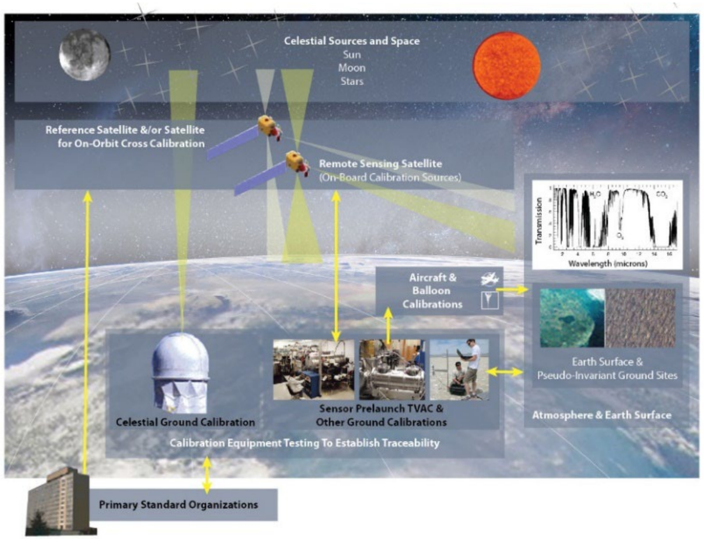

# Calibration Considerations and Scoring the Quality of Calibration

Joe Tansock, Distinguished Calibration Engineer
Space Dynamics Laboratory
416 E. Innovation Avenue
North Logan, UT 84341
(435) 713-3554
joe.tansock@sdl.usu.edu

# Outline

- Introduction to “Guidelines for Radiometric Calibration of Electro-Optical Instruments for Remote Sensing, NISTHB 157”
- Calibration Timeline (calibration should be addressed throughout the sensor lifetime)
- Why calibration is necessary
- Calibration Success Example
- Typical Imaging Radiometer Calibration Parameters
- Calibration lessons learned
- Why is on-board source important to calibration
- On-board calibration source types
- Potential on-orbit calibration sources
- Considerations for scoring the quality of calibration
- Summary

# Publication (NIST HB 157)




https://www.sdl.usu.edu/capabilities/testing-calibration/electro-optical-calibration/

