Progress on Extra-terrestrial Target Based Calibration techniques using PLEIADES-HR satellites

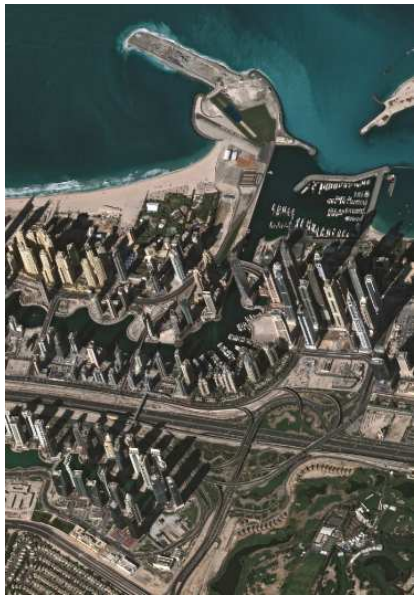
A. Meygret, G. Blanchet, S. Colzy*, F. Mounier*, L. Gross-Colzy*, C. Buil

*

CEOS/WGCV/IVOS, Tucson 15-17 march 2017

OVERVIEW OF PLEIADES HR MISSION & SATELLITE

MISSION

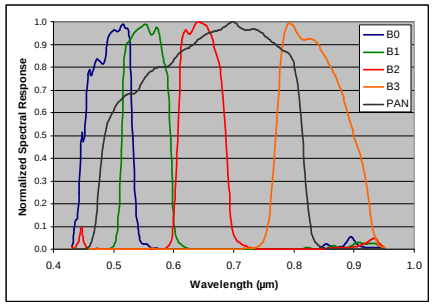


Dubai from PHR1A ©CNES 2011

Spatial resolution

Panchromatic : 70 cm
XS (B, G, R, NIR): 2.80 m

Simultaneous PA + XS acquisition
Swath: 20 km



SATELLITE

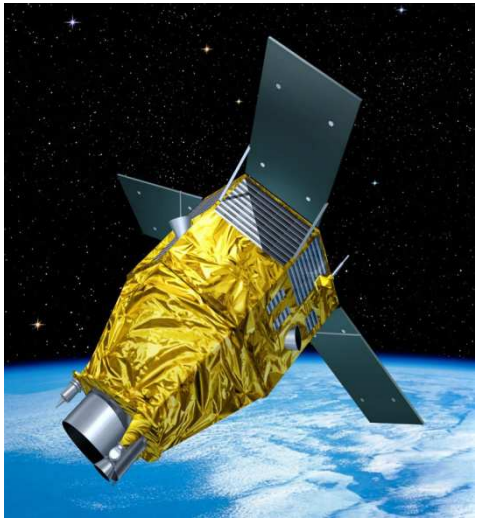
- **Mass : < 1 T**
- **Power : Lithium-ion batteries**

Rigid AsGa solar panels

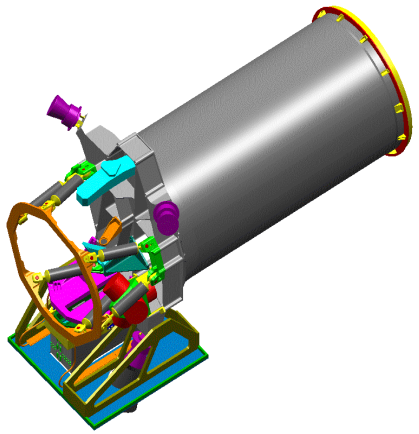
- **AOCS : Gyro actuators**

Star sensors
Optical fiber gyros

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



INSTRUMENT



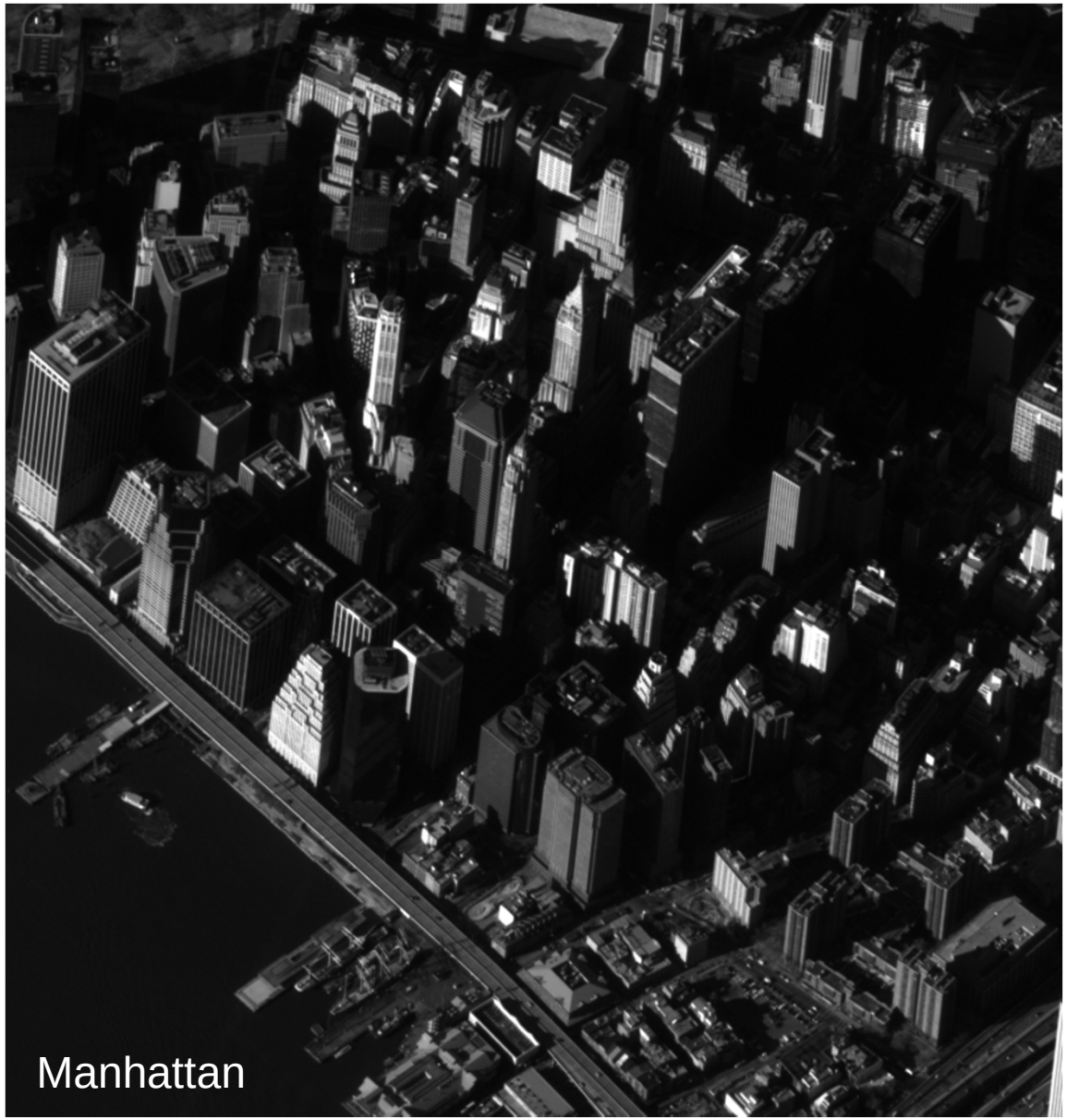
- **Korsch camera**
- **Focal length 12.90m**
- **Diameter 0.65m**

- **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**

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

THE PLEIADES SYSTEM

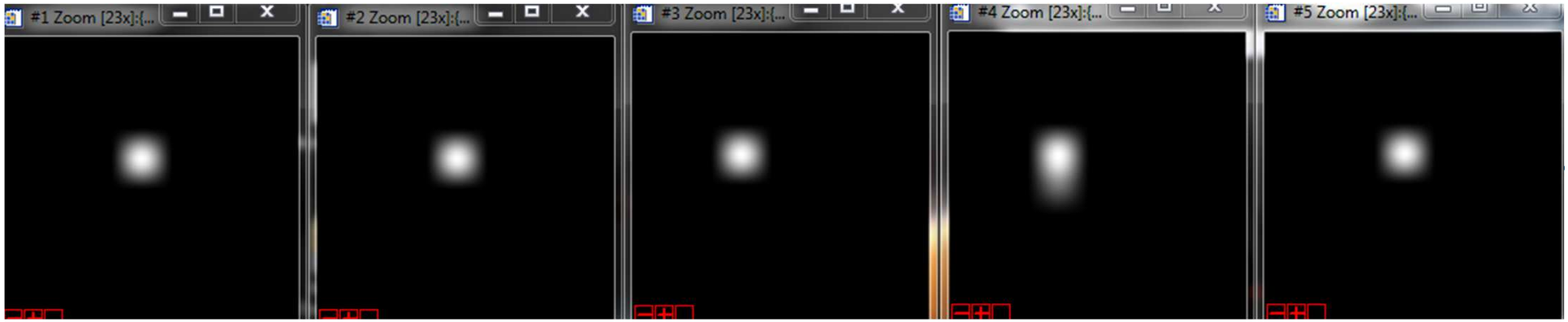


Satellites with a very high level of agility (60° in 25s) !

