The stars: an absolute reference for on-orbit calibration Application to PLEIADES 1A

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CEOS/WGCV/IVOS, Beijing 18-21 july 2016

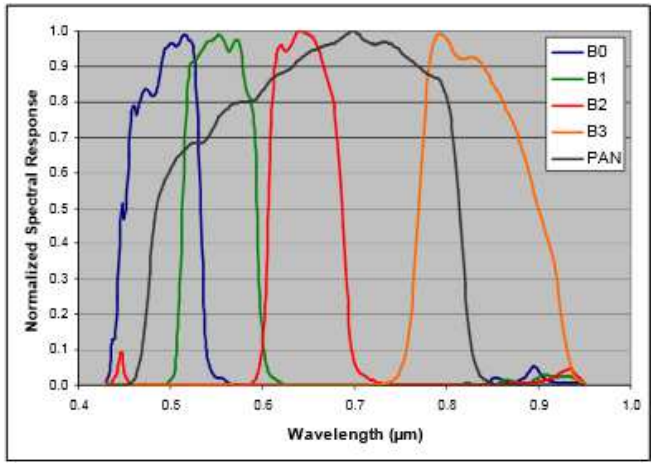
THE STARS: AN ABSOLUTE REFERENCE FOR ON ORBIT CALIBRATION

- The spectral irradiance of some stars is known with a very high accuracy (close to 1%)
- No atmosphere to manage…
- They are regularly used by astrophysicists to calibrate their instruments
- The objective of this study was :
  - to demonstrate that they can be used for the on orbit calibration of high resolution optical sensors
  - To use PLEIADES 1A thanks to its agility for this demonstration

PLEIADES MISSION

Spatial resolution:

- **Panchromatic: 0,70 m (product resampled @ 0.5m to improve robustness to ground processing)**
- **XS (B, G, R, NIR): 2.80 m**

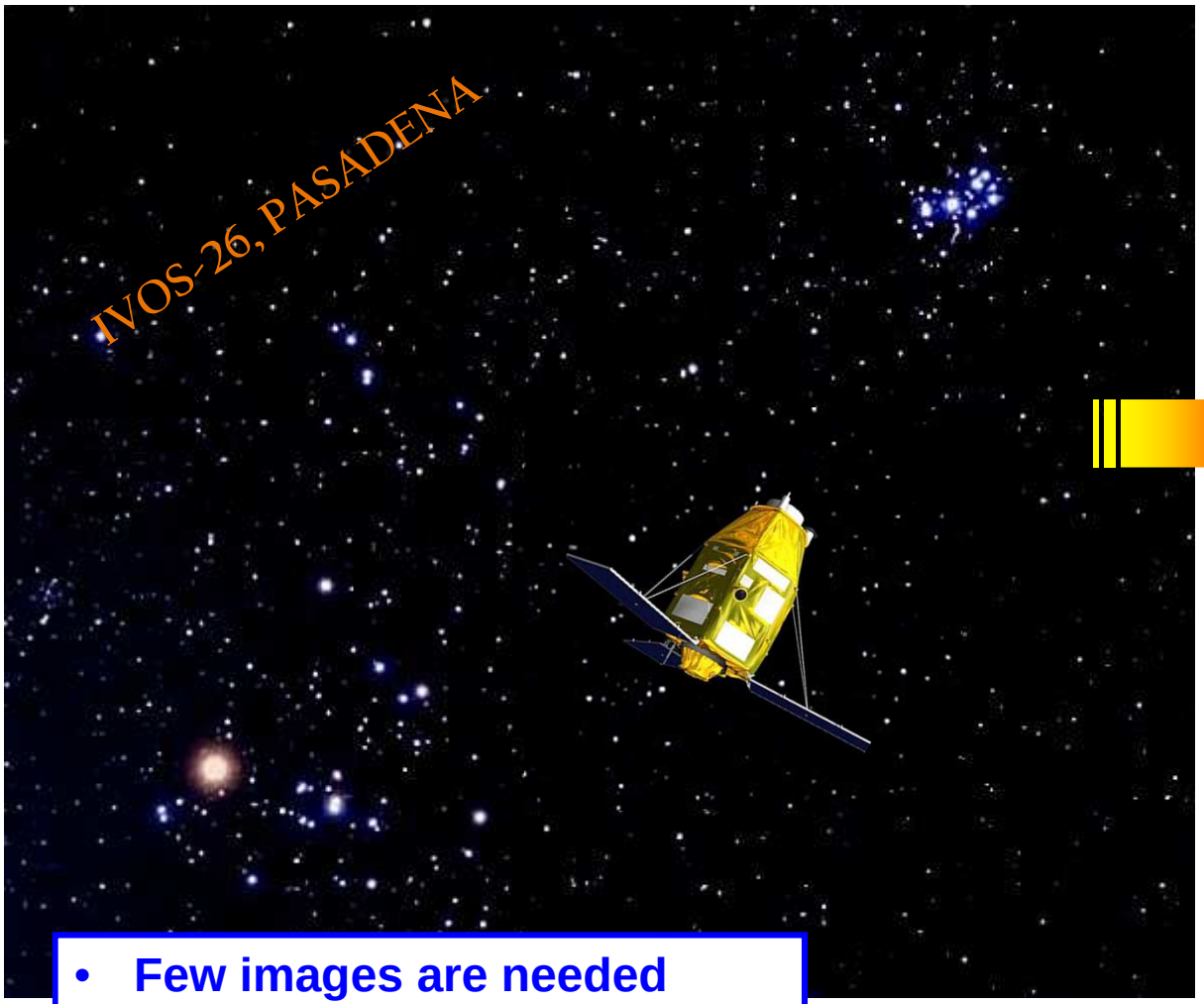


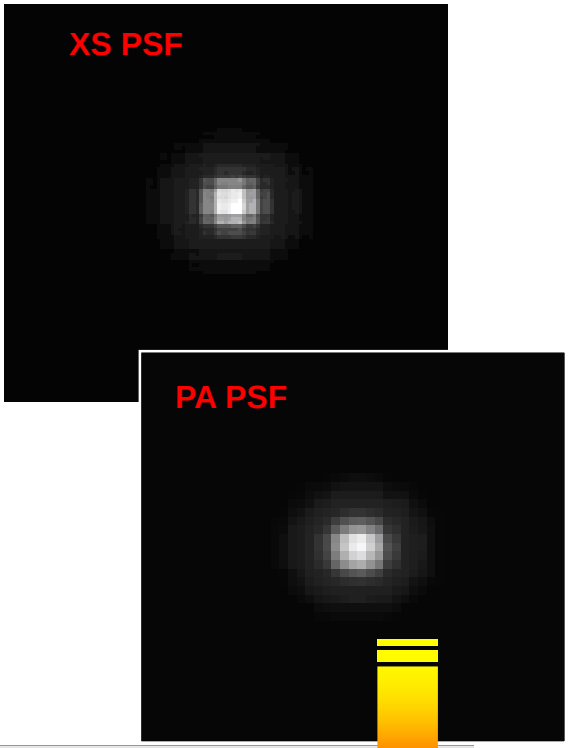
- **PHR1A launch: December 17, 2011**
- **PHR1B launch: December 2, 2012**