https://nvlpubs.nist.gov/nistpubs/hb/2015/NIST.HB.157.pdf

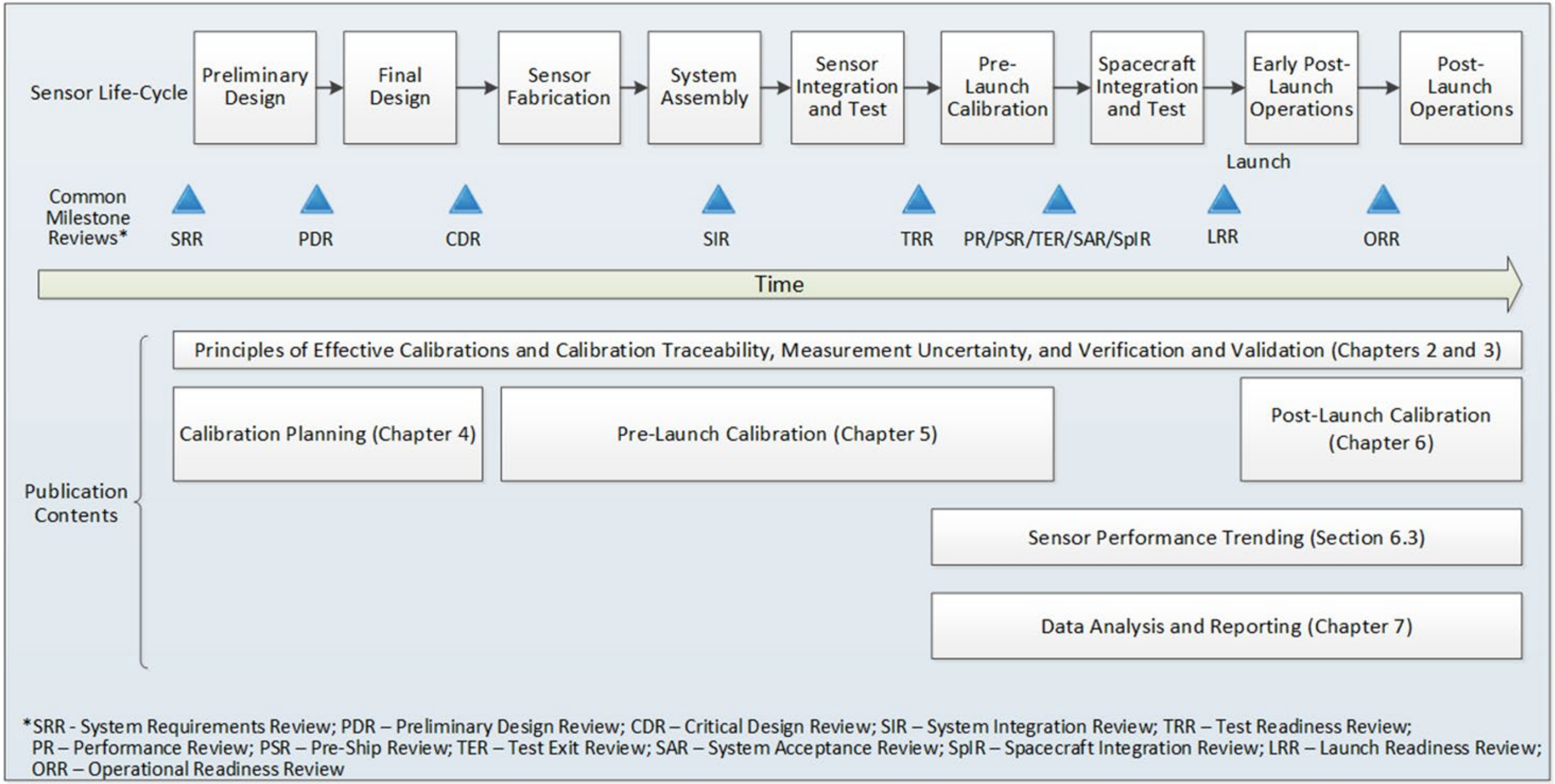
Or perform an internet search on NIST HB 157

- Presents guidelines on conducting a radiometric calibration of an electro-optical (EO) sensor for space-based remote sensing
- Intended as a useful reference for planning and successfully carrying out a sensor calibration
  - Managers, technical oversight personnel, scientists, and engineers
- Represents lessons learned by authors from academic institutions, US government, and industry (22 nationally recognized authors)

*Guidelines for Radiometric Calibration of Electro-Optical Instruments for Remote Sensing (NIST HB 157)

# Sensor Lifetime Timeline

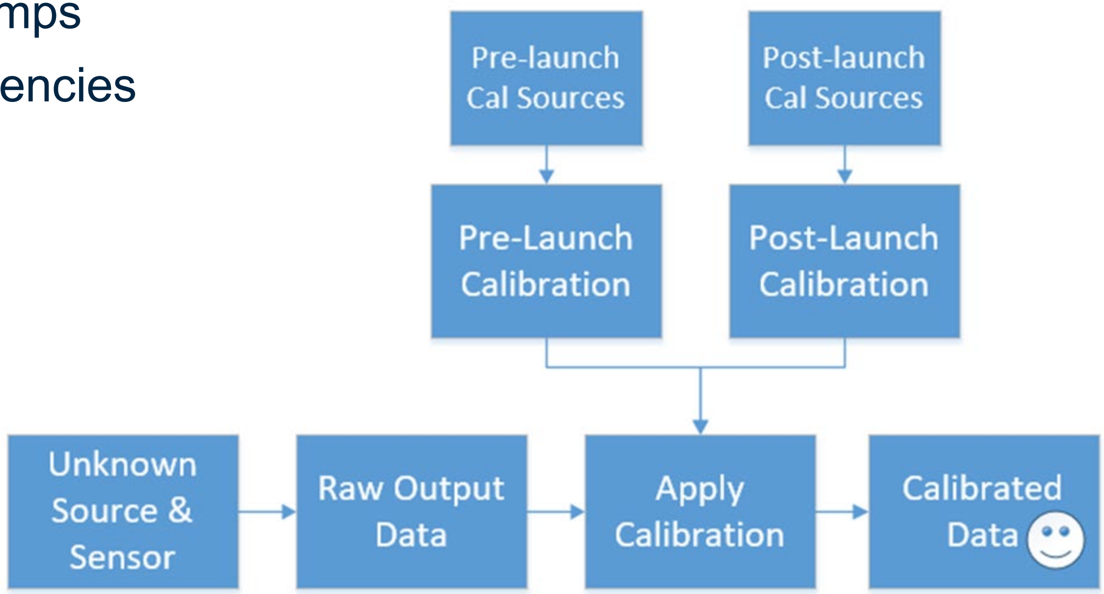
- Calibration should be addressed throughout the sensor lifetime