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: We have shown that stars can be used for the on orbit calibration of high resolution optical sensors using PLEIADES 1A, thanks to its agility



STARS SELECTION FOR CALIBRATION

Use of INDO-US library:

- ✓ **normalized irradiance spectrum (1245 stars)**

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

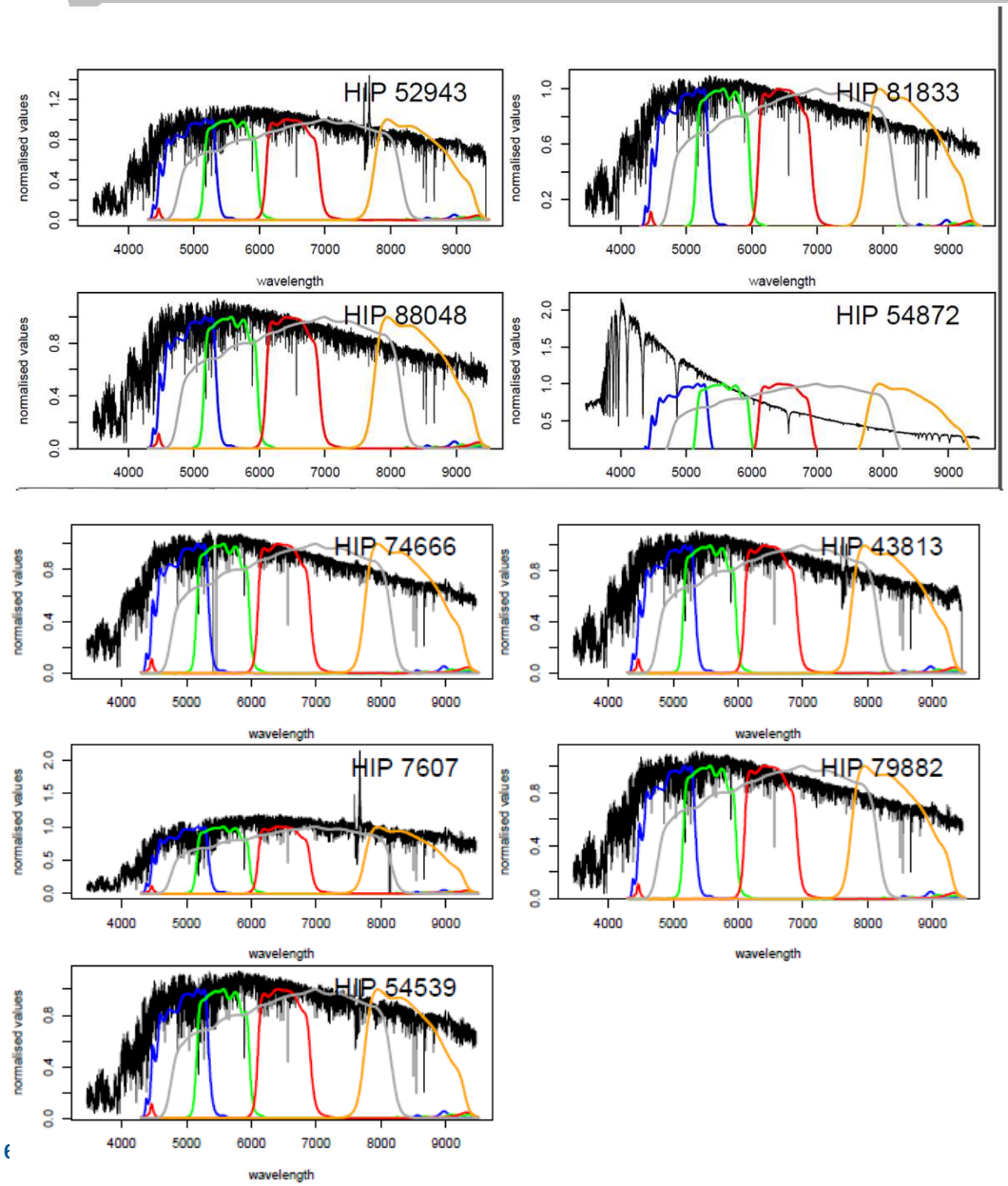
With:

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

- **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**

cnes

SELECTED STARS : SPECTRAL IRRADIANCE



- **Radiance test: $Lk_{min}<Lk<Lk_{sat}$**

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

* 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

- **Type of star:**

Classe	température	Couleur de l'étoile	raies d'absorption
O	> 25 000 K	Bue	azote, carbone, hélium et oxygène
B	10 000 - 25 000 K	Blue-white	hélium, hydrogène
A	7 500 - 10 000 K	White	hydrogène

- **Accessibility according to the season and the satellite position**

THE PROCESSED IMAGES

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

- **~ 95 images processed**

	B0								B1								B2								B3								PAN							
	26/02/2016	04/05/2016	05/05/2016	01/08/2016	03/08/2016	04/08/2016	05/09/2016	06/09/2016	26/02/2016	04/05/2016	05/05/2016	01/08/2016	03/08/2016	04/08/2016	05/09/2016	06/09/2016	26/02/2016	04/05/2016	05/05/2016	01/08/2016	03/08/2016	04/08/2016	05/09/2016	06/09/2016	26/02/2016	04/05/2016	05/05/2016	01/08/2016	03/08/2016	04/08/2016	05/09/2016	06/09/2016	26/02/2016	04/05/2016	05/05/2016	01/08/2016	03/08/2016	04/08/2016	05/09/2016	06/09/2016
7607			5								2								1								3								1					
43813	10								10								10								10								10							
52943	10								10								10								10								10							
54539	10			9			10		10			9			10		10			9			10		10			9			10		10			9			8	
54872						10								10								10								10								8		
74666		4						1		4						1		4						1		4						1		4						1
79882		9			10					9			10					9			10					9			10					9			10			
81833			10								10								10								10								10					
88048		5								5								5								5								5						

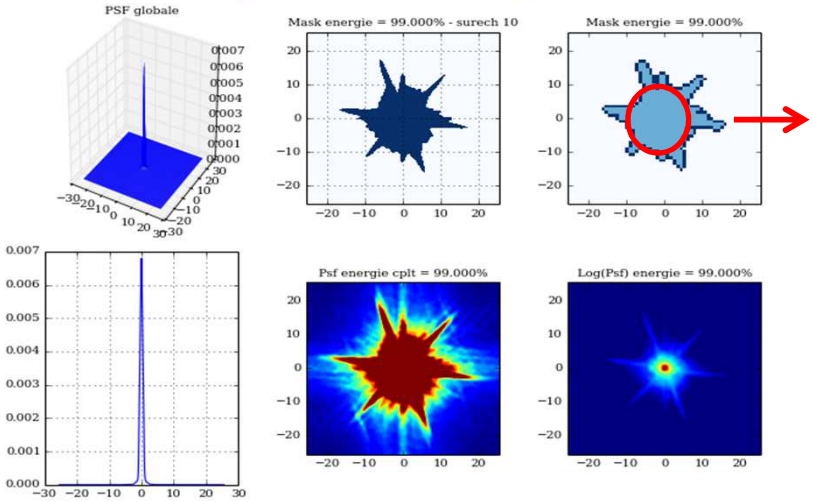
CALIBRATION PRINCIPLE

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

	B0	B1	B2	B3	PAN
98% (PSF)	7	7	8	9	15
99% (PSF)	12	13	14	16	26

CALIBRATION RESULTS FOR PLEIADES 1A

	B0	B1	B2	B3	PAN
Ak(star)/Ak(official)	0,992	1,023	1,023	1,021	1,000
Standard deviation	0,040	0,030	0,025	0,025	0,010

