MODIS Calibration and Characterization for the Reflective Solar Bands (RSB)

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RSB Group (MODIS Characterization Support Team)

Ocean Color Calibration and Characterization Review Meeting, February 11-12, 2004
Outline

• Instrument Background
• Reflective Solar Bands (RSB) Calibration Overview
  – Pre-launch calibration activities
  – On-orbit calibration algorithm
• Calibration Results and Discussions
  – Solar diffuser (SD) bi-directional reflectance factor (BRF)
  – Temperature correction coefficients
  – Response versus scan angle (RVS)
  – SD screen (SDS) vignetting function (VF)
  – SD degradation using SD stability monitor (SDSM)
  – m1 trending results
Outline

• Challenging Issues and Concerns
  – BRF error’s impact on RSB calibration
  – Instrument and focal plane temperature effects
  – On-orbit RVS characterization limits
  – Polarization (SBRS/MCST/Miami)
  – SD screen vignetting effect – observations and simulation results (Xiong/Waluschka)
  – Scattering (SBRS/Waluschka)
  – Earth shine (Wolfe)
  – Calibration (detector’s response) stability
• 36 spectral bands with wavelengths from 0.4 to 14.5 µm
• Spatial resolution at nadir: 250m (2 bands), 500m (5 bands) and 1000m
• 4 FPAs: VIS, NIR, SMIR, LWIR
• On-Board Calibrators: SD/SDSM, SRCA, and BB (plus space view)
• 12 bit (0-4095) dynamic range
• 2-sided paddle wheel scan mirror scans 2330 km swath in 1.47 sec (1354 data frames, ±55º)
• Day data rate = 10.6 Mbps; night data rate = 3.3 Mbps (100% duty cycle, 50% day and 50% night)
Instrument Background

MODIS Design Parameters and Specifications

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²Spectral Radiance (W/m²-μm sr)
³SNR=Signal-to-noise ratio
⁴NEDT=Noise-equivalent temperature difference

1) Band 1 to 10: nm; Bands 20-39: μm
2) (W/m²-μm sr)
3) Performance goal is 30%-40% better than required
Instrument Background

MODIS Optics System
Instrument Background

MODIS Four Focal Planes (36 bands, 490 detectors)

S: scan direction;  T: track direction
B13 and B14 have 2 columns of detectors for TDI high and low gain outputs
Instrument Background

On-board Calibrators (OBCs)

Blackbody (BB)  Spectro-Radiometric Calibration Assembly (SRCA)

- BB for thermal emissive bands (TEB) calibration
- SD for reflective solar bands (RSB) calibration
- SDSM for monitoring SD degradation
- SRCA for spatial and spectral (RSB only) monitoring
• Calibration and Characterization:
  – SIS100 (Spectral Integration Sphere) used for RSB radiometric calibration in thermal vacuum (TV)
    • Calibration performed at three instrument temperature plateaus (hot, nominal, and cold)
    • Calibration parameters derived (detector’s response and its temperature dependence, noise characterization, non-linearity)
  – Spectral and spatial characterization (RSR; BBR)
  – Response versus scan angle measurements (RVS)
  – SD BRF measurements
  – Polarization characterization
Calibration Overview

MODIS Calibration Accuracy Requirements (RSB)

- 0.3Ltyp to 0.9Lmax; within ±45° of scan angle range:
  - Reflectance: 2%; Radiance: 5%
  - Polarization: 2% (except for B8 at 412nm)

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Calibration Overview

Pre-launch: Thermal Vacuum Chamber

Instrument Temperature Plateaus, SMIR and LWIR FPAs Temperatures (TEB)
Calibration Overview

Pre-launch

• Pre-launch calibration and characterization Results
  – Previous workshops
    • Examples from FM1 Pre-launch Calibration (pages 29-41, 56-64)
  – Science meeting briefings
  – Decisions for the on-orbit approach
    • Use on-board SD reflectance based calibration
    • Apply a simple linear algorithm (offset = 0)
    • Apply pre-launch RVS and temperature coefficients
    • Track SD degradation with SDSM
    • Derive and validate SD screen (SDS) vignetting function (VF)
    on-orbit
    • Use lunar observations to track the response stability
Calibration Overview

On-orbit Calibration

• Radiometric
  – Thermal emissive bands (TEB) by BB
  – Reflective solar bands (RSB) by SD/SDSM

• Spatial and Spectral
  – Spatial for RSB and TEB by SRCA
  – Spectral for RSB by SRCA

• Lunar Observations (support)
  – Instrument characterization
  – RSB response trending
  – RSB RVS
Calibration Overview

