Instrument Characterization for Ocean Color Remote Sensing

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Presentation to EUMETSAT, Darmstadt
My background:

- Phd in 2000, 'BRDF of Urban Areas'
- Joined SIMBIOS in 2000, then OBPG
- SIMBIOS Radiometric Intercomparisons
- MODIS and SeaWiFS calibration and characterization analysis
- VOST: VIIRS prelaunch and on-orbit characterization
- ORCA: instrument design support, PI of Instrument Incubator Program; candidate for PACE mission
- ACE, CLARREO, and HyspIRI: mission definition support
- MERIS Quality Working Group (ESA)
- Instrument development for GeoCAPE
- NASA civil servant since 2010
Overview:

1. Ocean color requirements
2. Sensor requirements
3. Sensor characterization prelaunch
4. Sensor characterization on-orbit
Calibration and Characterization:

Calibration: convert \( dn \) to radiance \( L \) for ideal conditions

\[
L = f(dn)
\]

\[
L = \text{gain} \times dn
\]

Characterization: what adjustments need to be made for non-ideal conditions:

\[
L = g(P, S, T, \text{etc.}) \times f(dn)
\]

\( g \) can depend on polarization, neighboring bright targets, temperature, etc.
Derivation of ocean color products

Measurement of TOA Radiances (calibration and characterization)

Conversion to water-leaving radiances (atm. corr., vic. cal., glint, etc.)

Derivation of ocean color products (chlorophyll concentration, attenuation coef., fluorescence line height, etc.)
1. Ocean color requirements

- Basic quantity: normalized water-leaving radiance nLw
- Some oceanographic variables can be expressed as function of nLw (chlorophyll concentration, suspended matter, attenuation coef., etc.)
1. Ocean color requirements

- Only 1%-15% of TOA signal is scattered within ocean
- If 5%, then 1% error in TOA signal leads to 20% relative error in nLw

Fig. provided by B. Franz, OBPG
1. Ocean color requirements

How can we achieve high radiometric accuracy?

1) Design and specifications

2) Prelaunch characterization and calibration

3) On-orbit monitoring
1. Ocean color requirements

- Historically: 5% goal for nLw at 443nm
- Requires better than 0.5% absolute calibration accuracy, unattainable from space (MODIS: about 2% in reflectance)
- Vicarious calibration (MOBY) adjusts absolute radiance level, so only relative calibration errors are important for ocean color
- Current relative accuracy is about 0.5% or more, goal for future missions probably about half that
2. Sensor requirements

- Ocean color requirements lead to sensor requirements, e.g. ACE Science Traceability Matrix (STM)

- Sensor requirements should be
  1) strict enough to ensure quality of data product
  2) achievable at reasonable cost
  3) testable
Specific calibration and characterization issues:

- **Polarization** (Meister et al., Applied Optics, 2005 (cover article); Kwiatkowska et al., Applied Optics, 2008; Waluschka et al., SPIE, 2007)
- **Straylight** (Meister et al., SPIE, 2008; Meister et al., ISPRS, 2005; Zhong et al., SPIE, 2007)
- **Gain trending, lunar** (Barnes et al., Applied Optics, 2004; Sun et al., SPIE, 2008; Eplee et al., SPIE, 2008; Patt et al., SPIE, 2005)
- **Gain trending, solar diffuser** (Meister et al., SPIE, 2008; Meister et al., SPIE, 2005)
- **Response versus scan** (Franz et al., JARS, 2008; Kwiatkowska et al., Applied Optics, 2008)
- **Striping** (Meister et al., SPIE, 2007, Meister et al., SPIE, 2006, Xiong et al., SPIE, 2007)
- **Linearity** (Meister et al., SPIE, 2007)
- **Temperature** (Eplee et al., SPIE, 2007)
- **Crosstalk, Spectral response, Sensor noise, Field-of-view, etc.**
Sensor requirements not strict enough: VIIRS

- Straylight contaminates high contrast scenes:

- MODIS Aqua: masking 2-3km away from cloud, removes about 50% of the ocean pixels
Sensor requirements not strict enough: VIIRS

- VIIRS structured scene (straylight) spec

<table>
<thead>
<tr>
<th>Band</th>
<th>Center Wavelength (nm)</th>
<th>Angular separation from bright target (milliradian)</th>
<th>Maximum allowed ratio of scattered radiance to typical radiance</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>412</td>
<td>6</td>
<td>0.01</td>
</tr>
<tr>
<td>M2</td>
<td>445</td>
<td>6</td>
<td>0.01</td>
</tr>
<tr>
<td>M3</td>
<td>488</td>
<td>6</td>
<td>0.01</td>
</tr>
<tr>
<td>M4</td>
<td>555</td>
<td>6</td>
<td>0.01</td>
</tr>
<tr>
<td>M5</td>
<td>672</td>
<td>12</td>
<td>0.02</td>
</tr>
<tr>
<td>M6</td>
<td>746</td>
<td>12</td>
<td>0.02</td>
</tr>
<tr>
<td>M7</td>
<td>865</td>
<td>12</td>
<td>0.02</td>
</tr>
</tbody>
</table>

- Cloud size is 12mrad x 12mrad
- 12mrad ~ 10km, 6mrad ~ 5km
- SeaWiFS would pass VIIRS spec in the NIR (SeaWiFS has correction, VIIRS will not; VIIRS straylight performance much better than SeaWiFS, comparable to MODIS)
3. Sensor Characterization: Overview

- **Polarization:**
  setup documentation (MODIS and VIIRS)

- **MODIS striping:**
  1) horizontal (detectors)
  2) vertical (subframes)
Linear Polarization: Electric Field Vector

- There are two types of polarization: linear and circular
- TOA radiances are partly (0-70%) linearly polarized
- Prelaunch characterization:
  send 100% linearly polarized into sensor, varying polarization angle from $0^\circ$-$180^\circ$ (15$^\circ$ steps for MODIS Aqua)
MODIS Polarization Characterization: Setup documentation

Solid line: Correct polarization Correction

Dashed line: Previous polarization correction
Impact of MODIS Polarization Characterization

nLw ratios MODIS/SeaWiFS for northern pacific

Fig. from Meister et al., 2005, Applied Optics
Orientation of the transmitted electric field vector when polarizing sheet is at 0deg:

BVO777:  

BVONIR:  

Polarizing sheet rotation angles:

0deg  

90deg  

270deg  

180deg  

SIS port 10.5 x 13.8 inches  
Polarizer I.D. 11.0 inches  
(all scaled to photo incl. FOVs)

VIIRS flight direction:  

VIIRS scan direction:  

(VIIRS scans from -55deg to +55deg view angle)  

FOV of VIIRS detector 16 (instrument engineering order)  

FOV of VIIRS detector 1 (instrument engineering order)  

FOVs are 7.39 x 6.82 inches
MODIS Aqua detector striping, nLw 412nm, before correction:

After correction:
MODIS subframe striping correction

- Subframes not linear versus radiance, prelaunch and on-orbit:

Figures from Meister et al., SPIE, 2007

- nLw 645nm (before/after correction):
MODIS Relative Spectral Response:

- Issues: detector dependence (real and smile correction), source intensity (low and not well known)
4. Sensor calibration on-orbit

- Problem: how to calibrate sensor several hundred miles away?
- Solution 1: carry calibration sources (solar diffuser, blackbody, spectral targets)
- Solution 2: use natural sources (moon, deserts, clouds, atmospheric absorption lines)
Sensor calibration: SeaWiFS

- SeaWiFS optics based on a telescope design, with well protected half-angle mirror
- SeaWiFS optics + detectors have degraded consistently => one analytical function sufficient to model sensor degradation
- Error of individual lunar measurements (~1%) does not affect calibration accuracy of SeaWiFS
First step: Sum all lunar pixels (radiance to irradiance)
Monthly SeaWiFS lunar irradiance measurements