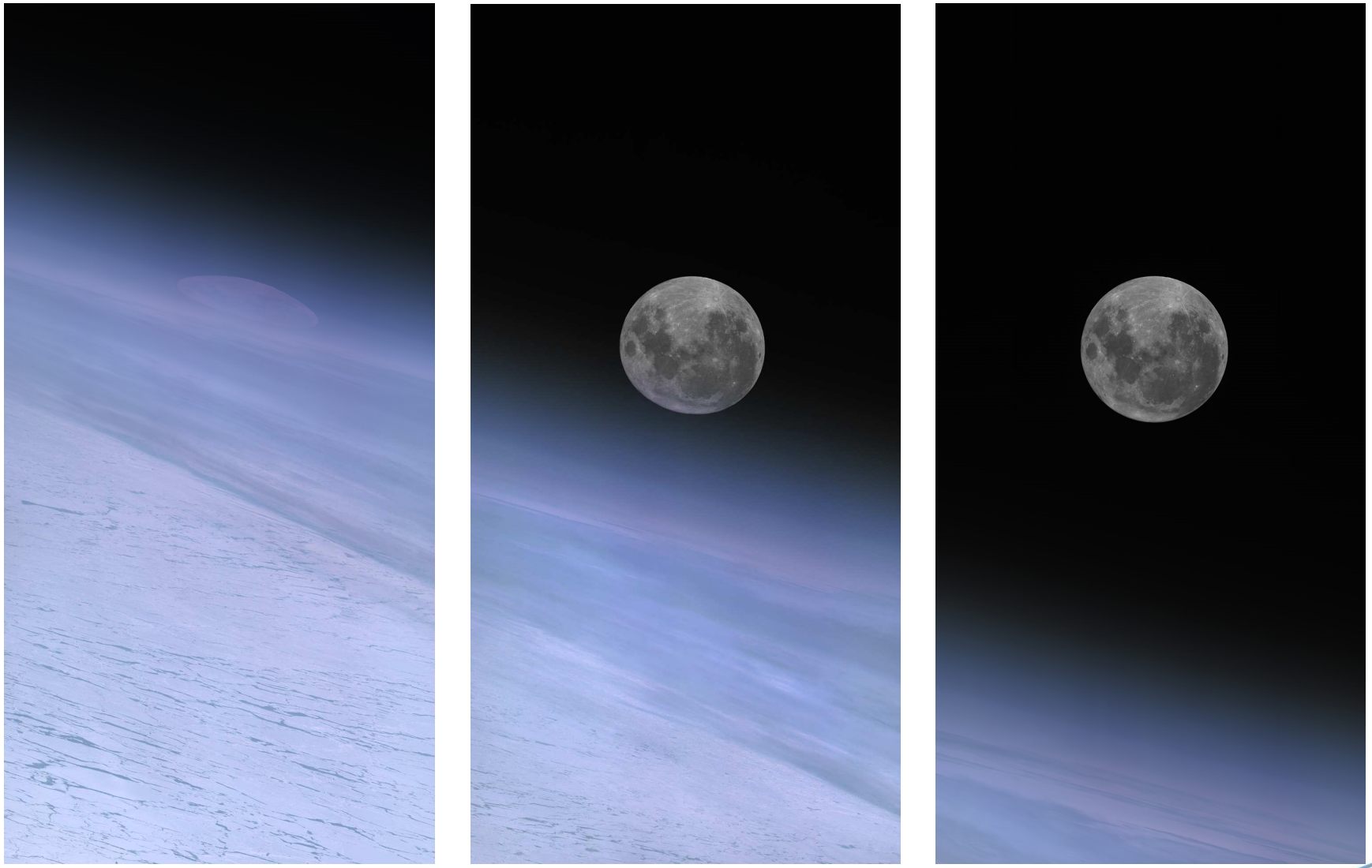
- Very good results compared to the official calibration
- Larger standard deviation for B0 because of the lower irradiance level
- Better consistency for PAN band because of the lower IFOV and higher « SNR »

CALIBRATION RESULTS FOR PLEIADES 1A SENSITIVITY ANALYSIS

hip	gap	B0	%diff B0	B1	%diff B1	B2	%diff B2	B3	%diff B3	PAN	%diff PAN
54539	-5	120,6107267	98,65%	132,9332474	99,03%	135,6154817	100,43%	109,6467538	100,74%	2076,705966	100,18%
	-4	120,9361557	98,91%	133,1465437	99,19%	135,4996083	100,34%	109,4927962	100,60%	2076,025119	100,14%
	-3	121,2620686	99,18%	133,383621	99,37%	135,3826165	100,26%	109,3353644	100,45%	2075,320893	100,11%
	-2	121,5917646	99,45%	133,6466616	99,56%	135,2624474	100,17%	109,1743981	100,30%	2074,59378	100,07%
	-1	121,9276762	99,72%	133,9316987	99,77%	135,1445319	100,08%	109,0105885	100,15%	2073,845196	100,04%
	0	122,2671172	100,00%	134,2341331	100,00%	135,0372096	100,00%	108,844849	100,00%	2073,076353	100,00%
	1	122,5939203	100,27%	134,5340081	100,22%	134,9244288	99,92%	108,6668958	99,84%	2072,287353	99,96%
	2	122,9040796	100,52%	134,8323092	100,45%	134,8127186	99,83%	108,4850342	99,67%	2071,477955	99,92%
	3	123,1754708	100,74%	135,1221655	100,66%	134,6979579	99,75%	108,2990853	99,50%	2070,650516	99,88%
	4	123,3990901	100,93%	135,3971314	100,87%	134,5790319	99,66%	108,1104084	99,33%	2069,810473	99,84%
79882	-5	99,16388687	98,88%	106,5188289	99,42%	102,5342325	100,53%	78,36761835	100,94%	1587,330665	100,38%
	-4	99,38784397	99,10%	106,6216177	99,51%	102,424916	100,43%	78,22166317	100,76%	1586,176143	100,30%
	-3	99,610041	99,32%	106,7349141	99,62%	102,3149002	100,32%	78,07545308	100,57%	1585,004175	100,23%
	-2	99,83449073	99,55%	106,8608645	99,74%	102,2034246	100,21%	77,92893771	100,38%	1583,815341	100,15%
	-1	100,061616	99,77%	106,9970418	99,87%	102,0931538	100,10%	77,78207509	100,19%	1582,611153	100,08%
	0	100,289701	100,00%	107,1413307	100,00%	101,9894246	100,00%	77,63526203	100,00%	1581,393142	100,00%
	1	100,5081792	100,22%	107,2813056	100,13%	101,880644	99,89%	77,48144264	99,80%	1580,161743	99,92%
	2	100,7155349	100,42%	107,4184801	100,26%	101,77045	99,79%	77,32617936	99,60%	1578,916676	99,84%
	3	100,8963879	100,60%	107,5491725	100,38%	101,6561987	99,67%	77,16918348	99,40%	1577,659331	99,76%
	4	101,0435378	100,75%	107,6694978	100,49%	101,5373326	99,56%	77,01122334	99,20%	1576,39343	99,68%

- **Weak sensitivity to the spectral response knowledge: Max variation for PHR-1A : ±1.5nm ⇒ <0.5% for B0**

THE MOON SEEN BY PLEIADES
on the 24th of november 2016



MOON BASED CALIBRATION

Today: Lunar calibration is mainly used as a multi-temporal calibration method (some cross-calibration exercises done)

⇒ Based on ROLO*

⇒ Considering than the ratio $I_{obs} = \frac{\sum_{i=1}^{N_p} L_i \cdot \Omega_i}{A_l(\alpha_l)} \cdot \left(\frac{D_{l-obs}}{384400}\right)^2 \left(\frac{D_{l-s}}{1AU}\right)^2$ **is constant**

Moon irradiance in the image

ROLO Irradiance integrated in the PHR spectral bands

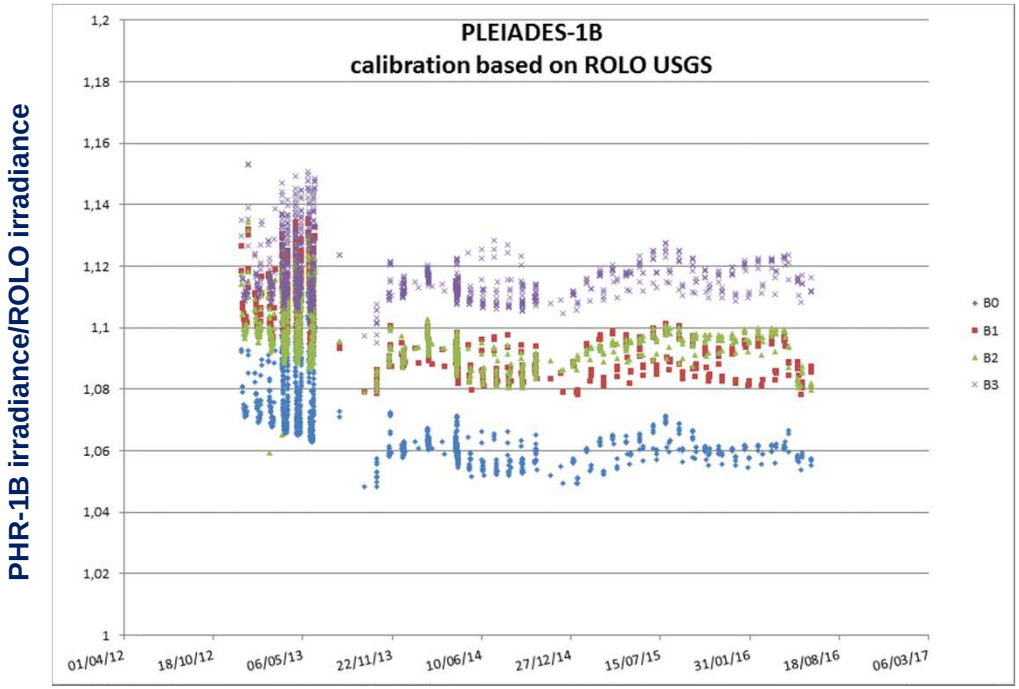
Normalization of the distances

⇒ For PLEIADES satellites regular acquisitions of the moon with a fixed phase of ±40° every month for the drift monitoring