On-orbit Calibration Schematic

SDSM Views: Sun, SD, Dark

1.44% Screen

Optional 7.8% Screen (Bands 8-16 saturate w/o screen)

To Scan Mirror

SD

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**Calibration Overview**

**Calibration Algorithm**

**SD Reflectance based linear approach:**

\[
\frac{\rho_{EV} \cdot \cos(\theta_{EV})}{\rho_{SD} \cdot \cos(\theta_{SD})} = \frac{dn_{EV}^* \cdot d_{Earth-Sun(EV)}^2}{dn_{SD}^* \cdot d_{Earth-Sun(SD)}^2}
\]

\[
dn_{EV}^* = (DN_{EV} - <DN_{SV}>) \cdot \left\{1 + k_{INST} \cdot (T_{INST(EV)} - T_{REF})\right\} / RVS_{EV}
\]

\[
dn_{SD}^* = (<DN_{SD} > - <DN_{SV}>) \cdot \left\{1 + k_{INST} \cdot (T_{INST(SD)} - T_{REF})\right\} / RVS_{SD}
\]

- \(\rho_{EV} \cdot \cos(\theta_{EV})\): EV pixel reflectance factor (\(\rho\) is the BRF and \(\theta\) is the solar zenith angle)
- \(dn_{EV}^*\): Detector’s EV “corrected” digital number
- \(d_{Earth-Sun(EV)}\): Earth-Sun distance at the time of EV observation
- \(T_{INST(EV)}\): Instrument temperature at EV observation
- \(T_{REF}\): Instrument reference temperature
- \(k_{INST}\): Instrument temperature correction coefficients
- \(DN\): Detector’s response (raw DN)
Calibration Overview

**Calibration Algorithm**

**EV Reflectance factor:**

\[ \rho_{EV} \cdot \cos(\theta_{EV}) = m_1 \cdot d_{n_{EV}}^* \cdot d_{Earth-Sun}^2 \]

**SD calibration coefficient:**

\[ m_1 = \frac{\rho_{SD} \cdot \cos(\theta_{SD})}{d_{n_{SD}}^* \cdot d_{Earth-Sun}^2} \]

*Consider SD degradation (\(\Delta_{SD}\)) and SD screen effect (\(\Gamma_{SDS}\)):*

\[ m_1 = \frac{\rho_{SD} \cdot \cos(\theta_{SD})}{d_{n_{SD}}^* \cdot d_{Earth-Sun}^2} \cdot \Delta_{SD} \cdot \Gamma_{SDS} \]

- \(\rho_{SD}\): SD pre-launch Bidirectional Reflectance Factor (BRF_{SD})
- \(\Delta_{SD}\): SD on-orbit degradation (determined by SDSM)
- \(\Gamma_{SDS}\): SD screen vignetting function (1 for open mode)
Calibration Overview

Calibration Algorithm

**EV Radiance:**

\[
L_{EV} = \frac{E_{Sun} \cdot \rho_{EV} \cdot \cos(\theta_{EV})}{\pi \cdot d_{Earth\_Sun(EV)}^2}
\]

**Solar Irradiance** \(E_{SUN}:

- 0.4-0.8 \, \mu m \, Thuillier \, et \, al., \, 1998;
- 0.8-1.1 \, \mu m \, Neckel \, and \, Labs, \, 1984;
- Above 1.1 \, \mu m \, Smith \, and \, Gottlieb, \, 1974

**Others:**

- Thermal leak applied for SWIR bands (B5-7, B26)
- Leak coefficients determined from EV night time data
- B26 de-striping algorithm added (from C. Moeller of Wisconsin)
Results and Discussions
(SD BRF characterization)

\[
m_1 = \frac{\rho_{SD} \cdot \cos(\theta_{SD})}{dn_{SD}^* \cdot d^2_{Earth-Sun(SD)}} \cdot \Delta_{SD} \cdot \Gamma_{SDS}
\]
Results and Discussions
(SD BRF characterization)

- **Pre-launch** characterization performed by Santa Barbara Remote Sensing (SBRS)
- A scattering goniometer used in a comparison mode
- Traceability maintained from standard reference (characterized at NIST) \( \Rightarrow \) secondary reference (characterized at SBRS) \( \Rightarrow \) MODIS SD
- BRF calibrations performed at 400, 500, 600, 700, 900, and 1700nm over a two-dimensional grid of nine incident directions
- 2100nm BRF derived from Total Integrated Scatter (TIS) and BRF at other wavelengths
- Quadratic fitting applied to the BRF surfaces at characterized wavelengths
- Interpolation used to obtain BRF for MODIS spectral bands

\[
BRF_{\lambda}^{PL} (\theta_{SD}, \phi_{SD}) = a_0 + a_1 \theta_{SD} + a_2 \phi_{SD} + a_3 \theta_{SD}^2 + a_4 \phi_{SD}^2 + a_5 \theta_{SD} \phi_{SD}
\]

