The contribution of ROSAS automated photometric station to vicarious calibration of PLEIADES PHR1A satellite

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   Photometer characteristics and in-situ measurement protocol

2. Photometer in-situ calibration
   Satellite sensor calibration principle

3. Overview of PLEIADES satellite & calibration principles
   On-orbit PHR1A calibration over LaCrau site: data & processing

4. Some feed-back from PHR1A in-orbit test phase
   The future: planned and possible evolutions
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LaCrau calibration site – ROSAS Robotic station

**Photometer:**
Made by CIMEL
AERONET concept (AErosol RObotic NETwork)
dedicated to atmosphere characterization
Optical head: 2 collimators
2 detectors: Silicium (visible and NIR)
   InGaAs detector (SWIR)

**Configuration:**
Wheel wearing 9 filters:
380, 440, 550, 670, 740, 870, 937, 1020, 1600 nm
380 nm → atm. molecular scattering
740 nm → vegetation red edge
937 nm → water vapor
1020 nm → aerosols
Mounted on top of a post 10m high.

**Site:**
LaCrau (South East of France, near Marseille)
Flat plain of 20 km diameter, covered with white pebbles and grass
Used since 1987 (SPOT), automated since 1997
Measurement protocol

Every non cloudy day, 4 measurements scenarios are automatically and continuously performed.

**Sun Irradiance**
- Irradiance measurements pointing the Sun in each band

**Principal Plane**
- Sky radiances measurement in the vertical plane containing the Sun for 40 zenith observation angles for all bands except 937 nm

**Almucantar**
- Sky radiances measurement according to 2 half cones around vertical axis for 30 azimuth observation angles for all bands except 937 nm

**Ground**
- Surface radiances measurement for 12 zenith angles up to 60 degrees and 72 azimuth observation angles for 6 bands

The acquisitions are performed only when the air mass is lower than 5.
Measurement protocol

Every non cloudy day, 4 measurements scenarios are automatically and continuously performed.

<table>
<thead>
<tr>
<th>Sun Irradiance</th>
<th>Principal Plane</th>
<th>Almucantar</th>
<th>Ground</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filters 1-17-2-3-4-5-21-7-8-9</td>
<td>Filters 1-17-2-3-4-5-8-9</td>
<td>Filters 17-2-3-4-5-9</td>
<td>Filters 17-2-3-4-5-9</td>
</tr>
<tr>
<td>x 3 times</td>
<td>x 40 zenith angles</td>
<td>x 30 azimuth angles</td>
<td>x 12 zenith angles x 72 azimuth angles</td>
</tr>
</tbody>
</table>

Time sequence

<table>
<thead>
<tr>
<th>Filter number</th>
<th>Spectral band</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1020Si</td>
</tr>
<tr>
<td>2</td>
<td>870Si</td>
</tr>
<tr>
<td>3</td>
<td>670Si</td>
</tr>
<tr>
<td>4</td>
<td>440Si</td>
</tr>
<tr>
<td>5</td>
<td>550Si</td>
</tr>
<tr>
<td>7</td>
<td>937Si</td>
</tr>
<tr>
<td>8</td>
<td>380Si</td>
</tr>
<tr>
<td>9</td>
<td>740Si</td>
</tr>
<tr>
<td>17</td>
<td>1600InGaAs</td>
</tr>
<tr>
<td>21</td>
<td>1020InGaAs</td>
</tr>
</tbody>
</table>

Total duration of one cycle ≈ 100 mn
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Photometer in-situ calibration principles

Originality: possibility of in-situ calibration of the photometer

- Irradiance calibration:
  
  Solar irradiance extinction formula: Bouguer-Langley law

- Radiance calibration:

  Molecular scattering in short wavelengths

Same collimateur used

→ The radiance calibration can be propagated to other bands using an irradiance cross-calibration
### Photometer in-situ irradiance calibration

#### Langley-Bouguer principle:

\[
E_k = E_{0k} \cdot \left( \frac{d_0}{d} \right)^2 \cdot \exp \left( \frac{-\tau_k}{\cos \theta_s} \right) \cdot T_g
\]

- $E_k$: Irradiance measured at ground level
- $E_{0k}$: Top of atmosphere solar irradiance
- $d_0/d$: Earth-Sun distance variation
- $\tau$: Total optical thickness
- $\theta_s$: Sun zenith angle
- $T_g$: Total gaseous transmission

#### Radiometric model for Sun measurements:

\[
DC_k = A_k \cdot Gu_k \cdot E_k
\]

- $DC_k$: Digital Count
- $Gu_k$: Electronic Gain
- $A_k$: Irradiance Calibration coefficient

#### Bouguer line:

\[
\ln(\text{DC}_k) = -\tau_k \cdot \frac{m}{T_g} + \ln\left( A_k \cdot Gu_k \cdot E_{0k} \cdot \left( \frac{d}{d_0} \right)^2 \right)
\]

