Correction to Method of Establishing the Absolute Radiometric Accuracy of Remote Sensing Systems While On-orbit Using Characterized Stellar Sources

March 15, 2006
Howard S. Bowen and
Douglas M. Cunningham

Engineered for life
Presentation Outline

- Brief History of Related Events
- Overview of Original Method Used to Establish Absolute Radiometric Accuracy of Remote Sensing Instruments Using Stellar Sources
- Considerations to Improve the Stellar Calibration Approach
- Summary
Brief History of Related Events
Historical Perspective

- September 1994: IKONOS Launch
- March 2000: IOC Completed (4 Non-G&S Stars)
- March 2003: 2nd Stability Recheck (4 Non- & 7 G&S Stars)
- March 2004: 3rd Stability Recheck (4 Non- & 7 G&S Stars)
- March 2005: 4th Stability Recheck (4 Non- & 7 G&S Stars)
- March 2006: 5th Stability Recheck (4 Non- & 7 G&S Stars)
- November 2002: Stellar Calibration Method Presented at ISPRS Conference held in Denver, Colorado
- March 2004: 3rd Stability Recheck (4 Non- & 7 G&S Stars)
- March 2005: 4th Stability Recheck (4 Non- & 7 G&S Stars)
- March 2006: Stellar Calibration Correction Presented at JACIE Conference in Washington DC
Absolute Radiometric Calibration

The purpose of absolute radiometric calibration is to determine the expected response for any in-band entrance aperture radiance presented to the telescope.

\[
\text{CalCoef}_j = \frac{DC_j}{L_j}
\]

where:
- CalCoef = In-Band Calibration Coefficient \((DC/(W/m^2\text{-sr}))\)
- \(DC_j\) = Measured Digital Counts in the \(j^{th}\) band (DC)
- \(L_j\) = Entrance Aperture Radiance in the \(j^{th}\) band \((W/m^2\text{-sr})\)
Overview of Original Method Used to Establish Absolute Radiometric Accuracy of Remote Sensing Instruments Using Stellar Sources
Original Method to Establish Absolute Radiometric Calibration Accuracy Using Stellar Sources

- Identify Acceptable Radiometrically Characterized Stars
  - Compute Broadband Entrance Aperture Flux Density
- Gather Stellar Response Data
  - Extract Stellar Scene Data (sum digital counts)
- Generate Calibration Coefficient
- Verify Results Using Independent Sources
- Determine System Stability
- Determine System Linearity
Bright Star Catalogue Stars
-1.46 < Vmag < 8.0 = 9110 Items
Bright Stars most likely to be compatible with IKONOS-like Remote Sensing Instruments

Bright Star Catalogue Revision 5.0 Histogram

Remote Sensing Compatible

Visual Magnitude Bins

Stars per Magnitude

2.0 < Vmag < 4.0

468 Stars
BSC Remote Sensing Compatible Stars (468) and Spectrophotometric Standard Stars (28)
# Remote Sensing Compatible Spectrophotometric Standard Stars (28) (Excluding Vega and 1 repeated star)