***Guidelines for Radiometric Calibration of Electro-Optical Instruments for Remote Sensing (NIST HB 157)**

# Why is Calibration Necessary?

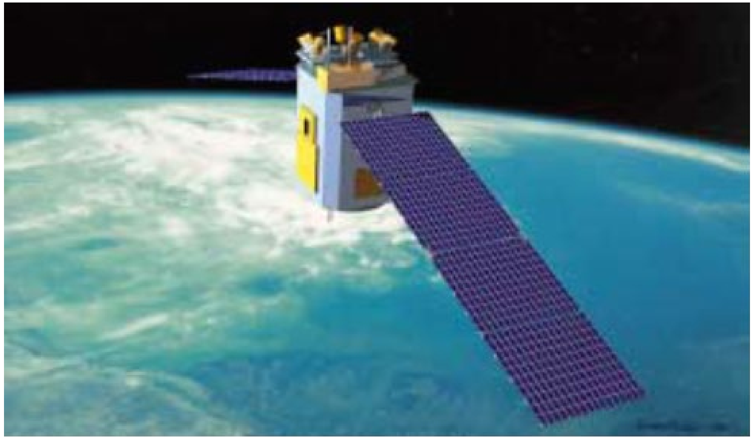
- EO sensors require calibration to:
  - Identify and quantify a sensor's response to radiometric sources
  - Characterize interactions and dependencies between the between the optical, electronic components and temps
  - Discover sensor performance dependencies
  - Evaluate systematic errors
  - Verify requirements




*Guidelines for Radiometric Calibration of Electro-Optical Instruments for Remote Sensing (NIST HB 157)

# Calibration Success Example

- SABER (Sounding of the Atmosphere using Broadband Emission Radiometry)
  - 10-channel radiometer – spans range of wavelengths from 1.27 to 17 μm
  - Launched December 7, 2001
- Calibration planning began early in the sensor design[1]
  - SABER leadership made the decision early on to build the best calibrated instrument with available resources.
    - This focus on calibration affected many subsequent decisions on parts selection and testing
  - Coordinated with science, instrument, and calibration teams
  - Iterated on calibration approach (strawman plan formulated)
  - Updated sensor design capability to support calibration
  - Drafted uncertainty budget and tracked throughout development process
  - Performed comprehensive ground calibration before launch
- Both pre-and post-launch calibrations were used to minimize uncertainty[2]
- SABER has been observing infrared radiation since January 2002 and continuing until the present day[3]
- As of last year 2023 there was >2200 peer-reviewed lifetime publications



Courtesy of NASA

[1]Tansock et al., SABER Ground Calibration, IJRS. 2003.

[2]Tansock et al., "An Update of the SABER Calibration."

[3]Mlynczak et al., "Infrared Radiation in the Thermosphere Near the End of Solar Cycle 24." Geophysical Research letters. 2018.

# Typical Calibration Equations and Parameters for Imaging Radiometer

- Radiance Calibration Equation
  - The radiance calibration equation converts sensor response in digital counts into physical units for an extended source

$$L_{M,k,t} = \frac{1}{\Re_L} r_{k,t} = \frac{1}{\Re_L}\left[\frac{B_k G_I}{F_{NUC,k}}\left[F_{Lin,k}\left(r_{T,k,t}\right) - F_{Lin,k}\left(r_{O,k,t}\right)\right]\right]$$

| | | | |
|---|---|---|---|
| $L_{M,k,t}$ | | $F_{Lin,k}\left(r_{T,k,t}\right)$ | |
| $\Re_L$ | Peak radiance responsivity (counts/Wcm$^2$sr) | $r_{T,k,t}$ | Raw pixel response (counts |
| $r_{k,t}$ | Corrected pixel response (counts) | $r_{O,k,t}$ | Raw pixel background response (counts) |
| $B_k$ | Bad pixel mask function (unitless) | $t$ | Time – parameters vary as function of time |
| $G_I$ | Integration time normalization (unitless) | $k$ | Pixel index – unique to each pixel |
| $F_{NUC,k}$ | Non-uniformity correction function (unitless) | | |