- $m$: Air mass = $1/\cos(\theta_s)$ is assumed $\approx 1$ except for 937 band

#### Fitting of Bouguer line (least squares method) over each non cloudy half-day

- ✔ Air mass=0 → Irradiance Calibration coefficient $A_k$
- ✔ Slope of the line → Total optical thickness $\tau_k$ for the period

The Irradiance Calibration coefficient obtained in situ is compared to laboratory results.
Langley-Bouguer for band 937:

Use of SMAC(*) coefficients (a, n) to estimate water absorption in this band

\[ E_k = E_{0k} \cdot \left( \frac{d_0}{d} \right)^2 \cdot \exp \left( -\frac{\tau_k}{\cos \theta_s} \right) \cdot T_g \cdot \exp \left( a \cdot (U_{H_2O} \cdot m)^n \right) \]

(*) Simplified Method for the Atmospheric Correction of satellite measurements in the solar spectrum

Bouguer line becomes:

\[ a \cdot U_{H_2O}^n \cdot m^n + \ln \left( A_{937} \cdot Gu_{937} \cdot E_{0.937} \cdot \left( \frac{d_0}{d} \right)^2 \right) = \ln \left( DC_{937} \right) + \tau_{937} \cdot m \]

Total optical thickness (\( \tau_{937} \)): deduced from neighbors bands (spectral dependence of aerosol optical thickness provided by Angstrom coefficient, according to Junge model)

Least squares fit \( \rightarrow \) estimation of top of atmosphere Digital Count (DC\(_{0.937}\)) and of water vapor content, assumed to be stable during the considered half-day period of time

From DC\(_{0.937}\) \( \rightarrow \) computation of irradiance calibration coefficient A\(_{937}\)

Major drawback: what if water vapor content is not stable during the considered period of time?
Photometer in-situ radiance calibration

Radiance Radiometric model:
\[ DC_k = B_k \cdot G_{k} \cdot L_k \]

<table>
<thead>
<tr>
<th>DC</th>
<th>Digital Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gk</td>
<td>Gain for radiance measurements</td>
</tr>
<tr>
<td>Bk</td>
<td>Radiance Calibration coefficient</td>
</tr>
</tbody>
</table>

At shorter wavelengths (380, 440, 550nm), the top of atmosphere radiance is dominated by Rayleigh scattering, and to a lesser extent by scattering from aerosols and surface. The total radiance \( L_k \) can be estimated for these wavelengths from Principal Plane measurements, using a radiative transfer code. \( B_k \) can be estimated in shorter wavelengths.

Radiance / Irradiance relationship:
\[ E_k = \Omega \cdot L_k \]
\[ \Omega = \frac{B_k}{A_k} \]

\( B_k \) estimated in shorter wavelengths by radiance calibration.
\( A_k \) already calculated in all bands by irradiance calibration.

\[ \rightarrow \text{Estimation of } \Omega \rightarrow B_k \text{ in all bands} \]
On-orbit calibration: averaging CIMEL Ground data and PHR1A measurements

Applying reference $A_k$ coefficients (computed before launch), each PHR1A measurement is averaged over 12 pixels XS / 47 pixels PAN around the photometer (i.e. a squared area of 33m), and can be associated to a top-of-atmosphere reflectance.
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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

**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

Launch of PHR1A: December 17, 2011
Launch of PHR1B: November, 2012
Absolute calibration methods used on PLEIADES (requirement: 5%):
✓ Absolute calibration on LaCrau site using ROSAS automated station, and on ocean sites
✓ Inter-instruments calibration on desert and antarctic sites
✓ Multi-temporal follow-up on desert sites and on moon acquisitions

![Images of various calibration sites including Algeria, Dome, Moon, and LaCrau]
### PHR1A first acquisitions over LaCrau

<table>
<thead>
<tr>
<th>Date</th>
<th>Hour</th>
<th>Sun Irr. meas. by photometer</th>
<th>Aerosol OT (550nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec 29 2011</td>
<td>10:42</td>
<td><img src="image1.png" alt="Graph" /></td>
<td>0.11</td>
</tr>
<tr>
<td>Jan 24 2012</td>
<td>10:41</td>
<td><img src="image2.png" alt="Graph" /></td>
<td>??</td>
</tr>
<tr>
<td>Feb 7 2012</td>
<td>10:33</td>
<td><img src="image3.png" alt="Graph" /></td>
<td>0.14</td>
</tr>
<tr>
<td>Feb 21 2012</td>
<td>10:26</td>
<td><img src="image4.png" alt="Graph" /></td>
<td>0.24</td>
</tr>
<tr>
<td>March 28 2012 (*)</td>
<td>10:49</td>
<td><img src="image5.png" alt="Graph" /></td>
<td>0.27</td>
</tr>
<tr>
<td>April 16 2012</td>
<td>10:53</td>
<td><img src="image6.png" alt="Graph" /></td>
<td>0.10</td>
</tr>
<tr>
<td>April 25 2012</td>
<td>10:34</td>
<td><img src="image7.png" alt="Graph" /></td>
<td>0.09</td>
</tr>
<tr>
<td>May 26 2012</td>
<td>10:45</td>
<td><img src="image8.png" alt="Graph" /></td>
<td>0.19</td>
</tr>
<tr>
<td>May 28 2012</td>
<td>10:30</td>
<td><img src="image9.png" alt="Graph" /></td>
<td>0.19</td>
</tr>
<tr>
<td>May 31 2012</td>
<td>10:57</td>
<td><img src="image10.png" alt="Graph" /></td>
<td>0.25</td>
</tr>
</tbody>
</table>