<table>
<thead>
<tr>
<th>RS ID</th>
<th>BSC ID</th>
<th>RA (J2000)</th>
<th>DEC (J2000)</th>
<th>Proper Name</th>
<th>Vmag</th>
<th>Spectral Type</th>
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<tbody>
<tr>
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<td>HR7001</td>
<td>18:36:56</td>
<td>38.7836</td>
<td>Alpha Lyrae</td>
<td>-0.03</td>
<td>A0V</td>
</tr>
<tr>
<td>HST 2</td>
<td>HR718</td>
<td>2:28:09</td>
<td>8.4601</td>
<td>Xi 2 Ceti</td>
<td>4.28</td>
<td>B9III</td>
</tr>
<tr>
<td>HST 3</td>
<td>HR1544</td>
<td>4:50:36</td>
<td>8.9002</td>
<td>Pi 2 Orionis</td>
<td>4.36</td>
<td>A1V</td>
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<tr>
<td>HST 4</td>
<td>HR3454</td>
<td>8:43:13</td>
<td>3.3986</td>
<td>Eta Hydrae</td>
<td>4.30</td>
<td>B3V</td>
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<tr>
<td>HST 5</td>
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<td>Theta Crater</td>
<td>4.70</td>
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<td>HST 6</td>
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<td>-5.5390</td>
<td>Theta Virginis</td>
<td>4.38</td>
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<td>108 Virginis</td>
<td>5.68</td>
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<td>HST 8</td>
<td>HR7596</td>
<td>19:54:44</td>
<td>0.2735</td>
<td>58 Aquilae</td>
<td>5.62</td>
<td>A0III</td>
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<td>HST 9</td>
<td>HR7950</td>
<td>20:47:40</td>
<td>-9.4958</td>
<td>Eta Aquarii</td>
<td>3.78</td>
<td>A1V</td>
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<tr>
<td>HST 10</td>
<td>HR8634</td>
<td>22:41:27</td>
<td>10.8314</td>
<td>Zeta Pegasi</td>
<td>3.40</td>
<td>B8V</td>
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<tr>
<td>HST 11</td>
<td>HR9087</td>
<td>0:01:49</td>
<td>-3.0275</td>
<td>29 Piscium</td>
<td>5.12</td>
<td>B7III</td>
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<tr>
<td>HST 12</td>
<td>HR153</td>
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<td>53.8969</td>
<td>Zeta Cassiopeiae</td>
<td>3.66</td>
<td>B2IV</td>
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<tr>
<td>HST 13</td>
<td>HR1996</td>
<td>5:45:59</td>
<td>-32.3065</td>
<td>Mu Columbae</td>
<td>5.17</td>
<td>O9V</td>
</tr>
<tr>
<td>HST 14</td>
<td>HR4554</td>
<td>11:53:49</td>
<td>53.6948</td>
<td>Gamma Ursae Majoris</td>
<td>2.44</td>
<td>A0V</td>
</tr>
<tr>
<td>HST 15</td>
<td>HR5191</td>
<td>13:47:32</td>
<td>49.3133</td>
<td>Eta Ursae Majoris</td>
<td>1.86</td>
<td>B3V</td>
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<td>G&amp;S 1</td>
<td>HR6787</td>
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<td>20.8144</td>
<td>102 Her</td>
<td>4.36</td>
<td>B2IV</td>
</tr>
<tr>
<td>G&amp;S 2</td>
<td>HR3454</td>
<td>8:43:13</td>
<td>3.3986</td>
<td>Eta Hydrae</td>
<td>4.30</td>
<td>B3V</td>
</tr>
<tr>
<td>G&amp;S 3</td>
<td>HR6588</td>
<td>17:39:27</td>
<td>46.0064</td>
<td>85 Iot Her</td>
<td>3.80</td>
<td>B3IV</td>
</tr>
<tr>
<td>G&amp;S 4</td>
<td>HR6556</td>
<td>17:34:56</td>
<td>12.5600</td>
<td>55 Alp Oph</td>
<td>2.08</td>
<td>A5III</td>
</tr>
<tr>
<td>G&amp;S 5</td>
<td>HR6561</td>
<td>17:37:35</td>
<td>-15.3986</td>
<td>55 Xi Ser</td>
<td>3.54</td>
<td>F0IVDe1 Scet</td>
</tr>
<tr>
<td>G&amp;S 6</td>
<td>HR1411</td>
<td>4:28:34</td>
<td>15.9622</td>
<td>77 The1 Tau</td>
<td>3.84</td>
<td>K0IIIbFe-0.5</td>
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<tr>
<td>G&amp;S 7</td>
<td>HR4247</td>
<td>10:53:18</td>
<td>34.2150</td>
<td>46 LMI</td>
<td>3.83</td>
<td>K0+III-IV</td>
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<tr>
<td>G&amp;S 8</td>
<td>HR4335</td>
<td>11:09:39</td>
<td>44.4986</td>
<td>52 Psi UMa</td>
<td>3.01</td>
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<tr>
<td>G&amp;S 9</td>
<td>HR5854</td>
<td>15:44:16</td>
<td>6.4256</td>
<td>24 Alp Ser</td>
<td>2.65</td>
<td>K2IIbCN1</td>
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<tr>
<td>G&amp;S 10</td>
<td>HR3905</td>
<td>9:52:45</td>
<td>26.0069</td>
<td>24 Mu Leo</td>
<td>3.88</td>
<td>K2IIICN1Ca1</td>
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<tr>
<td>G&amp;S 11</td>
<td>HR3845</td>
<td>9:39:51</td>
<td>-1.1428</td>
<td>35 Iot Hya</td>
<td>3.91</td>
<td>K2.5IIIbBa0.3</td>
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<tr>
<td>G&amp;S 12</td>
<td>HR2574</td>
<td>6:54:11</td>
<td>-12.0386</td>
<td>14 The CMa</td>
<td>4.07</td>
<td>K4III</td>
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<tr>
<td>G&amp;S 13</td>
<td>HR3003</td>
<td>7:46:07</td>
<td>18.5100</td>
<td>81 Gem</td>
<td>4.88</td>
<td>K4III-Ilb</td>
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<tr>
<td>G&amp;S 14</td>
<td>HR2905</td>
<td>7:35:55</td>
<td>26.8958</td>
<td>69 Ups Gem</td>
<td>4.06</td>
<td>M0III-Illb</td>
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<tr>
<td>G&amp;S 15</td>
<td>HR1556</td>
<td>4:52:32</td>
<td>14.2506</td>
<td>4 Omi 1Ori</td>
<td>4.74</td>
<td>S3.5/1-</td>
</tr>
</tbody>
</table>
Remote Sensing Compatible Spectrophotometric Standard Stars Spectral Data