* H.H. Kieffer, T.C. Stone, R.A. Barnes, S. Bender, R.E. Eplee, J. Mendenhall, L. Ong *On-orbit radiometric calibration over time and between spacecraft using the moon* SPIE 4881, pp. 287-298, 2003.

cnes

MOON BASED CALIBRATION



1435 PHR-1B moon images between december 2012 and june 2016

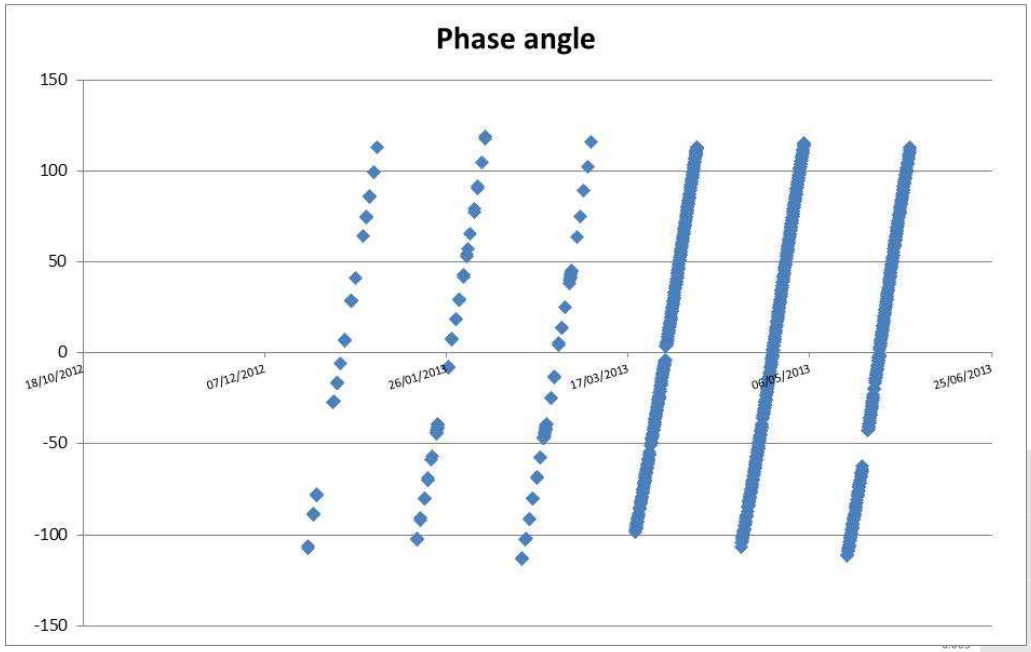
- **Limitations of moon-based calibration using ROLO lunar albedo model:**
  - **sensitivity to the phase angle: up to 4% for |phase angle|<90°**
  - **absolute limitation of the model: from 6% to 11% for blue to NIR bands**

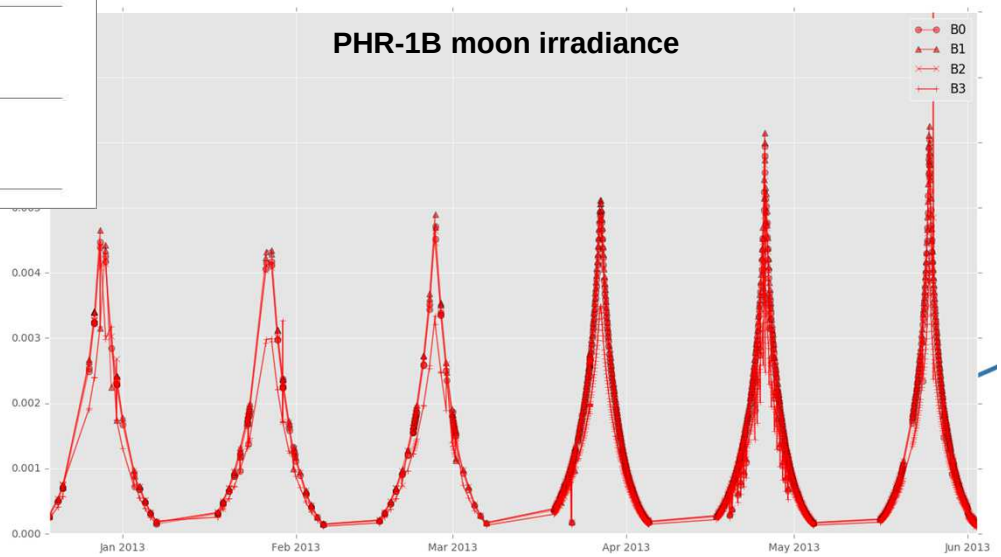
☺ **Proposal to Correct ROLO lunar albedo model using PLEIADES-HR satellites moon and stars observations**

cnes

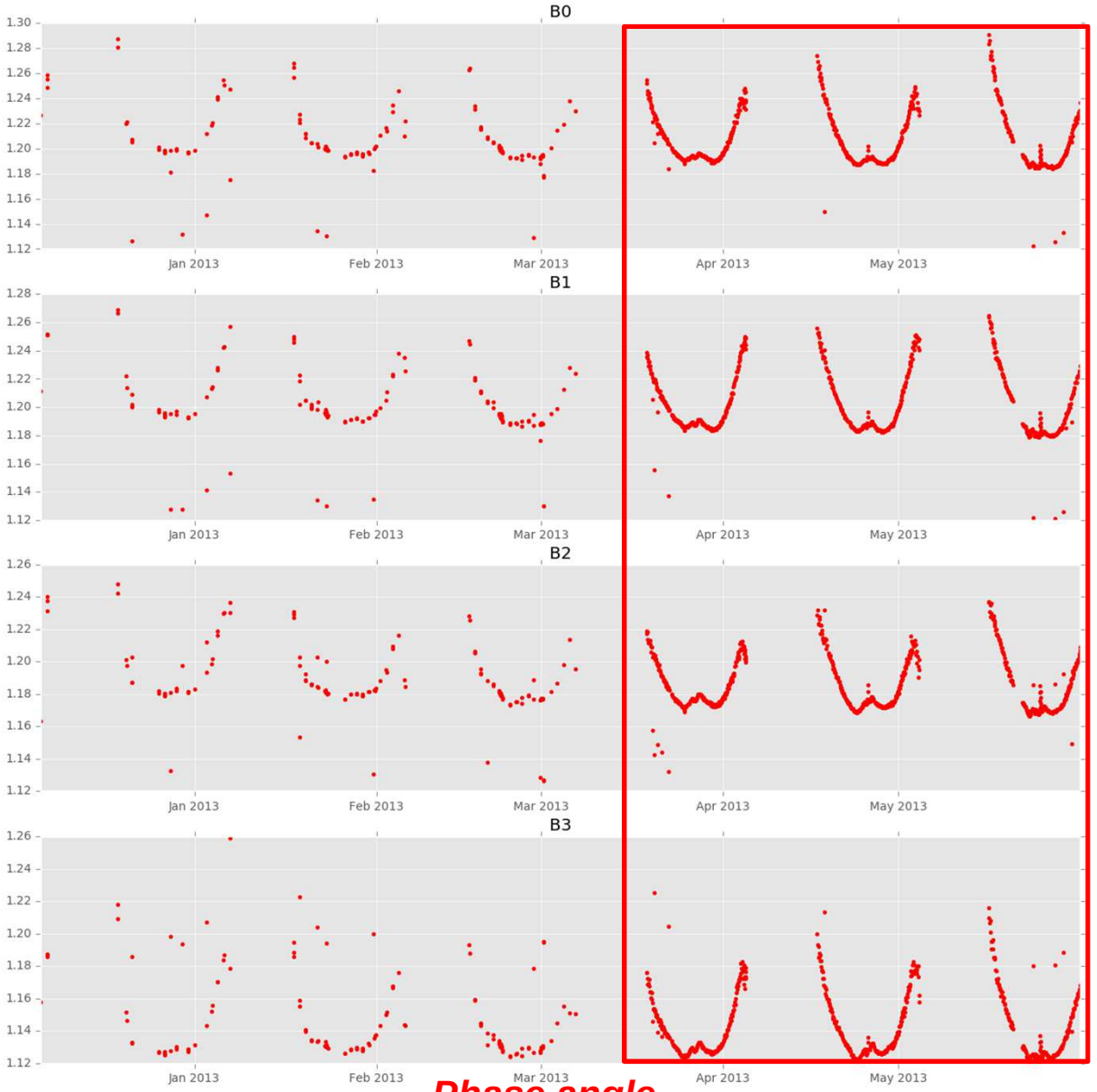
SENSITIVITY TO THE PHASE ANGLE

- 6 complete moon cycles observed by PHR-1B from december 2012 to june 2013
- 867 images
- up to less than 1° phase angle variation