- Characterization of parameters requires separation of responsivity domains
  - Radiometric, spatial, spectral, temporal, polarization

*Guidelines for Radiometric Calibration of Electro-Optical Instruments for Remote Sensing (NIST HB 157)

# Typical Calibration Equations and Parameters for Imaging Radiometer

- The radiometric model consists of additional parameters needed to understand and model instrument performance
- Source characterization parameters

| | | |
|---|---|---|
| Relative Spectral Response | Effective Field of View | Polarization Sensitivity |
| Near Angle Scatter | Focus | Point Response Function |
| IFOV Line-of-Sight Map | Waveband Crosstalk | Focal Plane Image Latency |

- Sensor performance metrics

| | |
|---|---|
| Noise-Equivalent Irradiance or target (NEI,NET) | Noise-Equivalent Radiance (NER) |
| Saturation-Equivalent Irradiance (SEI) | Saturation-Equivalent Radiance (SER) |
| Noise-Equivalent Delta Temperature (NEdT) | NUC and Stability (Fixed Pattern noise) |
| Response Repeatability & Response Noise | Dark Offset/Background Repeatability (Dark Noise) |
| Angle Repeatability & Jitter | 1/f Noise |
| Sensor Time-Stamp Characterization | Sensor Frequency Response |
| Dynamic Range | Saturation Behavior |
| On-Board Calibration Source Characterization | Any other unique sensor performance parameters |

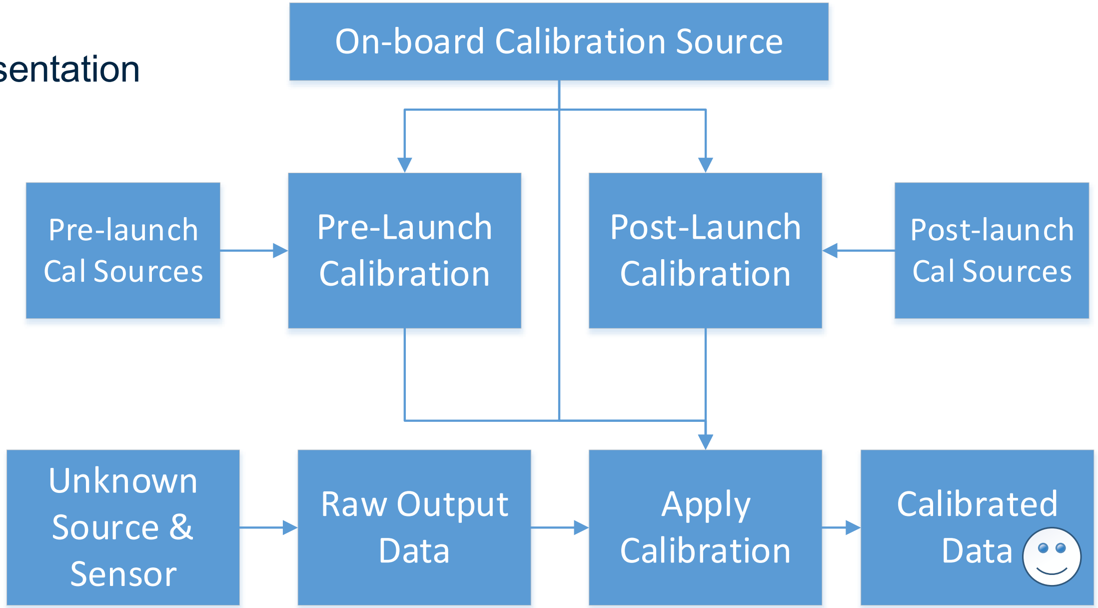
*Guidelines for Radiometric Calibration of Electro-Optical Instruments for Remote Sensing (NIST HB 157)

# Lessons Learned

- Principles of Effective Calibrations:

  1. Calibration planning should begin early
  2. Trade-Offs must be made
  3. Calibration must be traceable
  4. System-Level Testing provides the best representation
  5. Both Pre- and Post-Launch calibration are critical to a successful calibration