![Graph showing spectral data for various standard stars](image)

- HR7001, V=0.03
- HR718
- HR1544
- HR4554, V=4.3
- HR468
- HR4693
- HR551
- HR596
- HR950
- HR634
- HR087
- HR153
- HR1998, V=5.17
- HR4554, V=2.44
- HR5191, V=1.86
- G&S 6
- G&S 7, V=4.134
- G&S 8
- G&S 83
- G&S 86
- G&S 109
- G&S 118
- G&S 127
- G&S 134
- G&S 135
- G&S 142
- G&S 149
- G&S 150
- G&S 152
- G&S 158
**Hertzsprung-Russell Diagram Showing Remote Sensing Characterized Star Categories**

<table>
<thead>
<tr>
<th>Star ID(s)</th>
<th>Category</th>
</tr>
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<tbody>
<tr>
<td>HR7596</td>
<td>A0III</td>
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<tr>
<td>HR7001, HR4554</td>
<td>A0V</td>
</tr>
<tr>
<td>HR4963</td>
<td>A1IV</td>
</tr>
<tr>
<td>HR1544, HR7950</td>
<td>A1V</td>
</tr>
<tr>
<td>HR6561</td>
<td>A5III</td>
</tr>
<tr>
<td>HR153, HR6787</td>
<td>B2IV</td>
</tr>
<tr>
<td>HR6556</td>
<td>B3IV</td>
</tr>
<tr>
<td>HR1591, HR3454</td>
<td>B3V</td>
</tr>
<tr>
<td>HR9087</td>
<td>B7III</td>
</tr>
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<td>HR8634</td>
<td>B8V</td>
</tr>
<tr>
<td>HR4468, HR550</td>
<td>B9.5V</td>
</tr>
<tr>
<td>HR718</td>
<td>B9III</td>
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<tr>
<td>HR1411</td>
<td>F0IV</td>
</tr>
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<td>HR4247</td>
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</tr>
<tr>
<td>HR4335</td>
<td>K1III</td>
</tr>
<tr>
<td>HR3845</td>
<td>K2.5III</td>
</tr>
<tr>
<td>HR5854</td>
<td>K2IIIb</td>
</tr>
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<td>HR3095</td>
<td>K2IIIC</td>
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<tr>
<td>HR2905</td>
<td>M0III</td>
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<tr>
<td>HR1996</td>
<td>O9V</td>
</tr>
<tr>
<td>HR1556</td>
<td>S3.5</td>
</tr>
</tbody>
</table>