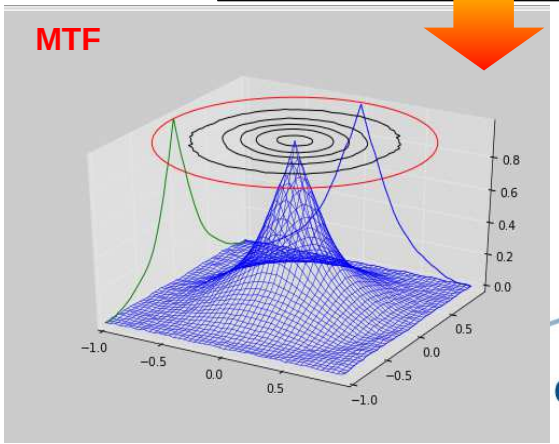
Swath: 20 km

Revisit Capability: 1 day with 2 satellites

ASSESSING THE RESOLUTION (MTF) WITH STARS





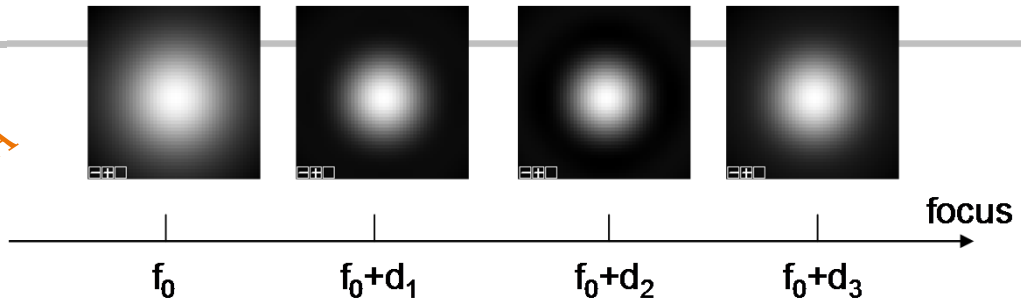


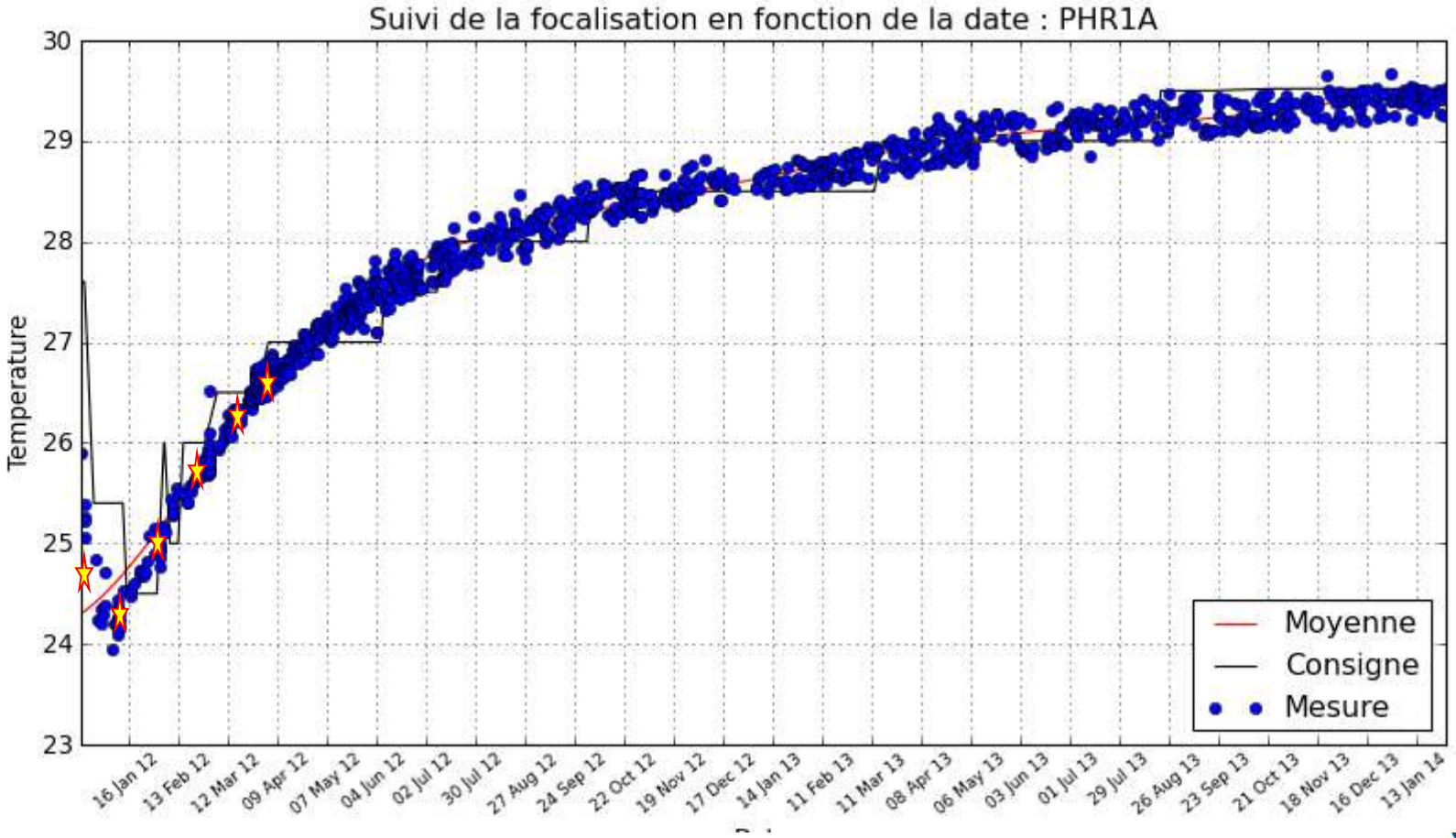
- Few images are needed
- No atmosphere
- Good accuracy
- 2D MTF assesment