On-board calibration source is common to both pre-launch and post-launch calibrations




*Guidelines for Radiometric Calibration of Electro-Optical Instruments for Remote Sensing (NIST HB 157)

# Additional Considerations and Lessons Learned

- Dedicated calibration team throughout the entire mission
- Good communication with sensor vendor, project/science team, flight/mission operation team, and data product developers and users
- Validation/verification via different approaches/independent implementation
- Experience from heritage and other sensors
- Different approaches/strategies for calibration update/adjustment (forward processing) and reprocessing
- Documentation

**Communications with Jack Xiong, Aug 23, 2021**

# Why is On-board Source Important to Calibration

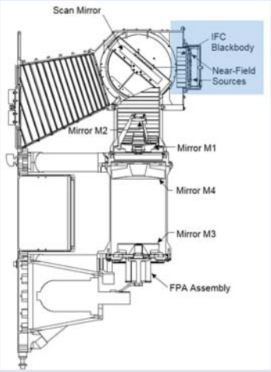
- Provides tie between pre-launch (i.e., ground calibration), other launch preparation activities
  - Spacecraft integration and launch readiness
  - On-orbit calibration (after launch)
- Allows for monitoring of sensor repeatability
  - Sensor response, noise, repeatability
- Allows for monitoring of sensor contamination
  - Monitor calibration response degradation due to contamination
  - Potentially quantify type and thickness of contamination (assuming spectral signatures are measured and then combined with degradation response level contamination thickness estimated)

*TIMED/SABER*

The SABER instrument used two approaches for the in-flight calibration (IFC) source designs:

- Full aperture flat plate cavity enhanced blackbody for MWIR and LWIR bands
- Near-field source lamps integrated into the full aperture blackbody for the near infrared (NIR) and short-wave infrared (SWIR) bands

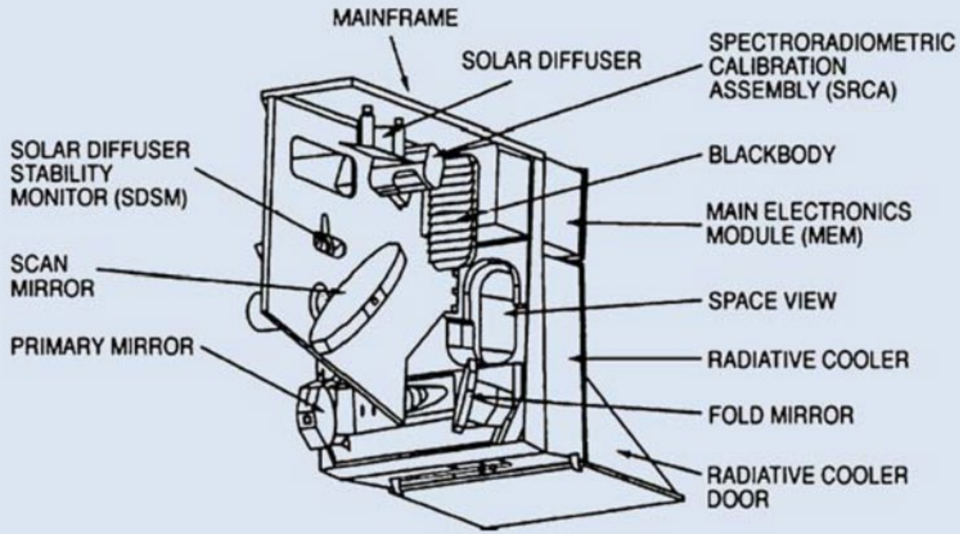
Calibration benchmarks were performed throughout the mission by rotating the scan mirror to view the blackbody and near-field sources (Tansock 2003).