**Diagam Notes:**
- The diagram shows the relationship between absolute magnitude and luminosity, with stars plotted according to their surface temperature and spectral class.
- **Sun** is highlighted, indicating its position in the H-R diagram.
- Various spectral classes are marked, including A, B, F, G, K, M, indicating different stages of stellar evolution.
- Bright stars and other notable stars are also labeled for reference.
Brightest G&S Stars and Those Used for IKONOS Absolute Radiometric Accuracy Assessment (7)
J.E. Gunn & L.L. Stryker – Stellar Spectrophotometric Atlas
3130 < \lambda < 10800 Å (1983), Remote Sensing Stellar Subset

![Graph showing flux vs. frequency for various stellar subsets](image-url)
Un-normalized Stellar Spectral Data v. Frequency
Remote Sensing Stellar Subset
Un-normalized Stellar Spectral Data v. Wavelength Remote Sensing Stellar Subset

![Graph showing un-normalized Stellar Spectral Data vs. Wavelength. The graph plots flux (in mW/m²·μm) against wavelength (in μm). The x-axis represents the wavelength ranging from 0.3 to 1.1 μm, and the y-axis represents the flux ranging from 0E-00 to 1.2E-05 mW/m²·μm. Each spectral subset is represented by a different color line.](image-url)
De-reddening Coefficients for Stellar Spectral Data
Remote Sensing Stellar Subset

![Graph showing de-reddening coefficients for stellar spectral data. The graph displays wavelengths ranging from 0.3 to 1.1 μm on the x-axis and flux in mW/m²-μm on the y-axis. Different stellar subsets are represented by distinct lines and colors.](image-url)
Re-reddened Stellar Spectral Data v. Wavelength
Remote Sensing Stellar Subset

![Graph showing stellar spectral data vs. wavelength]

- G&S 6
- G&S 7
- G&S 8
- G&S 83
- G&S 86
- G&S 109
- G&S 118
- G&S 127
- G&S 134
- G&S 135
- G&S 142
- G&S 149
- G&S 150
- G&S 152
- G&S 158

Flux (mW/m²-μm)

Wavelength (μm)
Subset of G&S Stellar Spectra Used To Assess IKONOS Absolute Radiometric Accuracy
**IKONOS MS Bands Relative Spectral Response (RSR)**
(http://www.spaceimaging.com/products/ikonos/spectral.htm)

<table>
<thead>
<tr>
<th>Band</th>
<th>Lower 50% (nm)</th>
<th>Upper 50% (nm)</th>
<th>Bandwidth (nm)</th>
<th>Center (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pan</td>
<td>525.8</td>
<td>928.5</td>
<td>403</td>
<td>727.1</td>
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<tr>
<td>MS-1 (Blue)</td>
<td>444.7</td>
<td>516.0</td>
<td>71.3</td>
<td>480.3</td>
</tr>
<tr>
<td>MS-2 (Green)</td>
<td>506.4</td>
<td>595.0</td>
<td>88.6</td>
<td>550.7</td>
</tr>
<tr>
<td>MS-3 (Red)</td>
<td>631.9</td>
<td>697.7</td>
<td>65.8</td>
<td>664.8</td>
</tr>
<tr>
<td>MS-4 (VNIR)</td>
<td>757.3</td>
<td>852.7</td>
<td>95.4</td>
<td>805.0</td>
</tr>
</tbody>
</table>

**Note:**
1. Spectral Bandwidths are Full-Width at Half-Max (FWHM)
2. Panchromatic Band does not incorporate spectral filtering - response is that of optics/detector only

*Values Shown in Color are Bandpass Definitions Using 50nm-interval Datasets Without Interpolation*
IKONOS Multi-spectral Bands RSR - 50nm Intervals
(as published on GeoEye website)
G&S Stellar Spectra and IKONOS MS Bands RSR

Flux (mW/m²-μm)

Wavelength (μm)

