PROBA-V Vicarious Calibration:
Investigation into the impact of in-orbit temperature variation

LIME (Lunar Irradiance Model ESA) model

Sindy Sterckx, Stefan Adriaensen (VITO)
LIME Model

- LIME = Lunar Irradiance Model of ESA
- Developed under ESA contract from 2017-2019
  - NPL (UK), UVa (ES) and VITO (BE)
- CIMEL instrument at 6 different wavelengths at 440, 500, 675, 870, 1020, 1640 [nm]
- The LIME model is derived from +/-300 (automated) irradiance measurements of the moon at Pico Teide (Tenerife)
- The model simulates the exo-atmospheric total irradiance to be observed by any sensor within the 400nm – 2500nm wavelength range
- Input to the model:
  - Timestamp, location -> observations between 2 and 90 degrees are accepted (both sides)
  - Sensor spectral response
- The approach to derive the model is highly similar to the USGS ROLO model (Kieffer and Stone, 2005) : the C parameter set was made band specific.
- The model is capable of providing the Degree of Linear Polarization (DoLP) as an output.
- The uncertainty at reflectance level is max 2%
LIME Model : consortium

➢ NPL : calibration of the instrument and uncertainty (both measurement and model)
➢ UVa : instrument automated operation @Tenerife (incl. database) and performing Langley estimations
➢ VITO : model derivation and uncertainties
### Lunar Irradiance Measurements CIMEL 440nm (@Tenerife)

#### Table of Coefficients

<table>
<thead>
<tr>
<th>$\lambda$ [nm]</th>
<th>$a_0$</th>
<th>$a_1$</th>
<th>$a_2$</th>
<th>$a_3$</th>
<th>$b_1$</th>
<th>$b_2$</th>
<th>$b_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>440</td>
<td>-2.82195</td>
<td>-0.67058</td>
<td>-0.35391</td>
<td>-0.01226</td>
<td>0.059246</td>
<td>0.005286</td>
<td>-0.00426</td>
</tr>
<tr>
<td>500</td>
<td>-2.51509</td>
<td>-1.01093</td>
<td>-0.06614</td>
<td>-0.05286</td>
<td>0.054643</td>
<td>0.009163</td>
<td>-0.00532</td>
</tr>
<tr>
<td>675</td>
<td>-2.38188</td>
<td>-0.67037</td>
<td>-0.28114</td>
<td>-0.0469</td>
<td>0.053769</td>
<td>0.006141</td>
<td>-0.00345</td>
</tr>
<tr>
<td>870</td>
<td>-2.26185</td>
<td>-0.60165</td>
<td>-0.31416</td>
<td>-0.03947</td>
<td>0.054968</td>
<td>0.010404</td>
<td>-0.00499</td>
</tr>
<tr>
<td>1020</td>
<td>-2.16789</td>
<td>-0.59006</td>
<td>-0.31791</td>
<td>-0.03482</td>
<td>0.057767</td>
<td>0.015604</td>
<td>-0.00728</td>
</tr>
<tr>
<td>1640</td>
<td>-1.75563</td>
<td>-0.60829</td>
<td>-0.27471</td>
<td>-0.04719</td>
<td>0.053116</td>
<td>0.006556</td>
<td>-0.00364</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\lambda$ [nm]</th>
<th>$c_1$</th>
<th>$c_2$</th>
<th>$c_3$</th>
<th>$c_4$</th>
<th>$d_1$</th>
<th>$d_2$</th>
<th>$d_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>440</td>
<td>0.002143</td>
<td>0.000571</td>
<td>0.001373</td>
<td>0.000412</td>
<td>0.393375</td>
<td>0.590169</td>
<td>0.000999</td>
</tr>
<tr>
<td>500</td>
<td>0.00182</td>
<td>0.000218</td>
<td>0.001304</td>
<td>0.000555</td>
<td>0.840597</td>
<td>0.388049</td>
<td>-0.00117</td>
</tr>
<tr>
<td>675</td>
<td>0.001496</td>
<td>0.000229</td>
<td>0.001521</td>
<td>0.000706</td>
<td>0.328802</td>
<td>0.496161</td>
<td>-0.00061</td>
</tr>
<tr>
<td>870</td>
<td>0.001364</td>
<td>8.25E-05</td>
<td>0.001628</td>
<td>0.000624</td>
<td>0.376939</td>
<td>0.479259</td>
<td>-0.00021</td>
</tr>
<tr>
<td>1020</td>
<td>0.001457</td>
<td>-3.04E-05</td>
<td>0.001754</td>
<td>0.001015</td>
<td>0.456871</td>
<td>0.453514</td>
<td>-0.00094</td>
</tr>
<tr>
<td>1640</td>
<td>0.001473</td>
<td>5.62E-05</td>
<td>0.001497</td>
<td>0.000949</td>
<td>0.420775</td>
<td>0.315047</td>
<td>-0.00021</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$p_1$</th>
<th>$p_2$</th>
<th>$p_3$</th>
<th>$p_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.449524</td>
<td>19.68723</td>
<td>10.78809</td>
<td>8.994821</td>
</tr>
</tbody>
</table>

### Reflectance vs. Phase Angle

The graph illustrates the reflectance of lunar irradiances measured using CIMEL 440nm equipment at Tenerife. The model curves are compared with the measured data points. The table above provides the coefficients used in the model. The reflectance values are plotted against the phase angle, showing a trend that aligns with the model predictions.
The uncertainty at model wavelengths is derived using Monte Carlo analysis: every input measurement to the model has been perturbated 1000 times.

Input irrad perturbated 1000x based upon meas. uncertainty.

Results: 1000 models.

1000 model results per observation.

Uncertainty is established at 2% (2 sigma).
LIME Model : comparison

- Comparisons with sensors and other models:
  - PROBA-V: large time series, fixed phase angle (+/-7°)
  - Pleiades-B: small dataset, full phase angle coverage
  - GIRO (model): detailed time-series
    Project reports on a dedicated cal-val portal CEOS
    [http://calvalportal.ceos.org/lime](http://calvalportal.ceos.org/lime)
  - Sentinel-3B: limited comparison

- Ongoing:
  - AIR-LUSI data comparison to LIME: possibility to look at spectral performance of the model.

- In general agreements are quite good between sensor and model. More comparisons are needed to reveal model weak points (like phase dependency)
LIME Model : future

➢ The model development is ongoing (‘maintenance’)
  ➢ Extra measurements for geometry
  ➢ ‘improvements’ to the model are planned: non-linear part of the model, solar irradiance, ...

➢ The uncertainties defined do not cover the complete model process
  ➢ Lunar reflectance spectrum interpolation
  ➢ Application of spectral response function

➢ Possible phase angle dependency needs to be addressed
  ➢ PROVA-V experimental phase supports this action

➢ More in depth comparison between LIME AIR-LUSI is ongoing: evaluation spectral performance,...
ESA has succeeded to build a new Lunar irradiance model in about 2 years (2017-2019). Maintenance is assured for the next 4 years.

The model has been applied operationally to calibrate PROBA-V.

Improvements to the model are planned in the next 2 years.