\( \theta_{SD} : \) SD Zenith, \( \phi_{SD} : \) SD Azimuth
Results and Discussions
(SD BRF characterization)

SBRS PFM BRF at 400nm (J. Young’s memo, PL3095-N06370A):

Average of and difference between pre and post BRF scale transfer

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Spatial uniformity and repeatability

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Results and Discussions
(SD BRF characterization)

SD Characterization Uncertainties (J. Young’s memo, PL3095-N06370A):

- NIST reference: 0.5%
- Characterization of SBRC scattering goniometer: 0.7%
- Transfer of NIST BRF scale to MODIS SD: 0.5%
- Solar diffuser characterization: 0.5%
- Solar diffuser spatial non-uniformities: 0.7%
- Interpolation angular / spectrally: 0.1%
- Prelaunch to orbit insertion BRDF change: 0.5%
- Characterization of 8.5% SD screen: 0.2%
- SDSM solar 2% attenuation and SDS impact: 0.5%
- On-orbit stray light elements during the use of the illuminated SD
- Solar illumination of the SD surrounds: 0.3%
- Earthshine through the SD door: 0.3%
- Earthshine through nadir aperture door: 0.1%

Errors can be different at different illuminating/viewing angles

RSS = 1.6%
Results and Discussions
(SD BRF characterization)

- **On-orbit** BRF validation performed using SD observation during yaw maneuvers at different azimuth angles
- Detector’s solar response is proportional to the BRF
- Bands 1-4 and 17-19 used to validate the BRF (bands 8-16 saturate without SD screen; crosstalk in SWIR bands 5-7 and 26)
- Results (Terra MODIS) agree with pre-launch values to within ±0.25%* (consistency checked among different detectors within a band; * B2 differences vary from -0.21 to 0.41%)
- Pre-launch BRF is used in the m1 calculation

\[ BRF_{SD} \propto \frac{dn_{SD}^*}{\cos(\theta_{SD})} \]

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Results and Discussions
(SD BRF characterization)

Terra B3 BRF: fitting (solid line); on-orbit data (symbols)

Symbols: Yaw numbers

Elevation angle (degree)
Results and Discussions
(SD BRF characterization)

Terra B3 BRF: pre-launch (solid line); on-orbit fitting (symbols)

Symbols: Yaw numbers
Results and Discussions
(Temperature correction coefficients)

\[ m_1 = \frac{\rho_{SD} \cdot \cos(\theta_{SD})}{dn^*_{SD} \cdot d_{\text{Earth-Sun}}^2} \cdot \Delta_{SD} \cdot \Gamma_{SDS} \]

\[ dn^*_{SD} = (\langle DN_{SD} \rangle - \langle DN_{SV} \rangle) \cdot \left\{ 1 + k_{\text{INST}} \cdot (T_{\text{INST(SD)}} - T_{\text{REF}}) \right\} \div RVS_{SD} \]
Results and Discussions
(Temperature correction coefficients)

Pre-launch characterization results
More examples in FM1 (Aqua MODIS) Pre-launch Calibration (pages 29-41)

TERRA MODIS R_ star and K_inst, Electronic side A, Band 8

Pre-launch calibration: \[ L_{SIS} = \frac{dn_{SIS}}{R^*} \]

Temperature correction coefficients:
\[ k_{INST} = \left\{ R^* (T_{REF}) / R^* (T_{INST}) - 1 \right\} / (T_{INST} - T_{REF}) \]
Results and Discussions
(Response versus scan angles)

- **Pre-launch** characterization and results
  - Examples in FM1 Pre-launch Calibration (pages 56-64)

- **On-orbit** RVS
  - Response trending from SD, SRCA, and Lunar observations
  - These three sectors have different angles of incidence (AOI) to the scan mirror
  - Results used to update pre-launch values (for VIS bands 8, 9, 3, and 10)
  - Ocean group applies “additional correction”
Results and Discussions
(Response versus scan angles)

Terra MODIS RSB Prelaunch RVS vs. AOI (solid: MS 1, dotted: MS 2)
Results and Discussions
(Response versus scan angles)

RSB Calibration Using the Moon

SD Calibration

\[ m_1 = \frac{BRF_{SD} \cdot \cos(\theta_{SD})}{<dn_{SD}^*> \cdot d_{Earth-Sun}^2} \cdot \Gamma_{SD} \cdot \Delta_{SD} \]

