33	0,27	0,2	0,3	0,28
B2	0,33	0,25	0,2	0,32	0,27
B3	0,32	0,25	0,2	0,31	0,27

⇒ **Good consistency with the official MTF**

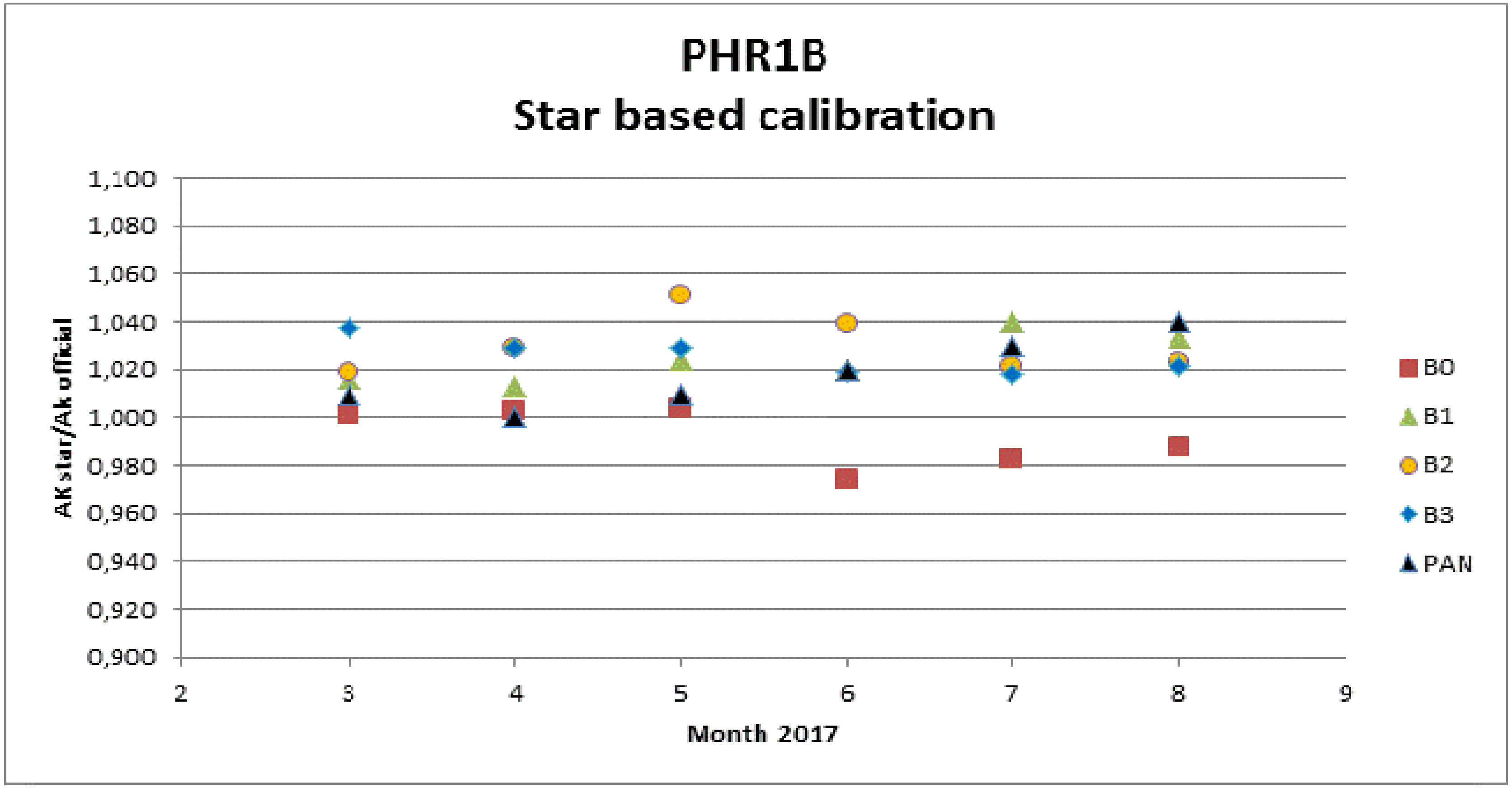
⇒ **Slight difference for B0 and B1 bands across the track: partially due to the aliasing stronger for short wavelengths (oversampling for official MTF = 4)**

STAR BASED CALIBRATION RESULTS



⇒ **Good stability of PHR-1A calibration measurements over 6 months**

STAR BASED CALIBRATION RESULTS



⇒ **Good stability of PHR-1B calibration measurements over 6 months**

STAR BASED CALIBRATION RESULTS

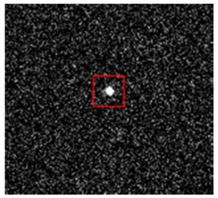
PHR-1A	B0	B1	B2	B3	PAN
Ak star / Ak official	0,998	1,036	1,026	1,025	1,029
Standard deviation	0,030	0,022	0,008	0,005	0,006

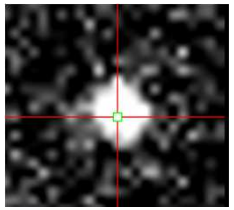
PHR-1B	B0	B1	B2	B3	PAN
Ak star / Ak official	0,992	1,024	1,030	1,025	1,018
Standard deviation	0,011	0,009	0,011	0,007	0,013

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

CONCLUSION

- It is possible to simultaneously retrieve MTF and absolute calibration using stars
- Very good calibration and MTF results for both PLEIADES satellites
- Operational at CNES for high resolution optical sensors
- Oversampling factor to be optimized but constrained by the number of observations





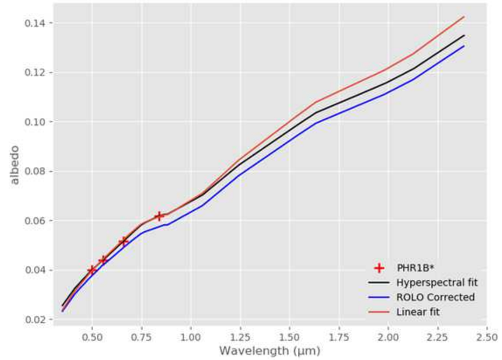
Next step : ROLO moon albedo model correction

- **PHR-1A used as a transfer radiometer to correct ROLO moon albedo model for its spectral bias and PHR-1B for its phase dependency (cf. IVOS 29 & SPIE 2017 Earth Observing Systems XXII - vol 10402)**
- **PHR-1B moon images acquired since the launch were reprocessed with optimized radiometric processing parameters**
- **ROLO albedo model correction based on these new star results: validation on going**

$$\rho_{ROLO\ corrected}(\lambda) = b(\lambda) * \rho_{ROLO}(\lambda) * \sum_{k=0}^{9} a_k\, g^k$$

☺ See IVOS 31…

Spectral correction



+ libration correction…

Phase angle correction