cnes

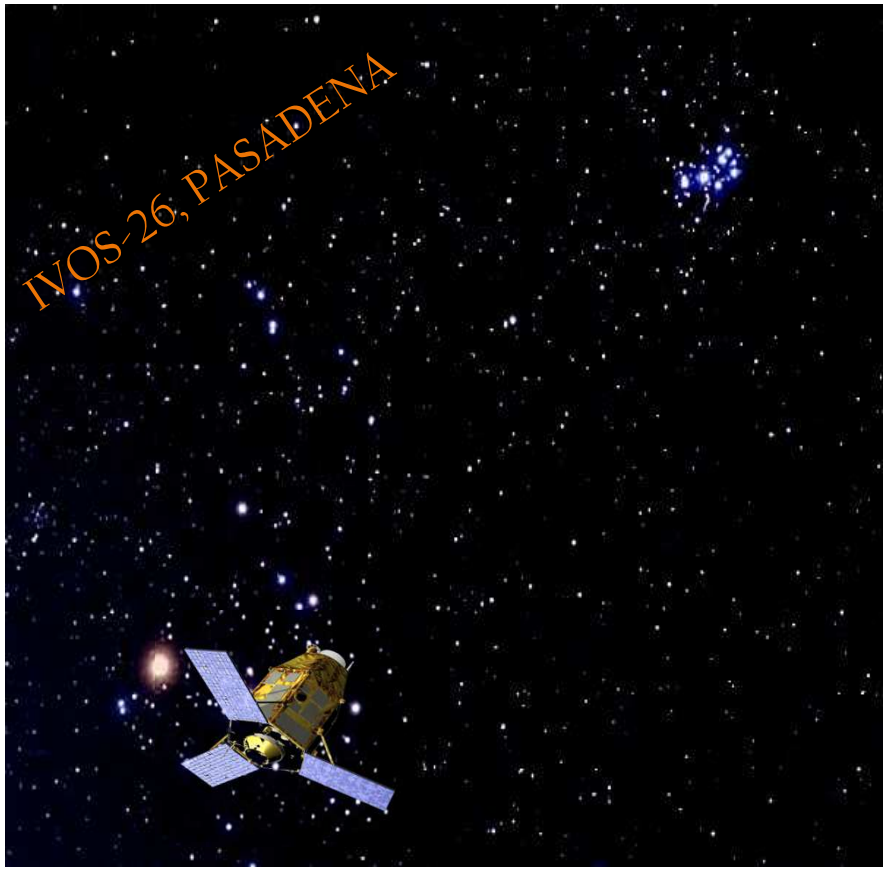
MONITORING THE BEST FOCUS

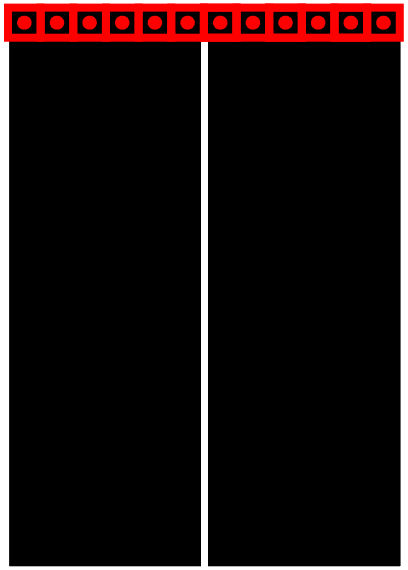
IVOS-26, PASADENA



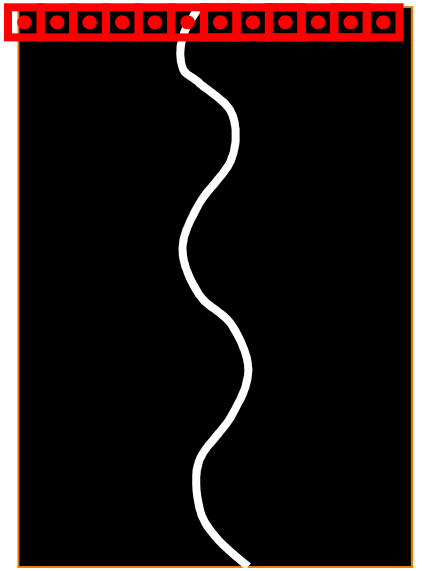


STAR ACQUISITION IN STEADY MODE FOR IN-FLIGHT MICROVIBRATIONS ASSESSMENT

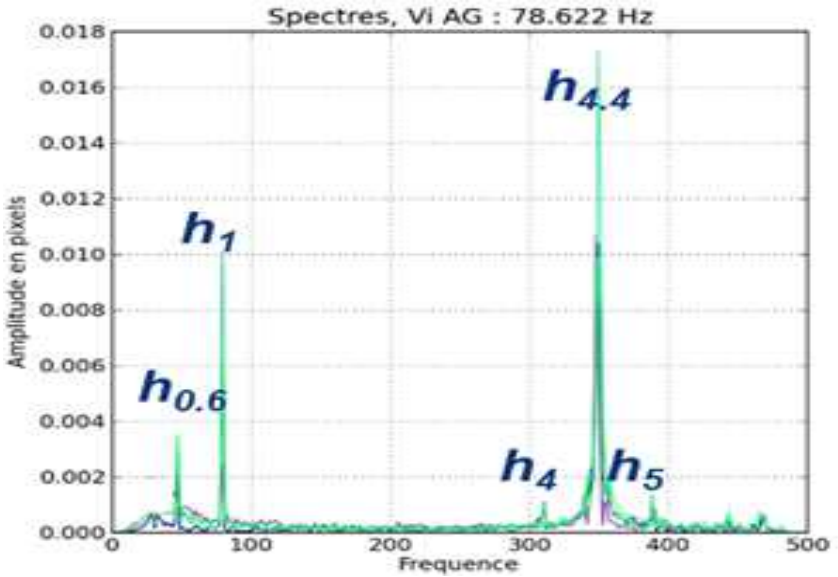




without µvib



with µvib

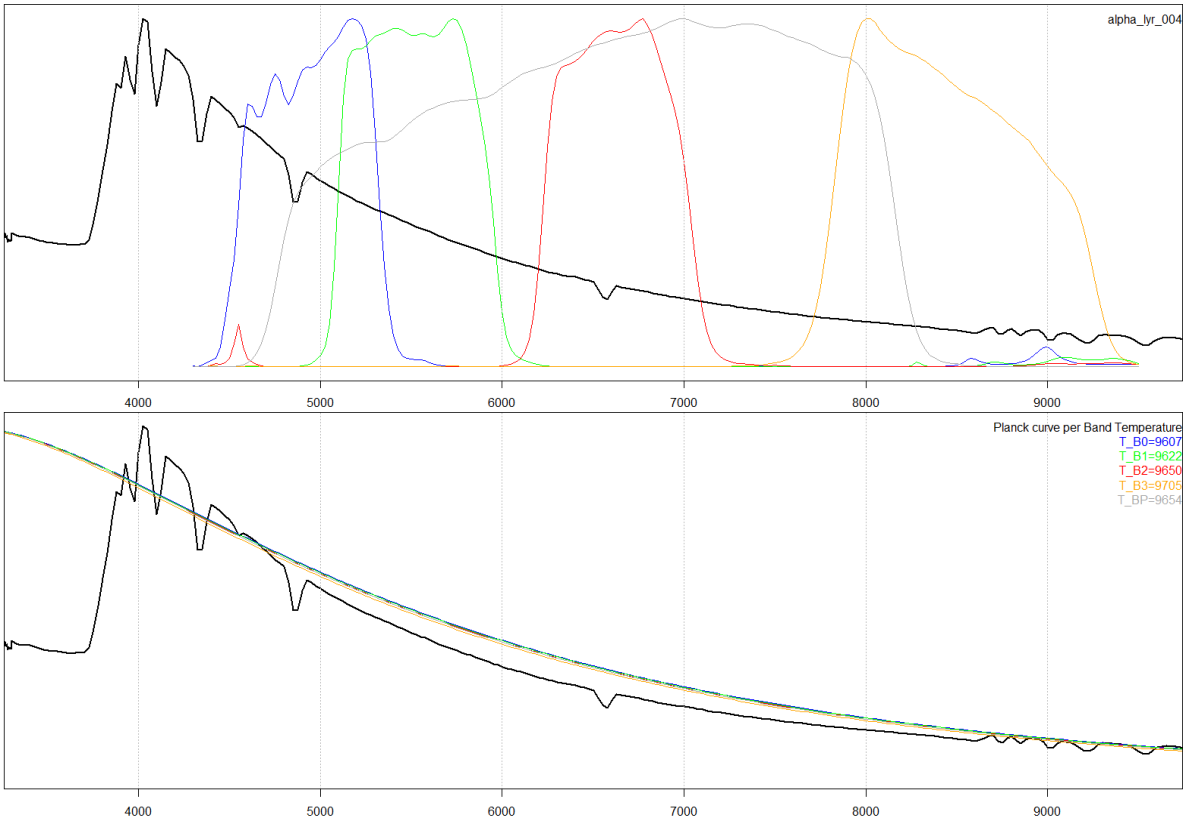


- ☞ **Microvibration amplitude <0.02 pixels**
- ☞ **Accuracy: few nrad**

WHICH STARS FOR RADIOMETRIC CALIBRATION?

3 libraries used to select stars:

- ✓**CALSPEC: absolute irradiance spectrum (92 stars)**
- ✓**MILES: normalized irradiance spectrum (945 stars)**
- ✓**INDO-US: normalized irradiance spectrum (1245 stars)**



DIFFERENT TYPE OF STARS

Star	*	Star	use?
· *inCl	*iC	Star in Cluster	
· *inNeb	*iN	Star in Nebula	
· *inAssoc	*iA	Star in Association	
· *in**	*i*	Star in double system	
· V*?	V*?	Star suspected of Variability	
· Pec*	Pe*	Peculiar Star	
· · HB*	HB*	Horizontal Branch Star	
· · YSO	Y*O	Young Stellar Object	
· · · Ae*	Ae*	Herbig Ae/Be star	
· · Em*	Em*	Emission-line Star	yes
· · · Be*	Be*	Be Star	
· · BlueStraggler	BS*	Blue Straggler Star	
· · RGB*	RG*	Red Giant Branch star	
· · AGB*	AB*	Asymptotic Giant Branch Star (He-burning)	
· · · C*	C*	Carbon Star	
· · · S*	S*	S Star	yes
· · SG*	sg*	Evolved supergiant star	
· · · RedSG*	s*r	Red supergiant star	
· · · YellowSG*	s*y	Yellow supergiant star	
· · · BlueSG*	s*b	Blue supergiant star	
· · post-AGB*	pA*	Post-AGB Star (proto-PN)	
· · WD*	WD*	White Dwarf	
· · · pulsWD*	ZZ*	Pulsating White Dwarf	
· · low-mass*	LM*	Low-mass star (M<1solMass)	
· · brownD*	BD*	Brown Dwarf (M<0.08solMass)	
· · Neutron*	N*	Confirmed Neutron Star	