(*) March 28: 24 acquisitions from 10:47 to 10:51
Other acquisitions: March, 9 and June, 4: totally cloudy

**Sun Irradiance**
Digital Count - 380Si
Average of 3 measurements

**Aerosol Optical Thickness**
550Si

- May 26
- July 12

- Direct transmission
- Diffuse transmission
- \( \tau_a \)
- Theorical diffuse transmission
- Theorical total transmission
- Theorical direct transmission
- Total transmission

(550Si)
On-orbit PHR1A calibration over LaCrau site: processing all and acquisitions

Aerosol Optical Thickness

Estimated surface reflectance (in geometrical conditions of satellite acquisition)

Calibration coefficients

<table>
<thead>
<tr>
<th>Date</th>
<th>Band 1 (blue)</th>
<th>Band 2 (green)</th>
<th>Band 3 (red)</th>
<th>Band 4 (PIR)</th>
<th>Band 5 (PAN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 28</td>
<td>0.93</td>
<td>1.02</td>
<td>1.02</td>
<td>0.91</td>
<td>0.98</td>
</tr>
<tr>
<td>May 26</td>
<td>0.89</td>
<td>1.01</td>
<td>1.02</td>
<td>0.88</td>
<td>0.96</td>
</tr>
<tr>
<td>July 10</td>
<td>0.92</td>
<td>0.99</td>
<td>0.95</td>
<td>0.91</td>
<td>0.94</td>
</tr>
<tr>
<td>July 12</td>
<td>0.95</td>
<td>1.07</td>
<td>1.03</td>
<td>0.98</td>
<td>1.02</td>
</tr>
<tr>
<td>July 24</td>
<td>0.91</td>
<td>0.99</td>
<td>0.94</td>
<td>0.92</td>
<td>0.95</td>
</tr>
<tr>
<td>July 29</td>
<td>0.90</td>
<td>0.97</td>
<td>0.94</td>
<td>0.91</td>
<td>0.94</td>
</tr>
</tbody>
</table>

On-orbit PHR1A calibration over LaCrau site: March 28, 2012: Video

Absolute azimuths

- 24 measurements
- 4 minutes total duration
- $\theta_s \approx 42$ deg
- $\theta_v$ min = 13.2 deg
- $\theta_v$ max = 57.7 deg

Relative azimuths

Zenithal view angle

Relative azimuth angle

Directional effects: video of PHR1-A
Over the city of Rio (Brasil)

Directional effects: video of PHR1-A
acquisitions on LaCrau March 28, 2012
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   The future: planned and possible evolutions
Analysis of the data

Key parameter: stability of the atmosphere

The computation of surface reflectance is based on the assumption of a stable atmosphere (direct and scattered flows are interpolated to the time of in-situ acquisitions). Thus, the accidents observed on the direct Sun irradiance measurements show that this assumption is not fulfilled, and the results not reliable.

Band in NIR (B3): not much scattering $\rightarrow$ more sensible to the errors on direct irradiance measurements.

If variations in Sun irradiance measurements $\rightarrow$ error on downward flux $\rightarrow$ error on the surface reflectance evaluation
When the maximum of Sun irradiance is lower than the one observed on other days $\rightarrow$ there is an attenuation caused by clouds $\rightarrow$ the atmosphere is likely to be unstable

When aerosol optical thickness is variable (and up to 0.45) $\rightarrow$ results not reliable (looking for a stable day)
filters: studies in progress

Possible evolutions of the photometer:

- adding a filter in SWIR for future missions calibration needs (VENμS, SENTINEL2)

- replace 380 by 415nm:  
  - closer to SENTINEL2 and VENUS bands
  - reduced scattering noise

photometer equipment: planned evolution

New electronic box operational in 2013: microstepping (positioning precision and better stability), remote command, new SD card, GPS (for datation), pressure, new tracking electronic, new tracking algorithm
The future: planned and possible evolutions (2/2)

Operational protocol at photometer level

For photometer calibration (937 nm band): Stability of water vapor content over a half-day period of time → use of selected stable periods of time in the day?
The content measured shall be compared to the NCEP data

Cross-calibration in-situ with a spectro photometer: planned (started in July 2012)

Ground site: look for an additional site?