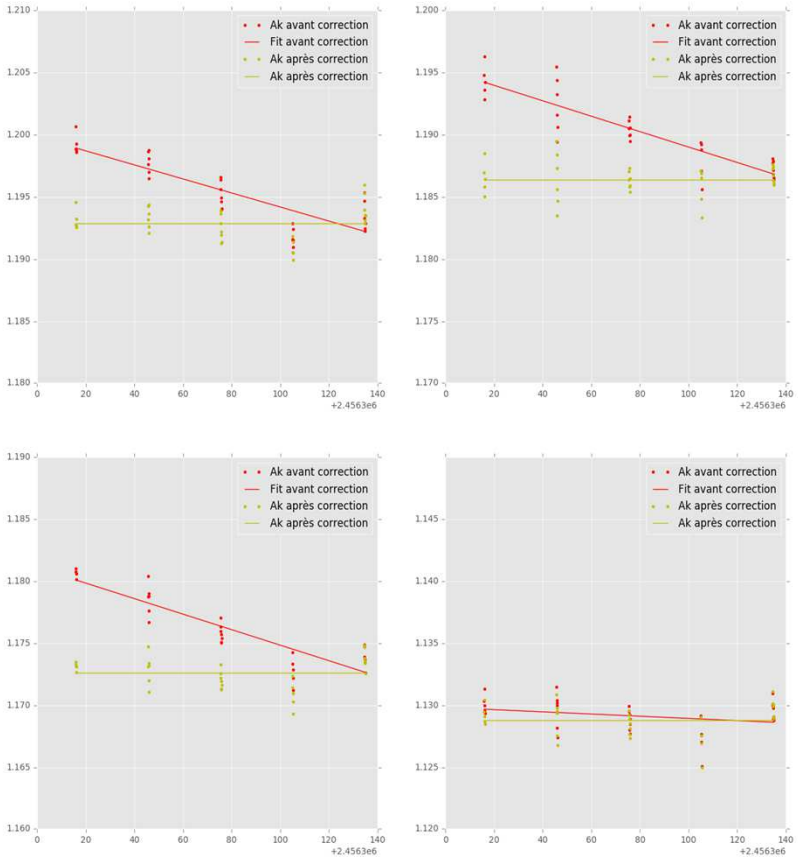




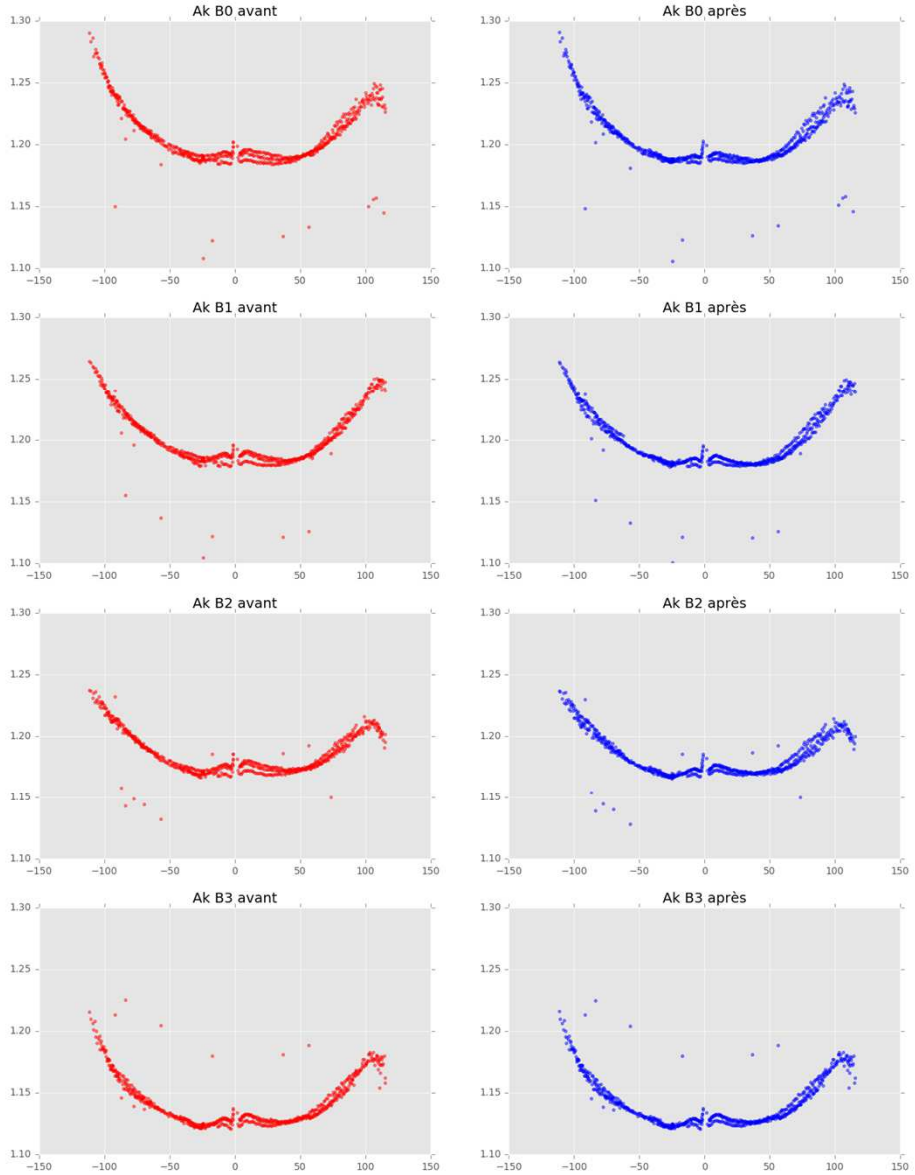
SENSITIVITY TO THE PHASE ANGLE



SENSITIVITY TO THE PHASE ANGLE: DRIFT CORRECTION



Drift correction using measurements around -40° phase angle



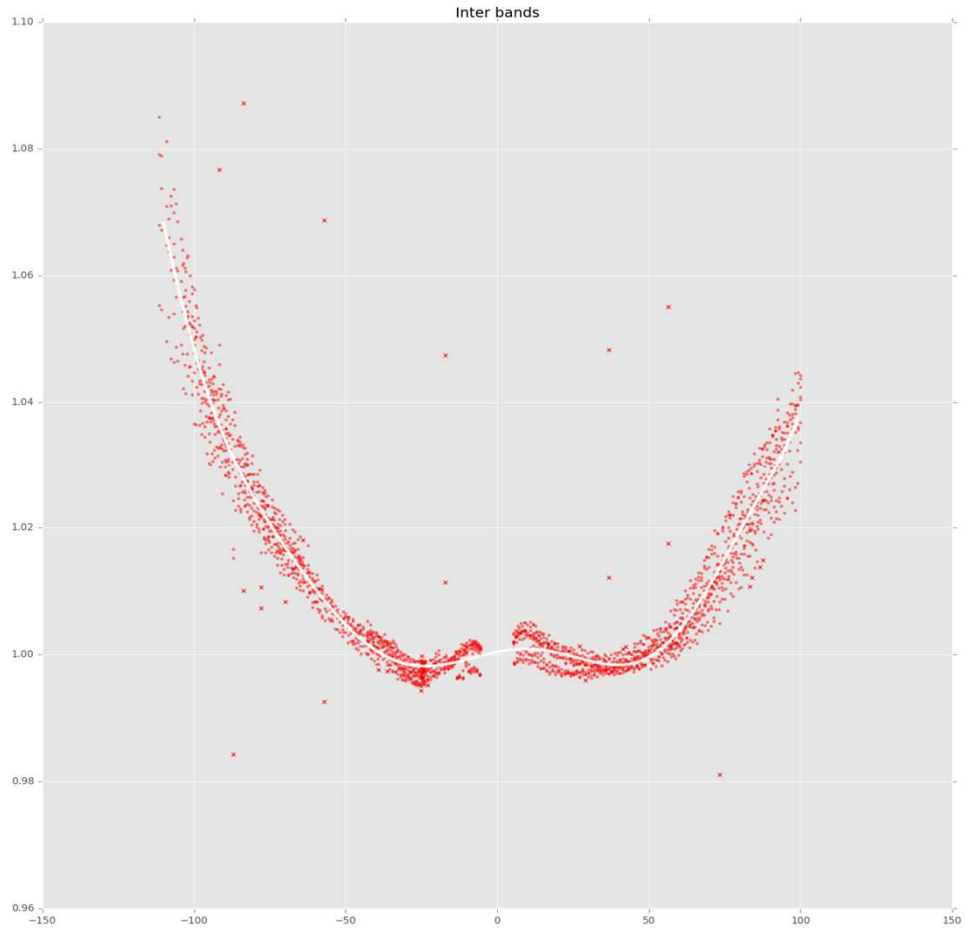
Phase angle

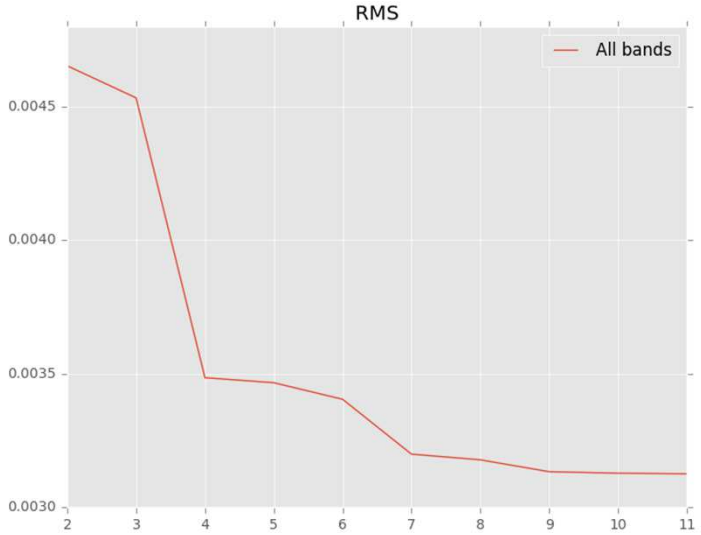
PHR-1B irradiance/ROLO irradiance for 3 cycles