· · OH/IR	OH*	OH/IR star	
· · CH	CH*	Star with envelope of CH type	
· · pMS*	pr*	Pre-main sequence Star	
· · · TTau*	TT*	T Tau-type Star	
· · WR*	WR*	Wolf-Rayet Star	
· PM*	PM*	High proper-motion Star	yes
· HV*	HV*	High-velocity Star	
· V*	V*	Variable Star	
· · Irregular_V*	Ir*	Variable Star of irregular type	no
· · · Orion_V*	Or*	Variable Star of Orion Type	no
· · · Rapid_Irreg_V*	RI*	Variable Star with rapid variations	no
· · Eruptive*	Er*	Eruptive variable Star	
· · · Flare*	Fl*	Flare Star	
· · · FUOr	FU*	Variable Star of FU Ori type	no
· · · Erupt*RCrB	RC*	Variable Star of R CrB type	no
· · · RCrB_Candidate	RC?	Variable Star of R CrB type candiate	no
· · RotV*	Ro*	Rotationally variable Star	no
· · · RotV*alf2CVn	a2*	Variable Star of alpha2 CVn type	no
· · · Pulsar	Psr	Pulsar	no

SPECTRUM CONVERSION TO ABSOLUTE IRRADIANCE

$$E_{\lambda_n} = \frac{E_{\lambda\_norm_n} E_{5556\_abs}}{E_{5556\_norm}}$$

With:

$$E_{5556A} = 10^{(\log(E_{5556A}(Vega)x\,2.512^{-M}) - 0.006 + 0.018\,(B-V))}$$

- **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**
- **$E_{5556A(vega)}$ = 3.56 *10^{-12} W/m^2/Å**

STARS SELECTION FOR CALIBRATION

- **Radiance test: $L_{k_{min}} < L_k < L_{k_{sat}}$**

$$L_k = \left(\frac{f}{dx} \right)^2 \cdot E_k$$

*Hypothesis: the star irradiance is fully integrated by one pixel

With:

f: focal length
dx: pixel size
E_k: star equivalent irradiance
k: spectral band

Knowing that due to the MTF only a fraction of the irradiance is collected when the star is perfectly centered on the pixel (~1/3 for PAN band and 2/3 for XS bands)

Bande	PHR1A	PHR1B
PAN	352	342
B0	450	404
B1	443	403
B2	397	362
B3	263	236

$L_k$sat(W/m^2/sr/µm)