LaCrau: often windy, sparse vegetation, bad weather during winter season time → Find an additional site to La Crau (Spain ?) Better accessibility (meteo) and low spectral variations of surface reflectance. Use of one of the 20 desert sites?

Future: operational network of ground sites for calibration of High Resolution space sensors
There could be a network of instrumented sites, with no constraint on the instruments
Main advantages of a photometer: low cost, standard instrument (low maintenance costs)
Conclusions

- ROSAS automated photometric station is fully operational on LaCrau site
  - has been developed and progressively automatized for more than 20 years (SPOT satellites)
  - has been used in 2012 as a fully operational method for absolute radiometric calibration during PLEIADES 1A in-orbit test phase
  - will be used for future missions: SPOT6, PLEIADES 1B, VENμS, SENTINEL-2, …

- Results for absolute radiometric calibration or high resolution optical satellite instruments can be expected with a 5% accuracy
  - depends on the quality of the site (weather, low spectral variation of surface reflectance)
  - depends also on the level of priority given to these acquisitions in commissioning phase: the statistical approach demands several days with clear and stable atmosphere

- Most crucial improvements to be made and evolutions in progress:
  - the photometer itself and associated electronics and filters
  - the operational protocol and data processing
  - the look for additional sites
Thank you!
The contribution of ROSAS automated photometric station to vicarious calibration of PLEIADES PHR1A satellite

Additional slides
Photometer spectral characteristics

Samples the spectrum from 380nm to 1600nm
Wheel carrying 9 filters, narrow bands
2 collimators: Silicium detector (visible and NIR) / InGaAs detector (SWIR)
24 bits Analogical to digital Converter

<table>
<thead>
<tr>
<th>Central wavelength</th>
<th>Width</th>
<th>Detector</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>550 nm</td>
<td>10 nm</td>
<td>Si</td>
<td></td>
</tr>
<tr>
<td>670 nm</td>
<td>10 nm</td>
<td>Si</td>
<td>« Historical » SPOT spectral bands</td>
</tr>
<tr>
<td>870 nm</td>
<td>10 nm</td>
<td>Si</td>
<td></td>
</tr>
<tr>
<td>1600 nm</td>
<td>50 nm</td>
<td>InGaAs</td>
<td></td>
</tr>
<tr>
<td>440 nm</td>
<td>10 nm</td>
<td>Si</td>
<td>calibration of SPOT/VEGETATION sensor blue band</td>
</tr>
<tr>
<td>740 nm</td>
<td>10 nm</td>
<td>Si</td>
<td>red edge (grass on test site)</td>
</tr>
<tr>
<td>937 nm</td>
<td>10 nm</td>
<td>Si</td>
<td>water vapor study</td>
</tr>
<tr>
<td>1020 nm</td>
<td>10 nm</td>
<td>Si, InGaAs</td>
<td>aerosols, cross-calibration of collimators</td>
</tr>
<tr>
<td>380 nm</td>
<td>5 nm</td>
<td>Si</td>
<td>absolute calibration of the photometer w.r.t. molecular scattering</td>
</tr>
</tbody>
</table>
Some feed-back from first measurements with PHR1A (1/2)

PHR1A February 21, 2012 (Panchromatic: resolution 0.7m)

\[ \theta_s = 57.7 \text{ deg} \]
\[ \theta_v = 27.3 \text{ deg} \]

Here it is!!
The measurements of the Sun irradiance at the time of the video is not reliable (variations up to 4%)
On-orbit PHR1A calibration over LaCrau site: March 28, 2012

From photometer measurements

Aerosol Optical thickness

Rayleigh Optical thickness

From photometer measurements

Surface Reflectance - Photometer bands

From photometer measurements

440Si
550Si
670Si
740Si
870Si

On-orbit PHR1A calibration over LaCrau site: March 28, 2012
On-orbit PHR1A calibration over LaCrau site: March 28, 2012

Surface Reflectance - Sensor bands

From photometer measurements
On-orbit PHR1A calibration over LaCrau site: March 28, 2012

Top-of-Atmosphere Reflectance - Sensor bands

From photometer measurements

Top-of-atmosphere reflectance measured by PHR1A on March 28, 2012
(after applying reference calibration coefficients Ak)
Roujean model

Semi empirical approach applicable to heterogeneous surfaces

\[ k_0 + k_1 \cdot f_1(\theta_s, \theta_v, \Delta \phi) + k_2 \cdot f_2(\theta_s, \theta_v, \Delta \phi) \]

(Linear 3 parameter model)