SeaWiFS Lunar Calibrations

Normalized Radiance

Band 1  Band 2  Band 3  Band 4
Band 5  Band 6  Band 7  Band 8

Days Since First Image
Lunar Calibration

- Application to space-based instruments requires using a photometric model
to accommodate unrestricted observation (illumination and view) geometry
- Currently, the radiometric quantity utilized is spatially-integrated irradiance
  - improved signal-to-noise through summation of pixels
  - enhanced freedom in model development
- USGS lunar irradiance model was built from database of spatially resolved images of the Moon acquired by the RObotic Lunar Observatory (ROLO)
  - 6+ years in operation, >85,000 individual Moon images
    - (many ×10^5 star images)
  - twin telescopes, 32 wavelength bands, 350–2450 nm

USGS campus
Flagstaff, AZ
Using the Moon — Lunar Irradiance Model


• empirically-derived analytic function in the geometric variables of phase and libration, for disk-equivalent reflectance $A$:

$$\ln A_k = \sum_{i=0}^{3} a_{ik} g^i + \sum_{j=1}^{3} b_{jk} \Phi^{2j-1} + c_1 \theta + c_2 \phi + c_3 \Phi \theta + c_4 \Phi \phi$$

$$+ d_{1k} e^{-g/p_1} + d_{2k} e^{-g/p_2} + d_{3k} \cos\left(\frac{(g - p_3)}{p_4}\right)$$

$g =$ phase angle
$\theta =$ observer selenographic latitude
$\phi =$ observer selenographic longitude
$\Phi =$ selenographic longitude of the Sun
Example of ROLO input file: Sirad