- **Type of star:**

Classe	température	Couleur de l'étoile	raies d'absorption
O	> 25 000 K	Bleue	azote, carbone, hélium et oxygène
B	10 000 - 25 000 K	bleue-blanche	hélium, hydrogène
A	7 500 - 10 000 K	Blanche	hydrogène

  - **0, A and B stars with no specific characteristic to advise against**
  - **High proper-motion star: high potential geographic move over years but no irradiance variation**
- **Accessibility according to the season and the satellite position**

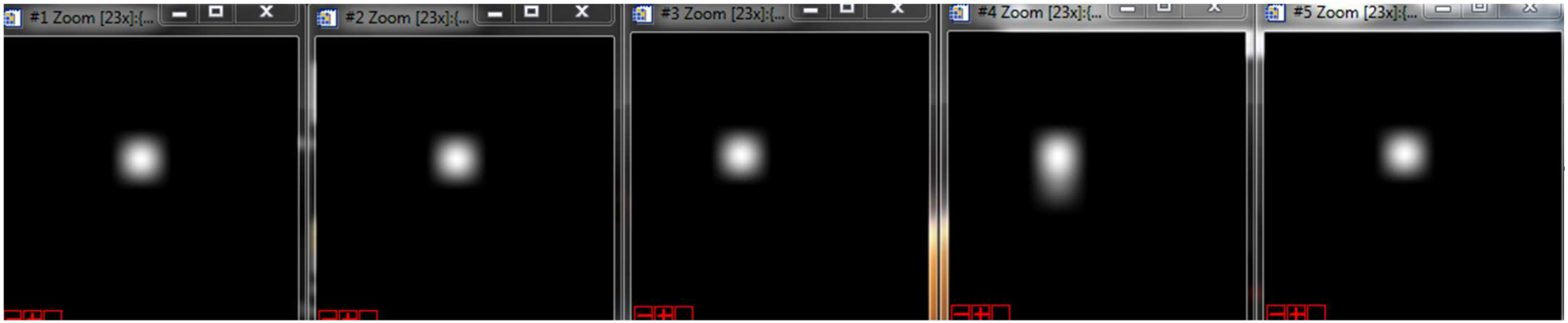
SELECTED STARS

catalogue	Names	talogue file(	Hip	B0	B1	B2	B3	PAN	TDI_optimal	TDI_ptogrammé	Otype
				L(W/m2/sr/µm)							
INDOUS	HD60179	s0262.fits	36849								**
ILES / INDOU	HD000886	s0011.fits / 886.fits	1067								bC**
MILES	HD112413	s0456.fits	63125								**
ILES / INDOU	HD205021	s0800.fits / 205021.fits	106032								bC**
INDOUS	Eta_Uma HD120315	120315.fits	67301	599,16	396,09	235,77	101,44	4232,25	3	13	V*
INDOUS	HD40183	40183.fits	28360								AI*
INDOUS	HD47105	47105.fits	31681								SB*
INDOUS	HD97603	97603.fits	54872	261,07	202,44	134,40	70,60	2303,26	6	7	PM*
INDOUS	HD93813	93294.fits	52943	111,26	122,17	123,05	99,23	1891,76	8	7	PM*
INDOUS	HD96833	96833.fits	54539	122,27	134,23	135,04	108,84	2073,08	7	7	*
INDOUS	HD76294	76294.fits	43813	111,33	118,94	113,23	86,08	1750,53	8	7	*
INDOUS	HD146791	146791.fits	79882	100,29	107,14	101,99	77,64	1581,39	9	7	*
INDOUS	HD204867	204867.fits	106278	141,43	142,01	123,54	78,47	1928,64	7	7	*
INDOUS	HD163917	163917.fits	88048	91,41	97,66	93,14	70,80	1442,96	10	10	PM*
INDOUS	HD135722	135722.fits	74666	81,39	82,13	83,19	63,32	1273,06	11	10	*
INDOUS	HD150997	150997.fits	81833	79,75	85,22	81,08	61,76	1257,87	11	10	PM*
INDOUS	HD 9927	9927.fits	7607	66,01	78,05	83,96	69,50	1269,49	11	10	*