*Guidelines for Radiometric Calibration of Electro-Optical Instruments for Remote Sensing (NIST HB 157)

# On-board Calibration Source (Types)

- Tungsten filament lamps (often in an integrating sphere, near-field or Jones source arrangement)
- Infrared thermal sources (glow bars, heated filaments in transistor cans, etc.)
- Blackbodies (care must be taken to not have the blackbody output be dependent on environmental surroundings)
- Solar diffusers (Jack Ziong reference)
- Ejected calibration sources (used on SPIRIT III)
- Custom calibration source assemblies (Spatial and spectral radiometric source assemblies)
- Emerging LED sources (emerging calibration source, 2022 launch of EnMAP)
- Quantum Cascade Laser (QCL) (preliminary qualification testing by PNNL and USU is promising but has not been baselined for flight – to my knowledge)



MODIS Scan Cavity and On-board Calibrators (Xiong 2003)

# On-orbit Calibration Sources

| Name | Description |
|---|---|
| On-board sources | Radiance and/or spectral reference sources that are contained within an EO sensor's optical path, are moved in or out of the sensor's optical path, or are viewed by means of a scan mirror while on orbit |
| Ejected sources | Sources that are ejected from the payload (Price et al. (2004) provides a discussion on the ejected reference spheres during the MSX mission.) |
| Stars | A limited number of stars that are in the IR spectral region and also have stable intensity with proven/measured stability of ≤ ≈3 % (Russell et al., 2012) |
| Moon | Natural Earth satellite with stable surface reflectance and no atmosphere (spatially and temporally variable, modeled at shorter wavelengths – USGS robotic Lunar Observatory (ROLO) project (Kieffer and Stone 2005) |
| Other celestial objects | Sun, planets, galaxies, nebulae, dark space scenes |
| Vicarious | Natural or artificial sites on the surface of the Earth (Czapla-Myers, 2011; Blonski et al., 2012; Schiller and Silny 2010) |
| Cross-calibration of on-orbit instruments | Comparison to a calibrated sensor in another orbit viewing the same Earth scene at the same time |
| Solar diffusers | On-board reflective surface that attenuates solar radiance to match sensor dynamic range (Xiong 2012; Guenther 2012) |
| Pseudo-invariant calibration sites (PICS) | Sites on Earth's surface (typically desert regions) that have repeatable radiant properties |

***Guidelines for Radiometric Calibration of Electro-Optical Instruments for Remote Sensing (NIST HB 157)**

# Considerations for Scoring the Quality of Calibration

| | | | |
|---|---|---|---|
| Domain | | | |
| | Radiometric | | |
| | | Responsivity | |
| | | | Radiance Responsivity |
| | | | Irradiance Responsivity |
| | | Bad pixel characterization and replacement | |
| | | Gain or integration time normalization settings | |
| | | Pixel non-uniformity and Stability (fixed pattern noise) | |
| | | Background/Dark | |
| | | Dynamic Range | |
| | | On-Board Calibration Source Characterizations | |
| | Spatial | | |
| | | Point response function (response of sensor to PSF) | |
| | | Modulation transfer function | |
| | | Line spread function | |
| | | Pixel line-of-sight knowledge (including distortion corrections/knowledge) | |
| | | Pixel Instantaneous Field-Of-View and effective-field-of-view | |
| | | Focus | |
| | | Sensor Field-Of-View | |
| | | Cross-talk (optical and electrical) artifacts | |
| | | Near angle scatter (within FOV) | |
| | | Large angle scatter (outside FOV) | |

- (1) Identify calibration parameters in preparation for scoring

| | | | |
|---|---|---|---|
| Domain | | | |
| | Spectral | | |
| | | Waveband Characterizations | |
| | | | In-Band Relative Spectral Response per waveband |
| | | | Out-of-band Relative Spectral Response per waveband |
| | | | Resolution |
| | | | Cut-on and cut-off characterization |
| | | | Bandwidth |
| | Temporal | | |
| | | Response repeatability | |
| | | Angular repeatability and jitter | |
| | | 1/F noise | |
| | | Sensor Frequency Response | |
| | | Sensor time-stamp | |
| | | On-board Calibration Source Response Repeatability | |
| | Polarization | | |
| | | Polarization sensitivity characterization | |

# Other Factors that Should be Considered When Scoring

- Is the calibration parameter affected by sensor temperature variations?
  - If so, has the characterization been bounded by maximum temperature swings of operation?
- Is the calibration parameter traceable to NIST or other standards?
- Overall Calibration
  - What was the rigor placed on various calibration phases? For example, planning, pre-launch, and post-launch calibrations.
- Documentation
  - Does sufficient documentation exists to document calibration plan, as-run procedures, and results?