SECTION = Observation Info
Instrument = SeaWiFS
User = Gene Eplee
Process = multimoon
Version = 2002apr03
Run_Time = 2005Jan05 14:00:00
BEGIN_FREE
   This is ROLO exchange SCT MOF Irradiance file.
   Prelaunch calibration with best time correction applied.
   The irradiances are integrated over pixels above 1% of maximum.
Col_0 = Obs_index   Col_1+ = Irradiance in bands
Units are: uW / m^2 / nm
Format = (i2,8f8.4)
-1  1      2      3      4      5      6      7      8
C_END
Example of ROLO input file: Sgeom

```
SECTION = Observation Info
Instrument = SeaWiFS
User = Gene Eplee
Process = multimoon
Version = 2002apr03
Run_Time = 2005Jan05 14:00:00
BEGIN_FREE

This is ROLO exchange SCT MOF Geometry file.
The Moon_Y_Size is defined by the 1% of maximum pixels.

Col_0 = Obs_index   Col_1 = Image_time   Col_2,3,4 = Spacecraft_X,Y,Z
Col_6 = Moon_Y_Size <mrad>   [ Col_7=Miss_Frac   Col_8=Clip_angle ]
Format = (i2,a19,3f7.1,f6.3,f7.4,f4.1)
C_END

<table>
<thead>
<tr>
<th></th>
<th>Date</th>
<th>Time</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>Moon_Y_Size</th>
<th>Miss_Frac</th>
<th>Clip_angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1997-11-14T22:50:09</td>
<td>4122.0</td>
<td>5570.3</td>
<td>1480.1</td>
<td>31.931</td>
<td>0.0000</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1997-12-14T12:18:26</td>
<td>945.1</td>
<td>6757.2</td>
<td>1912.9</td>
<td>31.517</td>
<td>0.0000</td>
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<td></td>
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<tr>
<td>3</td>
<td>1998-01-13T01:44:52</td>
<td>-2527.0</td>
<td>6418.3</td>
<td>1631.4</td>
<td>30.775</td>
<td>0.0000</td>
<td>0.0</td>
<td></td>
</tr>
</tbody>
</table>
```
**Example of ROLO output file: Lgeom**

```plaintext
SECTION = Observation info             ! ----------------------- Begin a section
Instrument = SeaWiFS                     ! Instrument making the observation
User = Gene Eplee                    ! Person submitting the calibration request
Source_Date = 2005Jan05 14:00:00         ! Run Date/Time of primary input file
Process = 2004jun24T12:14 & multimoon ! Name of process that generated this file
Version = 2005jul24                      ! Processing version
Run_Time = 2006Mar21 08:52:49            ! Local Date/Time of these calculations
BEGIN_FREE      ! Begins a free-form section describing the table section
This is a ROLO exchange for:   LCT MOF geometry
GUIDE to columns below:
Col          Key   units  Description   0          Row       -  Observation Count
-------      -------  -------          -------       -------       -------
1  TDB-2451545     day  Dynamical barycentric Days -2451545.
2       SunLon  degree  Selenographic longitude of the Sun
3       SunLat  degree  Selenographic latitude of the Sun
4       SC_Lon  degree  Selenographic longitude of spacecraft
5       SC_Lat  degree  Selenographic latitude of spacecraft
6     SC_Dist.      km  Distance of spacecraft from center of Moon
7   Sun_M_Dist      AU  Heliocentric range of the Moon
8      DistFac       -  Factor to correct irradiance to standard distances
9      PhaseAng  degree  Signed phase angle
10    Moon_mrad    mrad  Angular Diameter of the Moon from SC
11     Axis_Ang  degree  Position Angle of lunar axis, ccw from N
Format = (I3,1x,f13.6,1x,f8.2,1x,f5.2,1x,f6.2,1x,f6.2,1x,f6.2,1x,f8.1,1x,F9.7,1x,f9.6,1x,F8.3,1x,f8.4,1x,f8.3)
Range TDB-2451545 SunLon SunLat SC_Lon SC_Lat SC_Dist. Sun_M_Dist DistFac PhaseAng Moon_mrad Axis_Ang
C_END  End of label section
Row   TDB-2451545  SunLon SunLat SC_Lon SC_Lat SC_Dist. Sun_M_Dist  DistFac PhaseAng  Moon_mrad  Axis_Ang
       -------      -------  -------  -------       -------       -------       -------       -------       -------
-------
1   -777.547791  0.40  1.42  4.46  6.16 361263.7 0.9915820  0.868439  6.780  9.6185  -13.242
2   -747.986450  0.03  1.53  5.27  6.31 371926.9 0.9867886  0.911584  7.085  9.3427   -0.551
3   -718.426453  0.64  1.18  4.93  4.61 383036.8 0.9860848  0.965479  5.485  9.0717  11.964
```
Example of ROLO output file: Lirad

SECTION = Observation info ! Begin a section
Instrument = SeaWiFS ! Instrument making the observation
User = Gene Eplee ! Person submitting the calibration request
Process = 2004jun24T12:14 & multimoon ! Name of process that generated this file
Version = 2005jul24 ! Processing version
Run_Time = 2006Mar21 08:52:49 ! Local Date/Time of these calculations
Lunar_model = 311g = [coeff=r311g adjust=r311g05 ]
!! Corrections:
BEGIN_FREE ! Begins a free-form section describing the table section
This is a ROLO exchange for: LCT MOF Irradiance
See matching Geometry file for comments
GUIDE to columns below:
Headers: Row-1=band
Row-2=Nominal wavelength
Row-3=Effective wavelength for the Moon
Table : Col_0=count Col_1=oversample factor. Remaining columns are
% disagreement, with a row for each observation
(Spacecraft_Irradiance/ROLO_Irradiance -1.) in percent.
Format = (i3,f8.4,12f8.3)