SENSITIVITY TO THE PHASE ANGLE: MODELING USING ALL BANDS

- **Normalization to the same phase angle (0°)**
- **Polynomial fit for 5<|phase angle|<100**
- **Minimization of the residual error after fitting for a 9th degree polynomial**

PHR-1B irradiance/ROLO irradiance for 3 cycles





$$\rho_{ROLO\_corrected} = \rho_{ROLO} * \sum_{k=0}^{9} a_k x^k$$

x: phase angle

SENSITIVITY TO THE PHASE ANGLE CORRECTION: RESIDUAL ERROR

Bande	All Phi	[-90°,90°]	[-90°,-5°] U [5°,90°]
ALL	0.0075	0.0030	0.0030
B0	0.0090	0.0030	0.0030
B1	0.0050	0.0025	0.0025
B2	0.0100	0.0040	0.0040
B3	0.0070	0.0025	0.0025

- **Better efficiency of the correction between -90° and +90° phase angle: residual error < 0.4%**

SPECTRAL CORRECTION

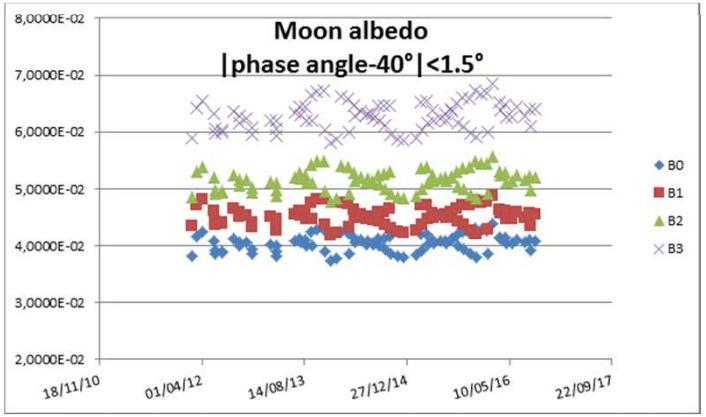
- **Stars irradiance knowledge transfered to the moon using PHR-1A as a transfer radiometer**

$$I_{moon}(B_i) = \frac{I_{star}(B_i)}{X_{star}(B_i)} * X_{moon}(B_i)$$

Stars based calibration

With I: irradiance
X: integrated signal in the image
Bi: spectral band i

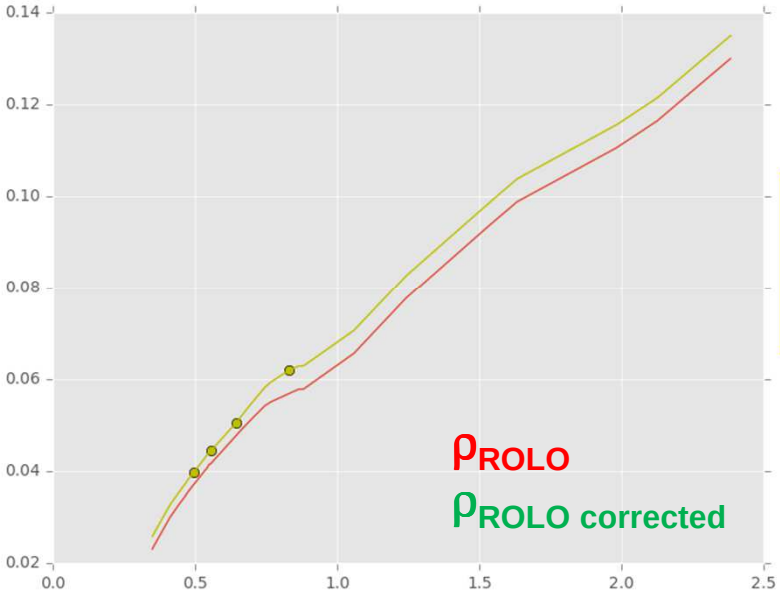
- **Advantage: Stars irradiance well mastered and no atmosphere to manage**
- **82 PHR-1A moon acqusitions used from february 2012 to september 2016 (|phase angle-40°|<1.5°)**



$$\rho_{moon}(Bi) = \frac{\pi \cdot I_{moon}(Bi)}{\Omega_{moon} \cdot E_s}$$

ROLO SPECTRAL CORRECTION

- **Normalization of the measurements to the same observations conditions (phase angle =40°,…) using ROLO phase angle corrected model**
- **Fit of the ROLO phase angle corrected model to the moon measurements using the « Hyperspectral method » (see PICSAR Workshop):**
  - **Go through the reference points**
  - **First derivative continuity at the reference point**
  - **Second derivative preservation**



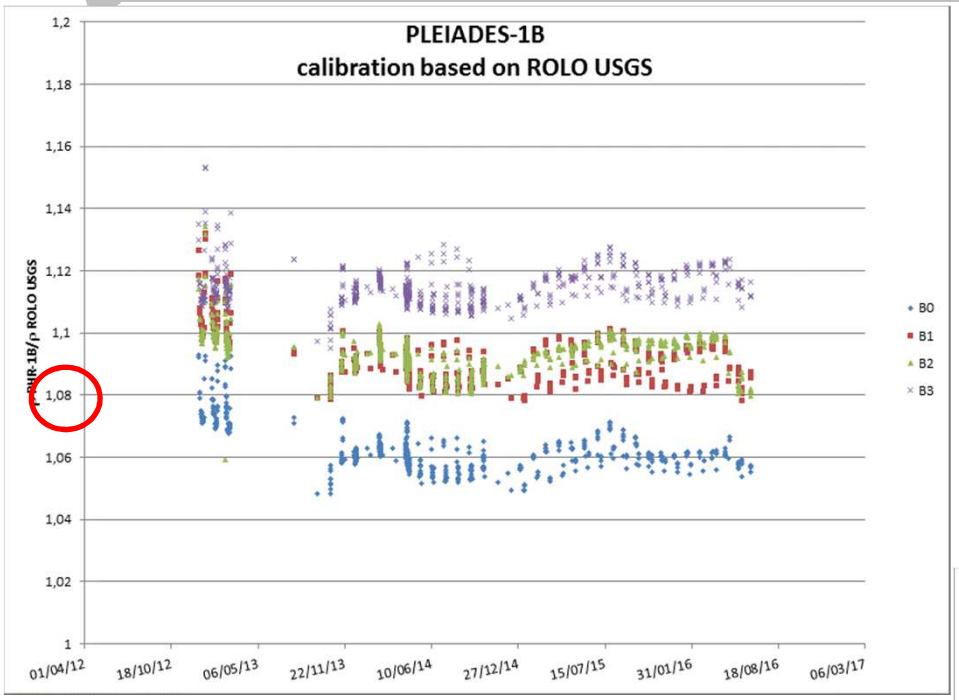
Proposed ROLO corrected model:

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

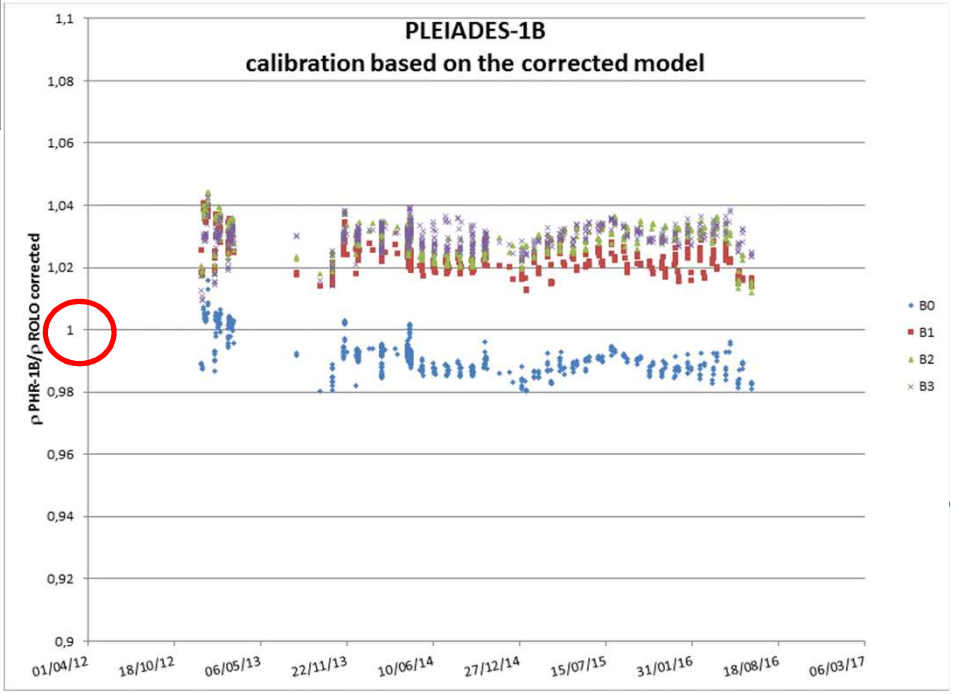
Spectral correction

Phase angle correction

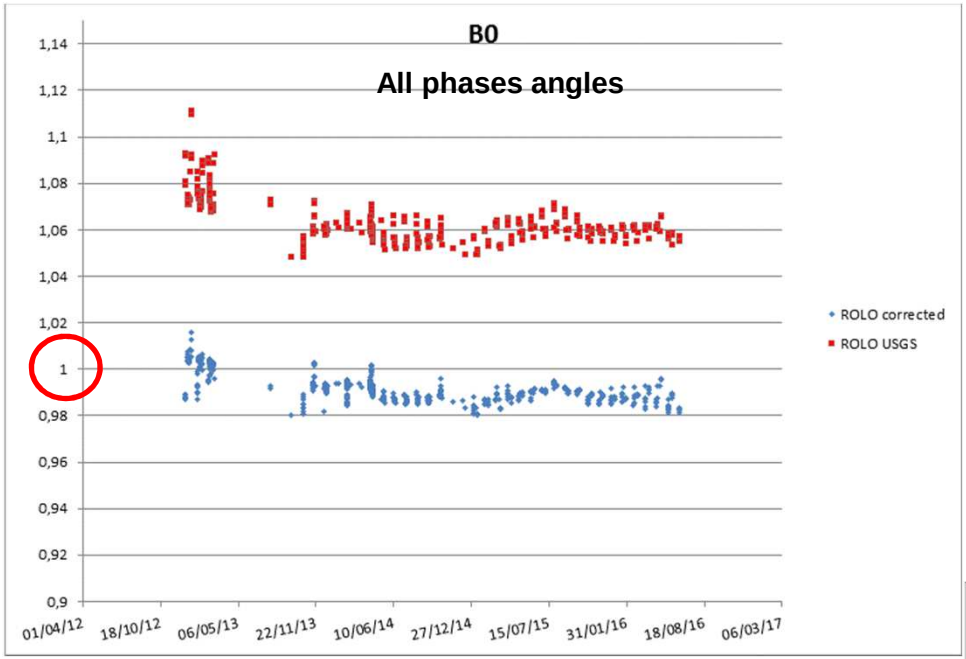
ROLO CORRECTED MODEL
VALIDATION: PHR-1B

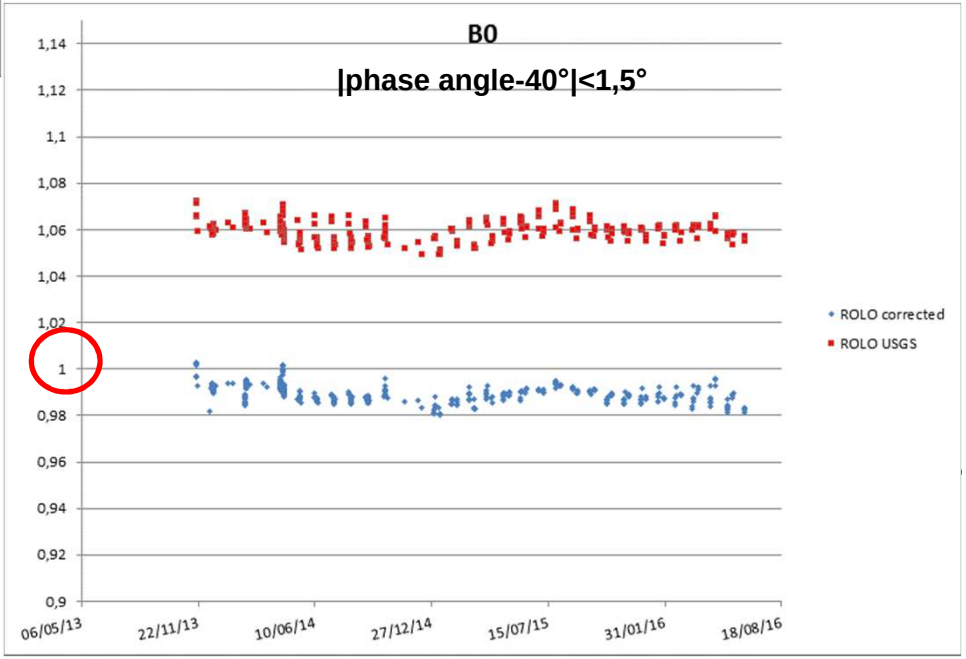


Validation based on 600 PHR-1B moon images acquired between december 2012 and june 2016 not used for the model correction

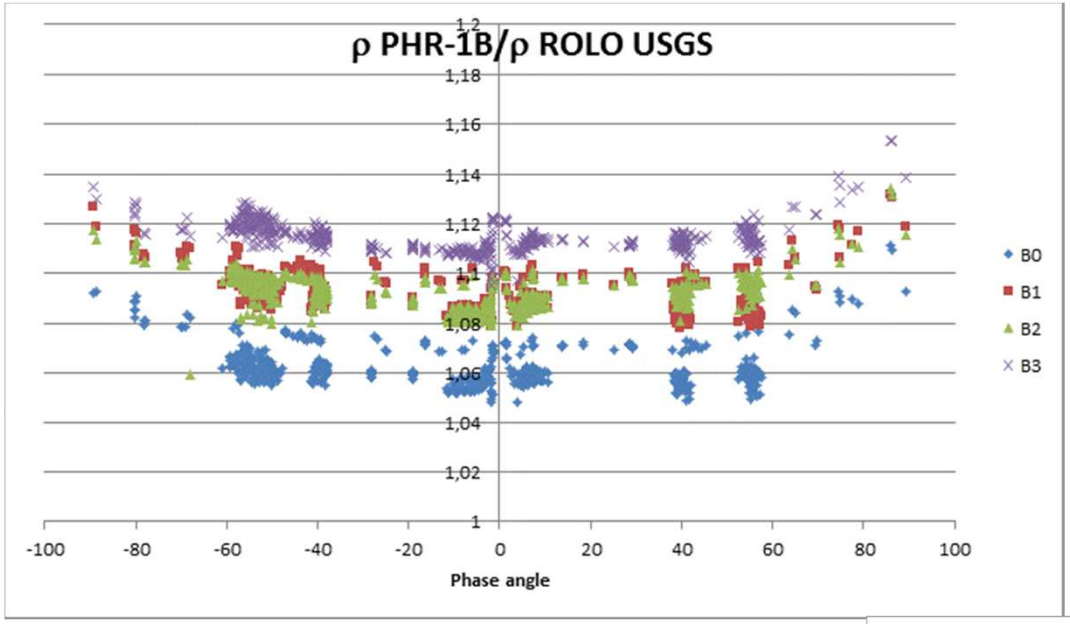


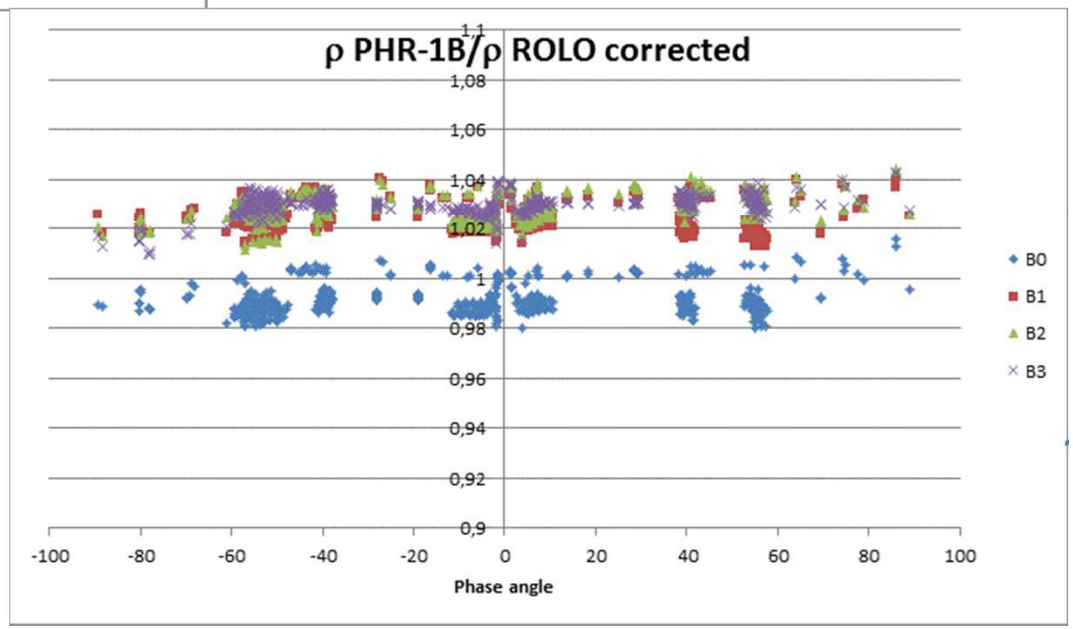
ROLO CORRECTED MODEL VALIDATION: PHR-1B B0