Moon Calibration

Geometry factors corrected:

\[ f = \frac{f_{phase-angle} \cdot f_{libration} \cdot f_{over-sampling}}{d_{Sun-Moon}^2 \cdot d_{Modis-Moon}^2} \]

How:
Nighttime orbits, SV port
0-20° roll maneuvers, 55° phase angle

Why:
No SD degradation, different AOI
Results and Discussions
(Response versus scan angles)

Geometry factors corrected:

\[ f = \frac{f_{\text{phase-angle}} \cdot f_{\text{libration}} \cdot f_{\text{over-sampling}}}{d_{\text{Sun-Moon}}^2 \cdot d_{\text{Modis-Moon}}^2} \]
Results and Discussions
(Response versus scan angles)

SD AOI = 50.2°

Moon AOI = 11.2°

Symbols are the band numbers; B-side response normalized to the A-side

Optics (scan mirror) degradation at different AOI
Time-dependent RVS implemented in MODIS L1B code using response trending results from SD, SRCA (AOI=38°), and the Moon
Results and Discussions
(SDS vignetting function)

\[ m_1 = \frac{\rho_{SD} \cdot \cos(\theta_{SD})}{dn_{SD}^* \cdot d^2_{Earth-Sun(SD)}} \cdot \Delta_{SD} \cdot \Gamma_{SDS} \]
Results and Discussions
(SDS vignetting function)

- No pre-launch characterization activities
- On-orbit characterization using ratio of detector’s solar response with SDS to that without SDS; on-orbit yaw maneuver data sets
- VF determined from bands 3-4 and 17-19 and applied to bands 8-16 which saturate without SDS
- Fitting results agree with observations to within about ±0.30%
- Results of quadratic fitting coefficients used in m1 calculation

\[
\Gamma_{SDS} = \left( \frac{dn_{SD}^*}{\cos(\theta_{SD})} \right)_{SDS\_Down} \div \left( \frac{dn_{SD}^*}{\cos(\theta_{SD})} \right)_{SDS\_Up}
\]
Results and Discussions
(SDS vignetting function)

VF for terra B3, Diff: [-0.19%, 0.20%]

<table>
<thead>
<tr>
<th>Band</th>
<th>Min_Diff</th>
<th>Max_Diff</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.1623</td>
<td>0.1942</td>
<td>0.0619</td>
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<tr>
<td>2</td>
<td>-0.2086</td>
<td>0.2472</td>
<td>0.0874</td>
</tr>
<tr>
<td>3</td>
<td>-0.1936</td>
<td>0.1970</td>
<td>0.0686</td>
</tr>
<tr>
<td>4</td>
<td>-0.1647</td>
<td>0.2310</td>
<td>0.0686</td>
</tr>
<tr>
<td>17</td>
<td>-0.2301</td>
<td>0.2554</td>
<td>0.0800</td>
</tr>
<tr>
<td>18</td>
<td>-0.2887</td>
<td>0.3357</td>
<td>0.0992</td>
</tr>
<tr>
<td>19</td>
<td>-0.2089</td>
<td>0.2661</td>
<td>0.0884</td>
</tr>
</tbody>
</table>

(diffERENCE IN %)
Results and Discussions
(SD degradation using SDSM)

\[ m_1 = \frac{\rho_{SD} \cdot \cos(\theta_{SD})}{d\eta_{SD} \cdot d^2_{Earth-Sun(SD)}} \cdot \Delta_{SD} \cdot \Gamma_{SDS} \]
### Results and Discussions

**(SD degradation using SDSM)**

#### SD (BRF) degradation from SDSM

\[
\Delta_{SD} = \frac{dc_{SD\_view}}{dc_{Sun\_view}}
\]

- Large ripples seen from SDSM Sun view response
- Ripples caused due to design error in a SDSM component
- This approach did not work
- Relative approach developed

<table>
<thead>
<tr>
<th>SDSM detectors</th>
<th>Center wavelength (nm)</th>
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<tbody>
<tr>
<td>D1</td>
<td>411.97</td>
</tr>
<tr>
<td>D2</td>
<td>465.69</td>
</tr>
<tr>
<td>D3</td>
<td>529.74</td>
</tr>
<tr>
<td>D4</td>
<td>553.75</td>
</tr>
<tr>
<td>D5</td>
<td>646.14</td>
</tr>
<tr>
<td>D6</td>
<td>746.62</td>
</tr>
<tr>
<td>D7</td>
<td>856.49</td>
</tr>
<tr>
<td>D8</td>
<td>904.29</td>
</tr>
<tr>
<td>D9</td>
<td>936.23</td>
</tr>
</tbody>
</table>