0.0E+00 2.0E-06 4.0E-06 6.0E-06 8.0E-06 1.0E-05 1.2E-05

G&S 7
G&S 83
G&S 109
G&S 127
G&S 134
G&S 142
G&S 150
Blue
Green
Red
NIR
IKONOS Stellar Calibration Coefficients 2001 Compared with JACIE 2001 Results

JACIE 2001 Coefficients (dashed lines):
- BLU: $y = 73.9x$
- GRN: $y = 73.3x$
- RED: $y = 99.3x$
- NIR: $y = 85.9x$

- Entrance-Aperture Radiance (W/m²-sr)
- Digital Counts

- G&S BLU
- G&S GRN
- G&S RED
- G&S NIR
- JACIE BLU
- JACIE GRN
- JACIE RED
- JACIE NIR

- Linear (G&S BLU)
- Linear (G&S GRN)
- Linear (G&S RED)
- Linear (G&S NIR)
# IKONOS Stellar Calibration Coefficients 2001 Compared with JACIE 2001 Results

<table>
<thead>
<tr>
<th>MS Band</th>
<th>JACIE 2001</th>
<th>Stellar 2001 FW</th>
<th>Δ Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue 445-516 nm</td>
<td>72.8</td>
<td>63.3x – 51</td>
<td>Δ = 14%</td>
</tr>
<tr>
<td>Green 506-595 nm</td>
<td>72.7</td>
<td>63.8x – 31</td>
<td>Δ = 13%</td>
</tr>
<tr>
<td>Red 632-698 nm</td>
<td>94.9</td>
<td>79.8x – 40</td>
<td>Δ = 20%</td>
</tr>
<tr>
<td>NIR 757-853 nm</td>
<td>84.3</td>
<td>67.0 – 31</td>
<td>Δ = 21%</td>
</tr>
</tbody>
</table>
Considerations to Improve the Stellar Calibration Approach
Traditional Remote Sensing System Calibration Methods Determine Entrance Aperture Radiance

Entrance Aperture Radiance
(W/m²-sr)

Digital Counts (DC)

Remote Sensing System

Uniform Extended Source
Typically the System Response Function Takes Into Consideration All of the Components of the System

\[
SRF = A_o \Omega_{det} \tau_{ota}(t, \alpha) \tau_{fltr}(\lambda) R_{det}(\lambda, T_{fp}) R_{elec}(\lambda, T_{elec}) \]

\[
R_{A/D}(\lambda, DC) \tau_{NL}(\lambda, DC, DC_0) \tau_{noise}(\lambda, L) \Delta \lambda
\]
Calibration Coefficient is the Relationship between Entrance Aperture Radiance and Digital Counts

\[
\text{Calibration Coefficient} \left( \frac{\text{DC}}{\frac{W}{m^2 - \text{sr}}} \right) = \frac{\text{Digital Counts (DC)}}{\text{Entrance Aperture Radiance} \left( \frac{W}{m^2 - \text{sr}} \right)}
\]
Stellar Calibration Uses Well-characterized Stellar Flux Densities Arriving at the Payload Aperture

Entrance Aperture Radiant Spectral Flux Density (W/m²)

Digital Counts (DC)

Remote Sensing System

Radiometrically Characterized Star
Stellar Calibration Method as Presented in 2002 ISPRS Paper

- Assumed
  - All of the energy was represented as if it was being captured within a single Instantaneous Field of View (IFOV) of the detector

- Did not consider Encircled Energy ($\varepsilon_f$) function for the optical system
  - Encircled Energy Function determines the amount of energy falling on the focal plane that is higher than the response threshold of a detector circuit

- Did not consider compression artifacts imposed on stellar scene data
  - Older Compression Algorithms and Points Sources don’t play well

- Did not include an absolute spectral reference associated with the vicarious ground calibration approach
  - Stellar Spectral Content versus Solar/2xAtmosphere/Ground Spectral Content
All Pixels with Measurable Response Summed to All Energy Contained Within Point Spread Function