ROLO CORRECTED MODEL VALIDATION: PHR-1B



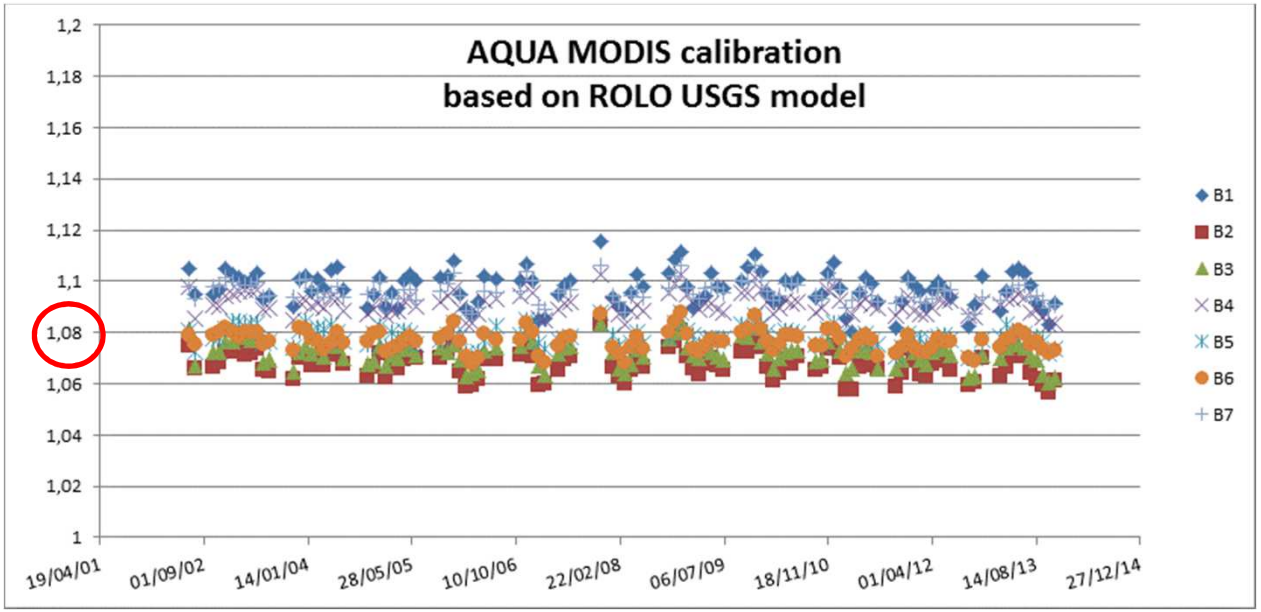


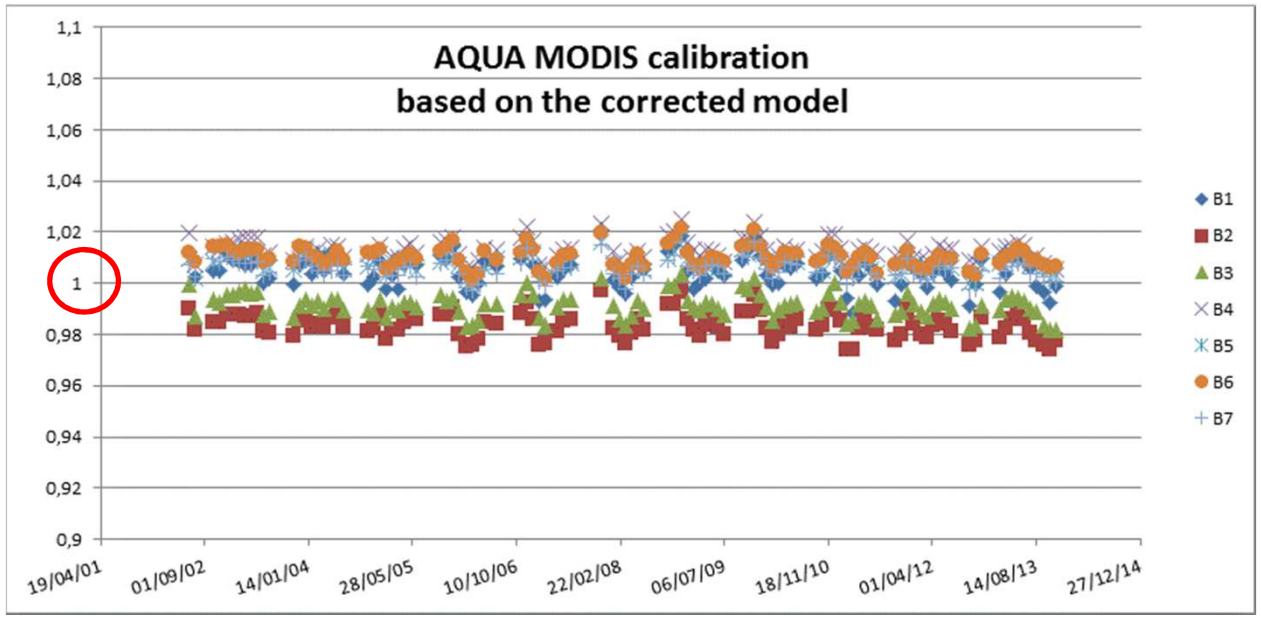
ROLO CORRECTED MODEL VALIDATION: PHR-1B

600 moon images	B0	B1	B2	B3
ρk PHR-1B/ρk ROLO USGS Mean value	1,063	1,092	1,093	1,115
Standard deviation	0,008	0,008	0,007	0,006
ρk PHR-1B/ρk ROLO corrected Mean value	0,992	1,024	1,029	1,030
Standard deviation	0,006	0,005	0,005	0,004

- **Results to be consolidated…**
- **Calibration with the corrected model is consistent with the official calibration by less than 3%**
- **The standard deviation is reduced thanks to the phase angle correction (strong weight of measurements performed around ±40°)**

ROLO CORRECTED MODEL VALIDATION: MODIS



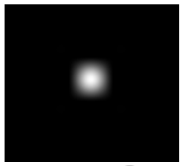


- **MODIS: 109 moon images acquired between june 2002 and november 2013**
- **Source data: NASA / J. Xiong**

ROLO CORRECTED MODEL VALIDATION: MODIS

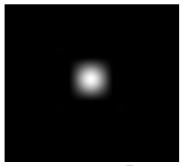
	B1	B2	B3	B4	B5	B6	B7
ρk MODIS/ρk ROLO USGS Mean value	1,097	1,068	1,072	1,091	1,079	1,077	1,096
Standard deviation	0,007	0,005	0,005	0,004	0,004	0,004	0,004
ρk MODIS/ρk ROLO corrected Mean value	1,005	0,984	0,991	1,013	1,008	1,010	1,006
Standard deviation	0,006	0,005	0,005	0,004	0,004	0,004	0,004

- **Results to be confirmed…**
- **Calibration with the ROLO corrected model is consistent with the official calibration by less than 2%**
- **The weak variation of the phase angle (around -55°) explains the weak standard deviation**



CONCLUSION - 1

- **Star based calibration**
  - **Confirmation that stars provide an accurate absolute reference for the on orbit calibration of high resolution optical sensors**
  - **Very good calibration results obtained with PLEIADES 1A: less than 2.5% compared to vicarious calibration**
  - **Next step: absolute calibration and MTF simultaneous inversion**



CONCLUSION - 2

- **Moon based calibration**
  - **ROLO model correction proposed to manage its sensitivity to the phase angle and its spectral bias using PLEIADES moon and stars observations**
  - **ROLO model correction:**
    - **Makes possible to use the moon as an absolute reference for the on orbit calibration of optical sensors**
    - **To be fully validated:**
      - **On going analysis of PHR data radiometric and geometric processing starting from images**
      - **Validity of the correction out of PLEIADES spectral range?**
    - **Will be implemented in MUSCLE-NG calibration environment**
    - **Will be tested on VENµS mission (12 spectral bands; launch 25th of july 2017)**