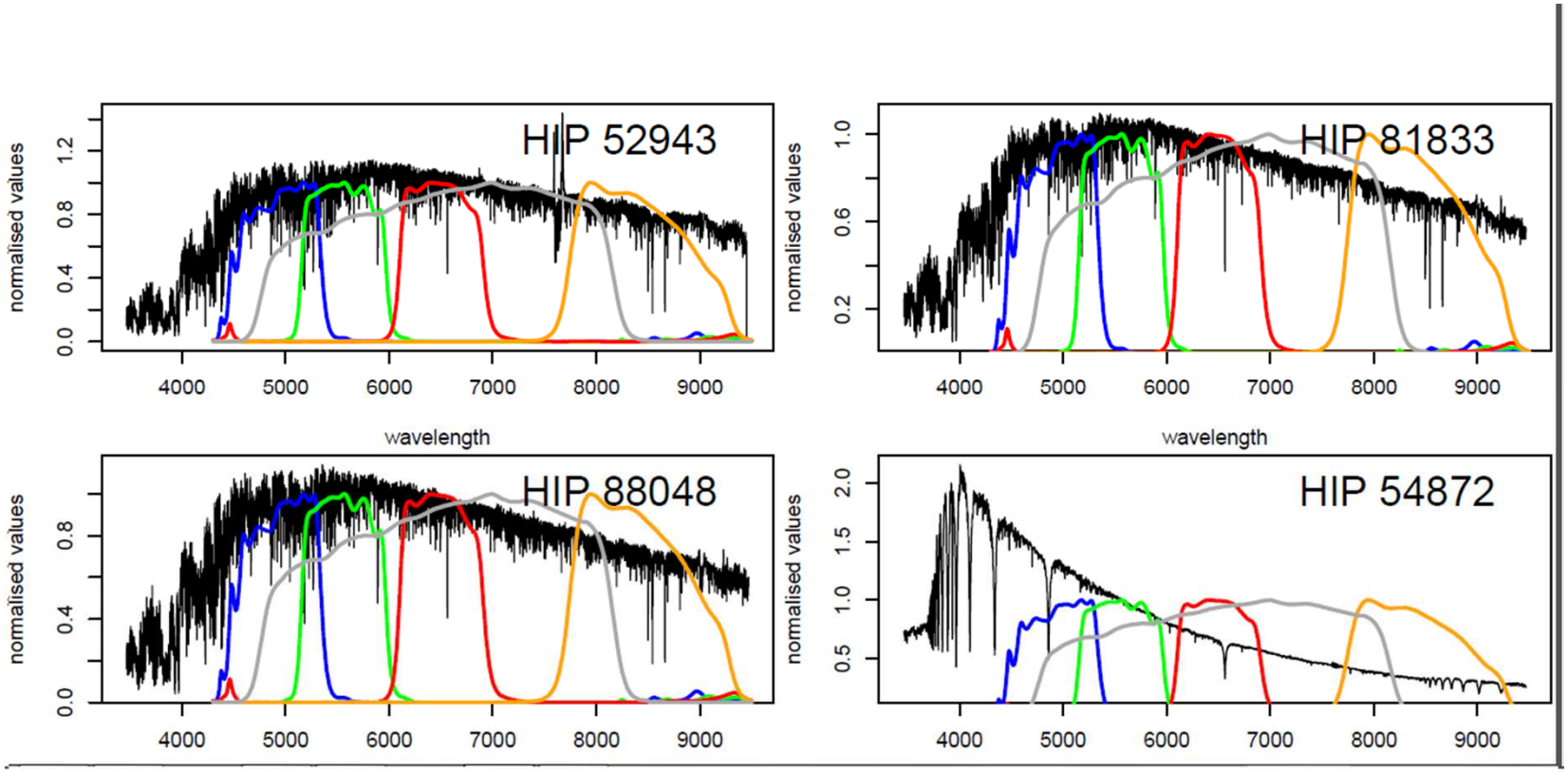
THE PROCESSED IMAGES

- **Automatic identification of the star using their accurate geolocation and Hipparcos catalog**
- **71 images processed**

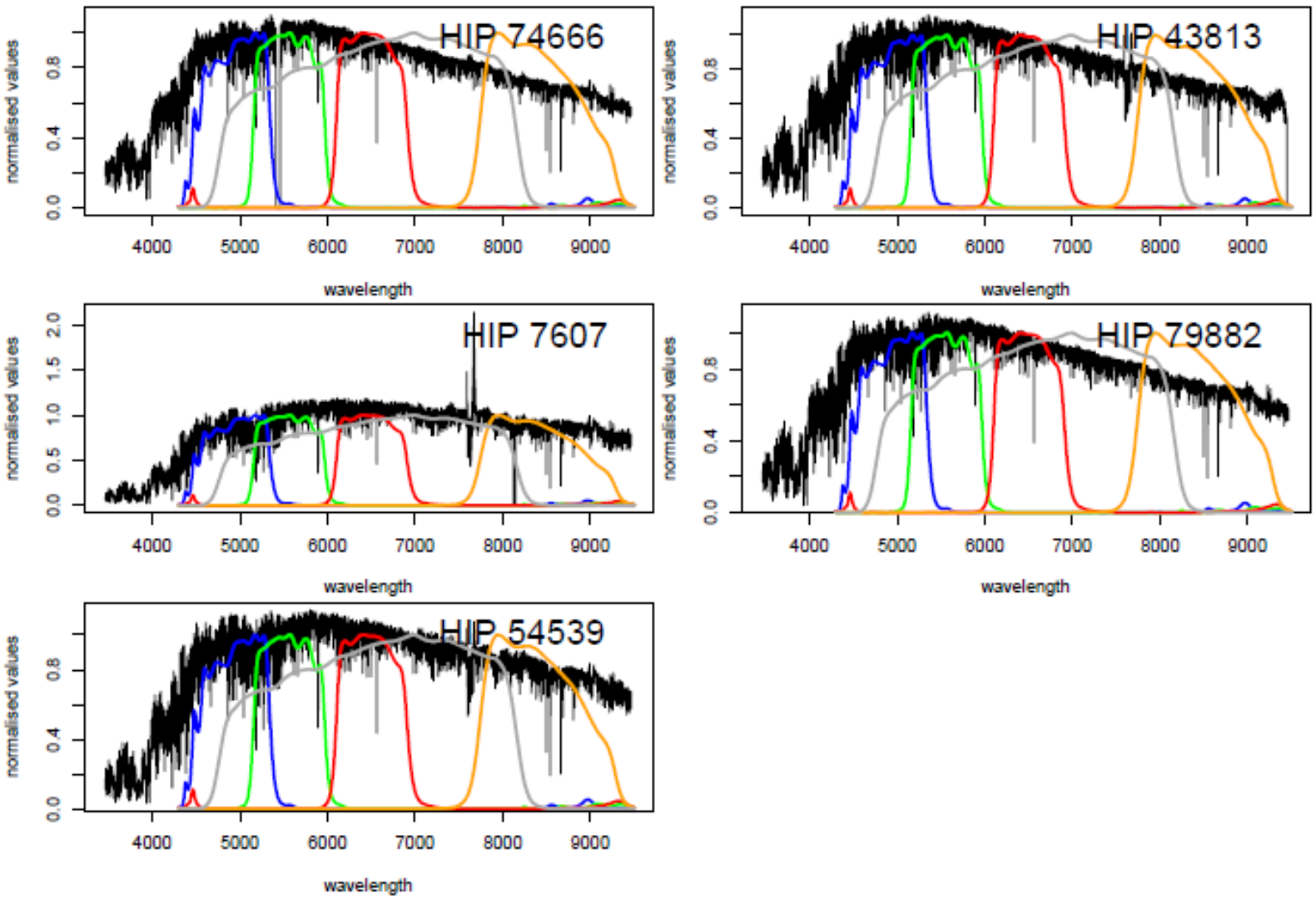
	pm				star				
	Hip 52943	Hip 54872	Hip 81833	Hip 88048	Hip 7607	Hip 43813	Hip 54539	Hip 74666	Hip 79882
B0	10	5	10	10	2	10	10	4	10
B1	10	5	10	10	1	10	10	4	10
B2	10	5	10	10	1	10	10	4	10
B3	10	5	10	10	2	10	10	4	10
PAN	10	3	10	10	1	10	10	4	10



SELECTED STARS : SPECTRAL IRRADIANCE (PM)



SELECTED STARS: SPECTRAL IRRADIANCE



CALIBRATION PRINCIPLE

Absolute calibration coefficient A_k for band k :

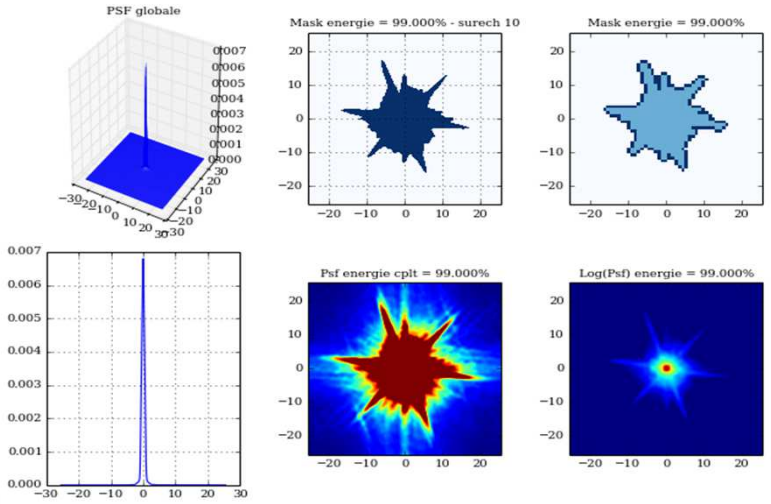
$$A_k = \left(\frac{dx}{f} \right)^2 \cdot \frac{\sum_p Z_k(p)}{E_k}$$