- **Theoretical Area of Point Source at Image Plane** $(A_p)$
- **Blurred Point Spread Function at Image Plane**
- **Image Pixels Summed to Collect Total Response (DC)**
- **Equivalent Detector Area** $(A_d)$
Average Number of Detectors within 7x7 pixel Area Summed to Produce the Total Digital Counts
Stellar Calibration Sensor Response Function Algorithm

\[
L_{i,j} = \int_{350\,\text{nm}}^{1100\,\text{nm}} \frac{F_i(\lambda)}{\Omega_{do}} * RSR_j(\lambda) * \varepsilon_{f_j}(A_m) * SCF_{i,j} \, d\lambda
\]

where:
- \( L_{i,j}(\lambda) \) = Equivalent Radiance of Star at the Aperture (W/m^2-sr)
- \( F_i(\lambda) \) = Spectral Flux Density at Entrance Aperture (W/m^2-\mu m)
- \( \Omega_{do} \) = Solid Angle of a single Detector (sr)
- \( RSR_j(\lambda) \) = Relative Spectral Response of jth Band (%)
- \( \varepsilon_{f_j}(A_m) \) = Encircled Energy Function of jth Band (%)
- \( SCF_{i,j} \) = Spectral Correction Function of jth Band (%)
CRSS w/simulated stellar PSF (log scale)
15x15, 48um pixels, $\lambda = 0.75$ um, Focus at 700 km
Point Source Illumination at Focal Plane Is Distributed According to Optical Transfer Function
Encircled Energy Function Describes Unaccounted Energy Due to Spatial Distribution at Focal Plane

Encircled Energy Function ($\varepsilon_f$)

Point Spread Function
Discrete Detectors in the Focal Plane Undersample the Point Source Energy Distribution

Encircled Energy Function ($\varepsilon_f$)

Point Spread Function

Undersampled PSF

Detectors
Low-contrast Stellar Scenes Cause Compression Artifacts that Contribute to Algorithm Uncertainty

Encircled Energy Function ($\varepsilon_f$)

Point Spread Function

Undersampled PSF

Compression Algorithm Artifacts
Empirical Encircled Energy Functions that Provide Match Between Stellar and Ground Results
Spectral Correction Function can be Employed to Reference the Stellar to a Solar/Ground Spectra

\[
SCF_{ij} = \frac{\int_{350nm}^{1100nm} L_{\text{star}}(\lambda) RSR(\lambda) d\lambda}{\int_{350nm}^{1100nm} L_{\text{gnd}}(\lambda) RSR(\lambda) d\lambda}
\]

where:
- \( L_{\text{star}}(\lambda) \) = Equivalent Radiance of Star at the Aperture (W/m\(^2\)-sr)
- \( L_{\text{gnd}}(\lambda) \) = Radiance of Reference Ground Scene at the Aperture (W/m\(^2\)-sr)
- \( RSR_j(\lambda) \) = Relative Spectral Response of jth Band (%)
- \( SCF_{ij} \) = Spectral Correction Function of jth Band (%)
Correlation between Corrected Stellar Calibration and Vicarious Ground Calibration Results

![Graph showing correlation between Radiance (W/m²sr) and Digital Counts. The graph includes data from various wavelengths and years.]

- Blue JACIE 2000
- Green JACIE 2000
- Red JACIE 2000
- Near Infrared JACIE 2000
- Blue JACIE 2001
- Green JACIE 2001
- Red JACIE 2001
- Near Infrared JACIE 2001
- Blue JACIE 2002
- Green JACIE 2002
- Red JACIE 2002
- Near Infrared JACIE 2002
- G&S Blue
- G&S Green
- G&S Red
- G&S Near Infrared
Topics for Future Investigations

- Add New Characterized Stars to Collection Plans
- Revisit Stellar Imaging Scenario
  - Develop Encircled Energy Function
    - Linear Array
    - Push-broom Scanning Systems
  - Separate data from compression noise
  - Determine uncertainty of measurement
- Collect and Analyze Additional Stellar Imagery
  - Analysis primarily uses only 7 stellar collects
Summary

- Additional research needed to further refine the algorithm