\(dc_{Sun\_view}\): SDSM detector’s Sun view digital count (DC) with dark signal subtracted

\(dc_{SD\_view}\): SDSM detector’s SD view digital count (DC) with dark signal subtracted and SD BRF factor corrected
Results and Discussions
(SD degradation using SDSM)

Large ripples seen in SDSM Sun view response

Original approach not working!!

\[ \Delta_{SD} = \frac{dc_{SD\_view}}{dc_{Sun\_view}} \]

SDSM data during SD calibration
Results and Discussions
(SD degradation using SDSM)

\[ \Delta_{SD} = \frac{dc_{SD}}{dc_{Sun}} \]

\[
\left\{ \frac{dc_{SD, view}^{D1}}{dc_{Sun, view}^{D1}} \right\} \left\{ \frac{dc_{SD, view}^{D9}}{dc_{Sun, view}^{D9}} \right\}
\]

SDSM data from Yaw

Normalize to SDSM D9 at 936nm

Terra MODIS SDSM D9 degradation trending

(Leland and Arecchi, 1995, SPIE, 2475, 384)
Results and Discussions
(SD degradation using SDSM)

Green: no-normalization to D9
Red: normalize to D9 at 936nm
Results and Discussions
(SD degradation using SDSM)
Results and Discussions
(m1 trending results)

Examples given for B8 and B11. All m1 trending results are available.
Results and Discussions
(m1 trending results)

Examples given for B8 and B11. All m1 trending results are available.
Results and Discussions
(Summary)

• MODIS RSB calibration error budget included
  – SD characterization errors (NIST reference, standard transfer, instrument effect, measurements errors
  – Pre-launch to on-orbit BRF change estimate
  – SD and SDSM screen impact
  – Stray light elements (e.g. Earthshine related)

• Considering all the factors identified in the calibration chain, the calibration is within the instrument specifications
  – Reflectance: ±2%; Radiance: ±5%

• Caveats
  – Polarization correction, if necessary, is used in the science application algorithm, not in the L1B calibration
  – RVS changes on-orbit, if not fully characterized, will cause additional errors (at different AOIs from that of the SD)
# List of Acronyms and Abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AOI</td>
<td>Angle of Incidence</td>
</tr>
<tr>
<td>BB</td>
<td>Blackbody</td>
</tr>
<tr>
<td>BBR</td>
<td>Band to Band Registration</td>
</tr>
<tr>
<td>BCS</td>
<td>Blackbody Calibration Source</td>
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<tr>
<td>BRDF</td>
<td>Bi-directional Reflectance Distribution Function</td>
</tr>
<tr>
<td>BRF</td>
<td>Bi-directional Reflectance Factor</td>
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<tr>
<td>EV</td>
<td>Earth View</td>
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<tr>
<td>FPA</td>
<td>Focal Plane Assembly</td>
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<tr>
<td>IFOV</td>
<td>Instantaneous Field Of View</td>
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<tr>
<td>NAD</td>
<td>Nadir Aperture Door</td>
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<tr>
<td>OBC</td>
<td>On Board Calibration</td>
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<tr>
<td>OOB</td>
<td>Out-of-Band</td>
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<tr>
<td>RSB</td>
<td>Reflective Solar Bands</td>
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<tr>
<td>RSR</td>
<td>Relative Spectral Response</td>
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<tr>
<td>RVS</td>
<td>Response Versus Scan Angle</td>
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<tr>
<td>TEB</td>
<td>Thermal Emissive Bands</td>
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<tr>
<td>SD</td>
<td>Solar Diffuser</td>
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<tr>
<td>SDS</td>
<td>Solar Diffuser Screen</td>
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<tr>
<td>SDSM</td>
<td>Solar Diffuser Stability Monitor</td>
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<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
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<tr>
<td>SIS</td>
<td>Spherical Integrating Source</td>
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<tr>
<td>SpMA</td>
<td>Spectral Measurement Assembly</td>
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<tr>
<td>SRCA</td>
<td>Spectro-Radiometric Calibration Assembly</td>
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<td>SVD</td>
<td>Space View Door</td>
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<tr>
<td>SVS</td>
<td>Space View Source</td>
</tr>
<tr>
<td>TDI</td>
<td>Time Delayed Integration</td>
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<tr>
<td>TOA</td>
<td>Top of Atmosphere</td>
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<tr>
<td>VF</td>
<td>Vignetting Function</td>
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