Where :

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

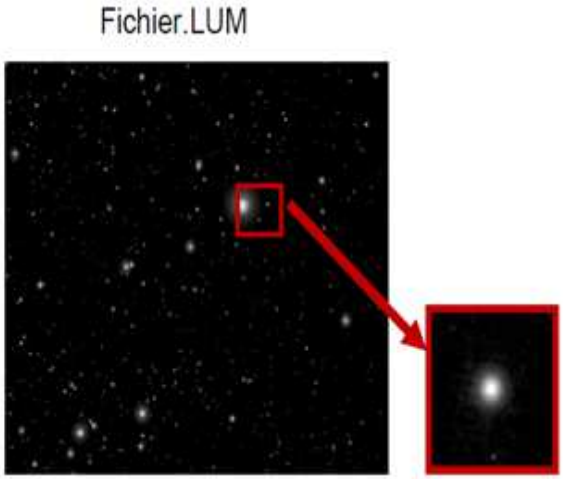
HOW TO INTEGRATE THE USEFUL SIGNAL?

Thresholding the PSF at 98 and 99%



	B0	B1	B2	B3	PAN
98 %	151	169	203	288	728
99 %	449	508	605	816	2142

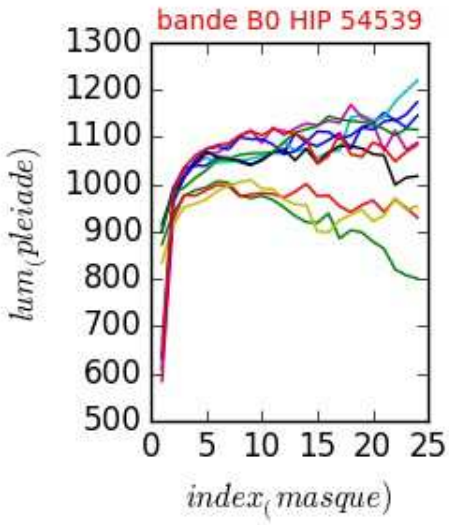
Using a square window

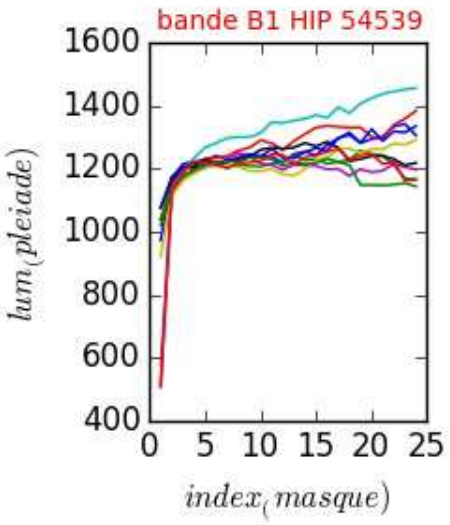


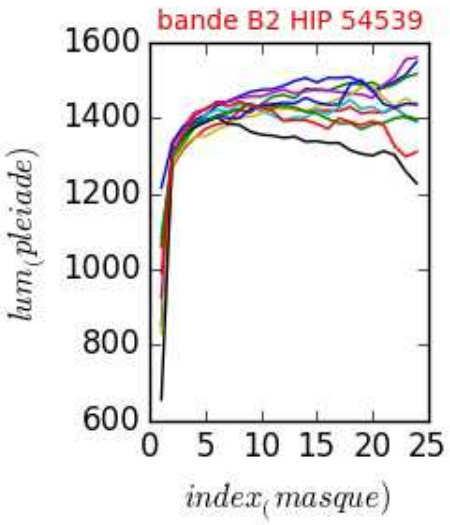
nb de pixel	index masque	Bande				
		B0	B1	B2	B3	PAN
9	1					
25	2					
49	3					
81	4					
121	5					
169	6					
225	7					
289	8					
361	9					
441	10					
529	11					
625	12					
729	13					
841	14					
961	15					
1089	16					
1225	17					
1369	18					
1521	19					
1681	20					
1849	21					
2025	22					
2209	23					
2401	24					

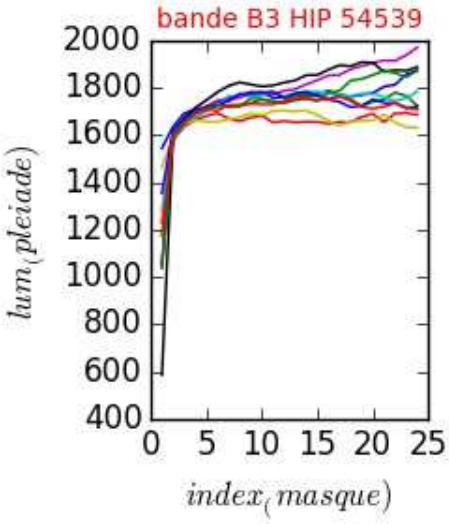
98%
99%

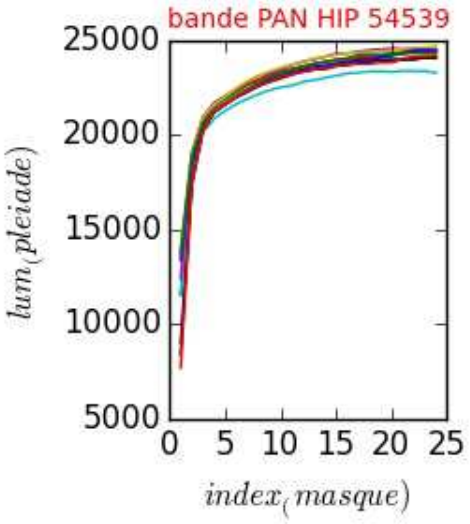
CALIBRATION RESULTS FOR PLEIADES 1A
SENSITIVITY TO THE WINDOW SIZE







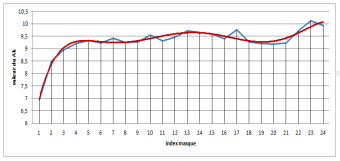




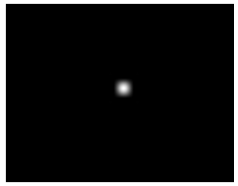
☞The residual signal is not only noise

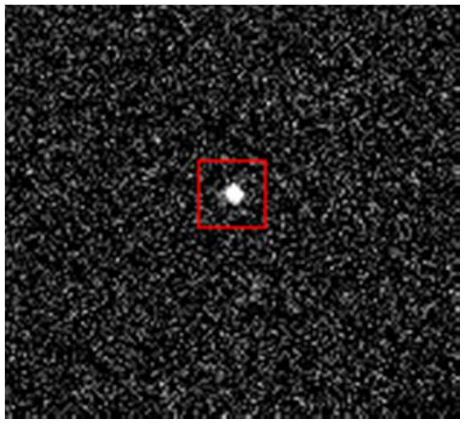
☞Importance of correctly sizing the integration window