# Considerations for Scoring the Quality of Calibration

- Assign weighting to each calibration parameter
  - The weighting is chose depending on importance of application
- Calculate weighted average to estimate overall score

$$E(Score) = \frac{\sum_{k=0}^{n} W_k Score_k}{\sum_{k=0}^{n} W_k}$$

Where

$Score_k$ =

| Not Assessed | Not Assessable | Basic | Intermediate | Good | Excellent |
|---|---|---|---|---|---|
| 0 | 1 | 2 | 3 | 4 | 5 |

and

$Weight_k$ ($W_k$) =

| Not Important | Moderatly Important | Important |
|---|---|---|
| 0 | 0.5 | 1.0 |

# Example/Mock Calibration Scoring

| Overall Score | $W_k$ | $Score_k$ | Calibration Parameter | Note |
|---|---|---|---|---|
| 3.3 | 0 | 0 | Radiance Responsivity | Not Required |
| | 0 | 0 | Irradiance Responsivity | Not Required |
| | 1 | 5 | Bad pixel characterization and replacement | Required for imaging |
| | 0 | 0 | Gain or integration time normalization | Not Required |
| | 1 | 4 | Pixel non-uniformity and Stability (fixed pattern noise) | Measured during pre-launch |
| | 1 | 4 | Background/Dark | Measured and method of correction verified pre-launch |
| | 0.5 | 4 | Dynamic Range | Measured pre-launch |
| | 1 | 4 | On-Board Calibration Source Characterizations | Characterization of on-board source, for imaging used to assess/monitor/update NUC |
| | 1 | 4 | Point response function (response of sensor to PSF) | Can be processed to assess imaging figures of merit |
| | 1 | 3 | Modulation transfer function | Imaging figure of merit |
| | 0 | 0 | Line spread function | Not Required |
| | 1 | 3 | Pixel line-of-sight knowledge (including distortion corrections/knowledge) | Measured during pre-launch |
| | 1 | 3 | Pixel Instantaneous Field-Of-View and effective-field-of-view | Measured during pre-launch |
| | 1 | 3 | Focus | Measured/verified during pre-launch calibration and verified on-orbit |
| | 1 | 4 | Sensor Field-Of-View | Measured/verified during pre-launch calibration and verified on-orbit |
| | 0.5 | 3 | Cross-talk (optical and electrical) artifacts | Assessment of pre-launch calibration measurements but not extensive |
| | 0.5 | 2 | Near angle scatter (within FOV) | Not measured pre-launch but assessment with optical analysis and measurement geometry |
| | 0.5 | 3 | Large angle scatter (outside FOV) | Component and system level optical analysis assessment |
| | 1 | 2 | In-Band Relative Spectral Response per waveband | Characterized pre-launch verified post-launch |
| | 0.5 | 1 | Out-of-band Relative Spectral Response per waveband | Assessed with component measurements |
| | 0.5 | 3 | Resolution | Resolution of RSR |
| | 0.5 | 4 | Cut-on and cut-off characterization | Cut-on and cut-off of RSR |
| | 1 | 4 | Bandwidth | FWHM of RSR |
| | 0.5 | 3 | Response repeatability | Assessed with external and internal on-board source |
| | 0.5 | 3 | Angular repeatability and jitter | Assessment |
| | 0.5 | 3 | 1/F noise | Measured but minimal analysis |
| | 0.5 | 2 | Sensor Frequency Response | Not measured but estimated based on system evaluation |
| | 0.5 | 3 | Sensor time-stamp | Measured but minimal analysis |
| | 1 | 4 | On-board Calibration Source Response Repeatability | Measured with moderate analysis |
| | 0.5 | 2 | Polarization sensitivity characterization | Not measured but optical analysis was performed |

Assumed application is an imaging system without absolute calibration

# Summary

- Consider "Guidelines for Radiometric Calibration of Electro-Optical Instruments for Remote Sensing, NISTHB 157" when planning calibration
  - Calibration should be addressed throughout sensor lifetime to include design, pre-launch and post-launch
  - Be mindful of lessons learned
  - On-board sources are important to calibration
  - As much as possible, take advantage of available on-orbit sources
- Proposed method of scoring calibration
  - Identify calibration parameters in preparation for scoring
  - Assign score and weight (i.e., importance) to each calibration parameter
  - Overall calibration score is then calculated using a weighted average of calibration parameters including weights
    - Allowing for the overall calibration score to be influenced by calibration parameters that are most important to the application