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-1</td>
<td>3.3198</td>
<td>0.006</td>
<td>1.245</td>
<td>4.170</td>
<td>3.263</td>
<td>4.037</td>
<td>5.621</td>
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<tr>
<td>2</td>
<td>-2</td>
<td>3.3734</td>
<td>0.047</td>
<td>1.290</td>
<td>4.180</td>
<td>3.314</td>
<td>4.239</td>
<td>5.835</td>
</tr>
<tr>
<td>3</td>
<td>-3</td>
<td>3.3924</td>
<td>-0.991</td>
<td>0.331</td>
<td>3.235</td>
<td>2.353</td>
<td>3.158</td>
<td>4.714</td>
</tr>
</tbody>
</table>
How to determine the apparent size of the moon:
How to determine the apparent size of the moon:
Apparent size of the moon as a function of time:

Mean Unnormalized Correction = 0.278
Lunar irradiances after ROLO and oversampling correction:
SeaWiFS temperature correction

- SeaWiFS band 8 calibration temperature dependence on-orbit differs from prelaunch measurements
- Successfully corrected using lunar data
- Prelaunch Tvac different from on-orbit temperature environment
- Additional change since 2005 could be related to SeaWiFS orbit drift

Fig. from Eplee et al., SPIE, 2007
Lunar irradiances after noise correction:

Next step: fit function (exponential, linear, etc.)
VIIRS On-Orbit Calibration:

Lunar Time Series
Solar Time Series
Comparison

Slides provided by G. Eplee, SAIC
Lunar Calibration Data

M4 Lunar Calibration Image Sequence

M4 Lunar Image Unaggregated

M6 Lunar Image Aggregated
## Lunar Calibrations

<table>
<thead>
<tr>
<th>Cal Date</th>
<th>Cal Type</th>
<th>Bands</th>
<th>Gains</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan 4</td>
<td>Roll</td>
<td>M3-M7</td>
<td>High, Low</td>
<td>-55.4</td>
</tr>
<tr>
<td>Jan 5</td>
<td>Serendipitous</td>
<td>M1-M3</td>
<td>High, Low</td>
<td>-44.5</td>
</tr>
<tr>
<td>Feb 3</td>
<td>Roll</td>
<td>M6,M8-M11</td>
<td>High, Low</td>
<td>-56.2</td>
</tr>
<tr>
<td>Feb 3</td>
<td>Roll</td>
<td>M1-M5,M7</td>
<td>High, Low</td>
<td>-55.4</td>
</tr>
<tr>
<td>Mar 4</td>
<td>Serendipitous</td>
<td>M3,M5-M11</td>
<td>High, Low</td>
<td>-48.9</td>
</tr>
<tr>
<td>Apr 2</td>
<td>Roll/Sector Rot</td>
<td>M1-M11</td>
<td>High</td>
<td>-51.2</td>
</tr>
<tr>
<td>May 2</td>
<td>Roll/Sector Rot</td>
<td>M1-M11</td>
<td>High</td>
<td>-50.9</td>
</tr>
<tr>
<td>May 31</td>
<td>Roll/Sector Rot</td>
<td>M1-M11</td>
<td>High</td>
<td>-53.0</td>
</tr>
<tr>
<td>Jun 28</td>
<td>Serendipitous</td>
<td>M8, M9, M11</td>
<td>High, Low</td>
<td>-66.7</td>
</tr>
<tr>
<td>Jun 28</td>
<td>Serendipitous</td>
<td>M5-M7,M10</td>
<td>High, Low</td>
<td>-65.7</td>
</tr>
<tr>
<td>Jun 29</td>
<td>Serendipitous</td>
<td>M1-M4</td>
<td>High, Low</td>
<td>-64.8</td>
</tr>
<tr>
<td>Oct 25</td>
<td>Roll/Sector Rot</td>
<td>M1-M11</td>
<td>High</td>
<td>-51.0</td>
</tr>
<tr>
<td>Nov 23</td>
<td>Roll/Sector Rot</td>
<td>M1-M11</td>
<td>High</td>
<td>-50.7</td>
</tr>
</tbody>
</table>
Lunar Data Analysis

Analysis methodology:
• Calibrate lunar radiances, compute disk-integrated lunar radiances
• Use IFOV to convert radiances to irradiances: rectangular pixels
• Band aggregation is accounted for by oversampling correction
• ROLO Model is used to compute lunar residual time series

Observations:
• Radiometric response degradation is strongest in the red (Bands M5-M7)
• Degradation in blue (Band M1) from “yellowing” of optics is observed

Concerns:
• Limited amount of low-gain calibration data
• Is observational noise low enough to allow a detector-specific calibration?