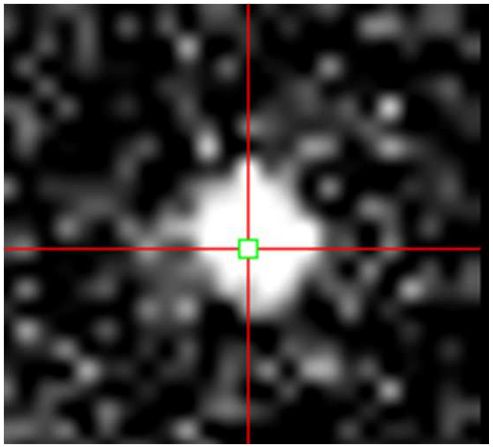
☞ Consistent results obtained by sizing the window according to the PSF or the inflection point



CALIBRATION RESULTS FOR PLEIADES 1A
SENSITIVITY TO THE WINDOW SIZE





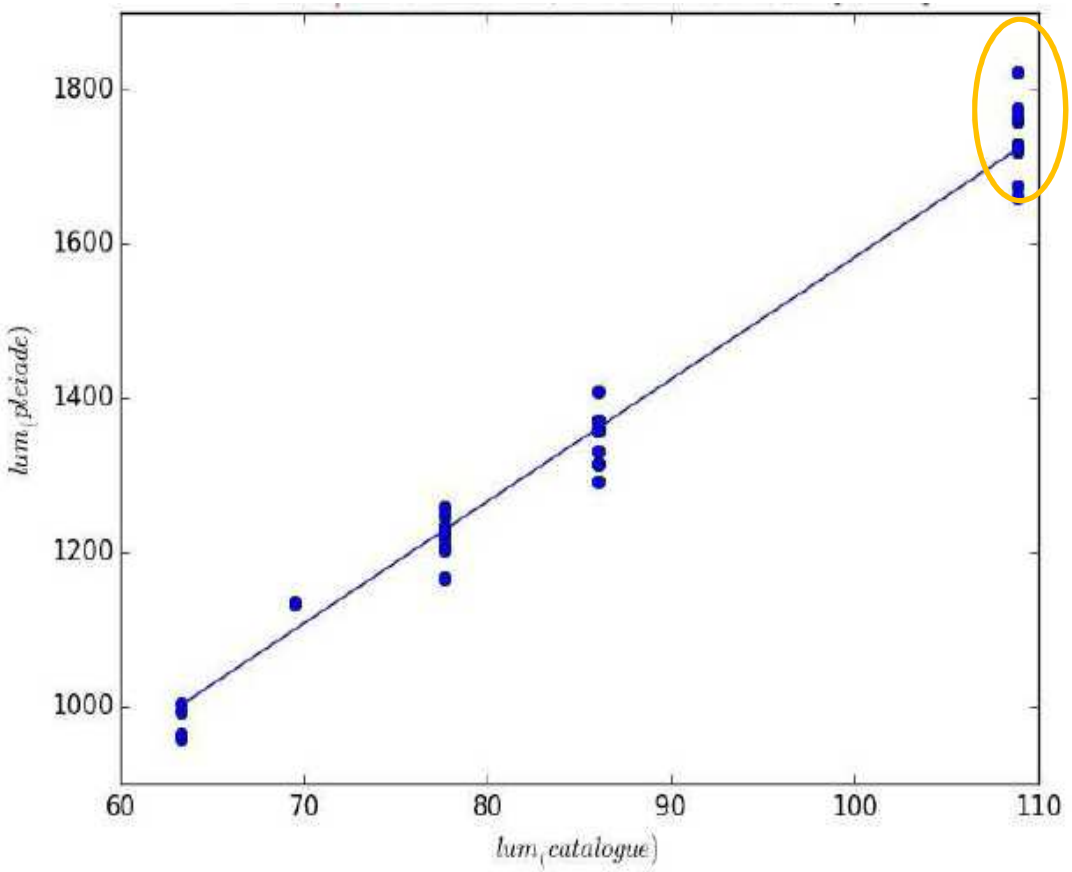


Mean standard deviation (%)	pm and star				
	B0	**B1**	**B2**	**B3**	**PAN**
98%	**4,0**	**2,7**	**2,0**	**1,9**	**0,6**
99%	5,1	3,2	3,8	3,1	1,0

☞**The optimal window size corresponds to 98% of the PSF**

CALIBRATION RESULTS FOR PLEIADES 1A

- **Calibration coefficient for each band assessed by a linear fit on the measured star signal as a function of the « catalog radiance »**

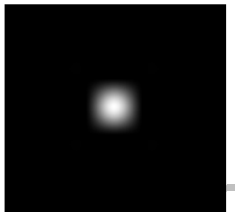


For each star, threshold at 3 sigma

CALIBRATION RESULTS FOR PLEIADES 1A

(Ak(star)-Ak(official)) / Ak(official)		pm and star			
	B0	**B1**	**B2**	**B3**	**PAN**
98%	**-3,0**	**1,2**	**2,0**	**3,2**	**0,1**
99%	-2,9	2,0	1,5	3,7	1,7

- **Very good results compared to the official calibration**
- **Better consistency for PAN band because of the better SNR**
- **Confirmation that the optimal window size corresponds to 98% of the PSF**



CONCLUSION & OUTLOOK

- **Stars provide an accurate absolute reference for the on orbit calibration of high resolution optical sensors**
- **Very good calibration results obtained with PLEIADES 1A (3%)**
- **Routine programmation to consolidate these results and assess the temporal stability**
- **To investigate the deviation for different views of the same star (B0 band)**
- **To select other stars (red)**
- **To build an error budget**
- **To fit ROLO model to star irradiance using PLEIADES1A so as to use the moon as a transfer target for the on orbit calibration of radiometers that cannot view the stars or for which the IFOV does not allow this measurement**
- **To implement the method in MUSCLE-NG (Multi Sensor Calibration Environment)**

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