The following plots show the High Gain, Mirror Side 0 data.
Solar Calibration Data

Solar diffuser provides spatially homogeneous light, opposite of lunar image.
Solar Diffuser Data Analysis

Analysis methodology:
• F-factor time series starting on January 2 are used for calibration
• SDSM-derived BRDF corrections are applied to F-factors
• Corrected F-factors are smoothed, then interpolated to a daily time basis
• Striping corrections are applied to corrected F-factors
• F-factors are interpolated between daily LUT entries in Ocean PEATE code

Observations:
• Radiometric response degradation is strongest in the red, ~zero in the blue
• Size of uncorrected F-factors for bands M1-M3 is ~ size of BRDF corrections

Concerns:
• NIR Degradation Anomaly for bands M5-M7
• BRDF Corrections for bands M1-M3
• Normalization of F-factor on January 2, at start of stable operations

The following plots show the High Gain, Mirror Side 0 data.
SDSM Normalized BRDF Time Series

Relative Reflectance

Time in Days since 1 Jan 2012 00:00:00 UT

Channel 1
Channel 2
Channel 3
Channel 4
Channel 5
Channel 6
Channel 7

Stable Calibration Data
Solar Time Series
Solar / Lunar Cal Comparison

Comparison methodology:
• Lunar and solar observations are at the same AOI on the half-angle mirror
• Determine F-factor at time of 1st lunar calibration
• Use lunar trend for each band to predict F-factor at the of subsequent calibrations
• Comparison of predicted lunar-derived F-factors with solar-derived F-factors

Observations:
• Lunar trends imply a BRDF overcorrection which decreases with wavelength

Concerns:
• Observational scatter in the lunar calibrations – at least a year of observations is required to assess the size of the scatter.
• Alternative F-factors are just now becoming practical
Solar / Lunar Comparison

VIIRS Solar / Lunar Calibration Time Series

Relative Response

Time in Days since 1 Jan 2012 00:00:00 UT

Band M4
Band M5
Band M6
Band M7
Lunar Cals

Stable Calibration Data
Solar / Lunar Comparison

VIIRS Solar / Lunar Calibration Time Series

Stable Calibration Data

Relative Response

0.96

0.97

0.98

0.99

1.00

1.01

Band M1

Band M2

Band M3

Band M4

Lunar Cals

Time in Days since 1 Jan 2012 00:00:00 UT
Conclusions:

• Ocean color requires relative accuracy better than 0.5% (goal for future sensors: 0.2%)
• This goal requires accuracy focused approach for
  1) sensor design and specifications
  2) prelaunch sensor characterization
  3) on-orbit monitoring
• NASA OBPG believes lunar measurements are most accurate for long term tending (depends on sensor design)
• In the past, each sensor had its own issues with regard to calibration/characterization, I expect that to continue for future sensors
Backup slides
Solar / Lunar Comparison

VIIRS Solar / Lunar Calibration Time Series

Percent Difference (solar-lunar)/lunar

Time in Days since 1 Jan 2012 00:00:00 UT

Band M1
Band M2
Band M3
Band M4
Band M5
Band M6
Band M7
2. Sensor requirements: Summary

Sensor requirements should

1) ensure quality of data product

2) be achievable at reasonable cost

3) testable
Orientation of polarization angle relative to MODIS leaving Polarization Source Assembly (PSA) not documented by Raytheon

Setup reconstructed with help of E. Waluschka

Fig. from Meister et al., 2005, Applied Optics
Band correlated noise:
Sensor requirements not strict enough: VIIRS

- Straylight masking influences global coverage
- Plot below shows reduction in coverage for masks around clouds for the 3 MODIS Aqua granules
- More straylight $\Rightarrow$ larger mask $\Rightarrow$ less coverage
Relative Spectral Response:

• SeaWiFS characterization: mixture of piece-part and system level characterization
• MODIS: system level characterization (double monochromator)
• VIIRS: system level characterization (double monochromator and laser)
• If well characterized, OOB is manageable
VIIRS Relative Spectral Response:

- Advantages: bright source, well calibrated
- Disadvantage: not continuous (delta lambda=0.1nm), flood illumination (crosstalk)
SeaWiFS RSR OOB for 870nm

- SeaWiFS spec: ratio out-of-band RSR to in-band RSR up to 5%
- Actual band 8 value: 3.7%
Spectral Response on-orbit (X. Xiong, MST 2010):

Aqua MODIS Center Wavelength Shift

Aqua MODIS Bandwidth Changes
Oversampling Correction

\[
f(t, \alpha, \gamma) = \frac{1}{Y_{\text{Moon}}(\alpha, \gamma)} \arctan \left( \frac{D_{\text{Moon}}}{R_{\text{Inst-Moon}}(t)} \right)
\]

- \(Y_{\text{Moon}}\) \(\equiv\) angular size of Moon in image
- \(D_{\text{moon}}\) \(\equiv\) diameter of Moon = 3476.4 km
- \(R_{\text{Inst-Moon}}\) \(\equiv\) Instrument-Moon distance
- \(t\) \(\equiv\) time of observation
- \(\alpha\) \(\equiv\) phase angle
- \(\gamma\) \(\equiv\) track angle
Lunar images may be oversampled:

MODIS band 1:
(image from presentation by J. Butler)
Sensor calibration: MODIS

- MODIS optics based on an (unprotected) rotating mirror
- Scan angle dependent degradation adds complexity to calibration approach

Fig. from Franz et al., 2008, Applied Optics
Sensor calibration: MODIS

- MODIS uses two calibration sources: solar diffuser (SD) and moon (through space view (SV) port)
- Interpolation over $\Delta \text{AOI}=40^\circ$ and 10% gain change problematic, extrapolation even more

<table>
<thead>
<tr>
<th></th>
<th>Start</th>
<th>SV</th>
<th>Nadir</th>
<th>SD</th>
<th>End</th>
</tr>
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<tbody>
<tr>
<td>Scan Pixel</td>
<td>1</td>
<td>23</td>
<td>677.5</td>
<td>979</td>
<td>1354</td>
</tr>
<tr>
<td>Scan Angle</td>
<td>-55.0</td>
<td>-53.2</td>
<td>0.0</td>
<td>24.5</td>
<td>55.00</td>
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<tr>
<td>Mirror AOI</td>
<td>10.5°</td>
<td>11.4°</td>
<td>38.0°</td>
<td>50.3°</td>
<td>65.5°</td>
</tr>
</tbody>
</table>

Table from Franz et al., 2008, Applied Optics
Lunar Time Series

VIIRS VisNir Lunar Calibrations

Includes Serendipitous Observations

Relative Response

Days since January 1 2012, 00:00 UT
Lunar Calibrations

Scheduled / Serendipitous Calibrations
  • Moon below horizon for 3 months during the year

Lunar residuals from the USGS ROLO Photometric Model of the Moon

Comparison of Solar / Lunar Calibrations
  • Same Angle of Incidence on Half-Angle Mirror

Alternate derivation of F-factor from lunar calibration time series
  • Compensates for uncertainties in diffuser BRDF correction
Solar Calibrations

SDSM time series (H-factor): BRDF change:

Solar Diffuser time series (F-factor)

BRDF-corrected F-factor:
1. Ocean color requirements

OBPG produces different levels of data products, starting from level 0 (uncalibrated DN):

1) Level 1: calibrated radiances

2) Level 2: ocean color products (snapshot, no spatial averaging)

3) Level 3: ocean color products averaged over time and space (8-day, monthly, etc.)