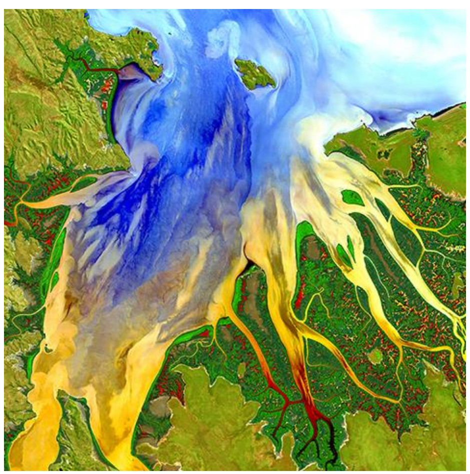
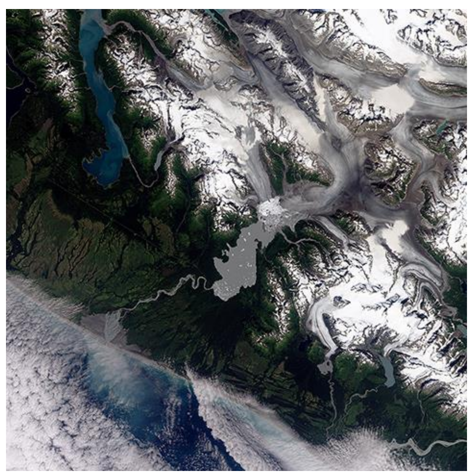
Pre-launch Transfer to Orbit Testing for the Operational Land Imager 2 (OLI-2)





Imagery Credit: **USGS/NASA Landsat**

Jordan Marks, Geir Kvaran, Nathan Leisso

Ball Aerospace

cal con
www.calcon.sdl.usu.edu

Outline

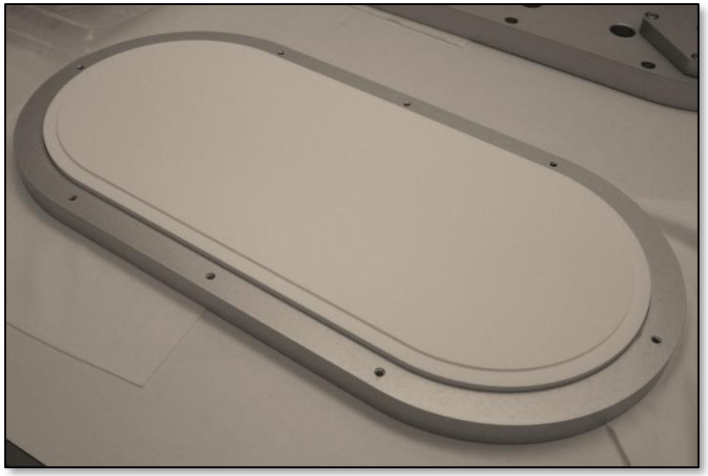
- **Overview of stable on-board calibration sources (stim lamps and diffusers)**
  - **Motivation for calibration source inclusion**
  - **Discussion of diffuser and stim lamp advantages and disadvantages as calibration sources**

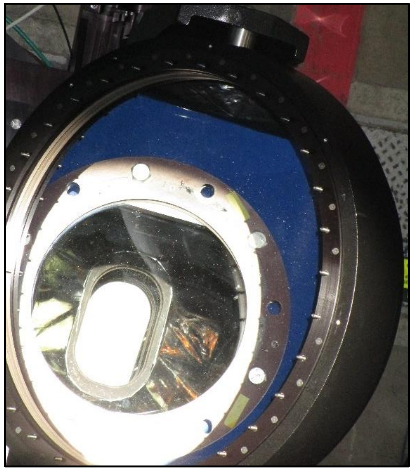
- **Transfer-to-orbit calibration methodology to assess stability of OLI-2 calibration sources between pre-launch and on-orbit environments**
  - **Improved approach for transfer-to-orbit**
  - **Pre-launch Testing Results**
    - **Diffuser On-Orbit Predictions**
    - **Stim Lamp Bulb Temperatures**

OLI-2 includes calibration sources to allow assessment of instrument stability between pre-launch and on-orbit

Diffusers

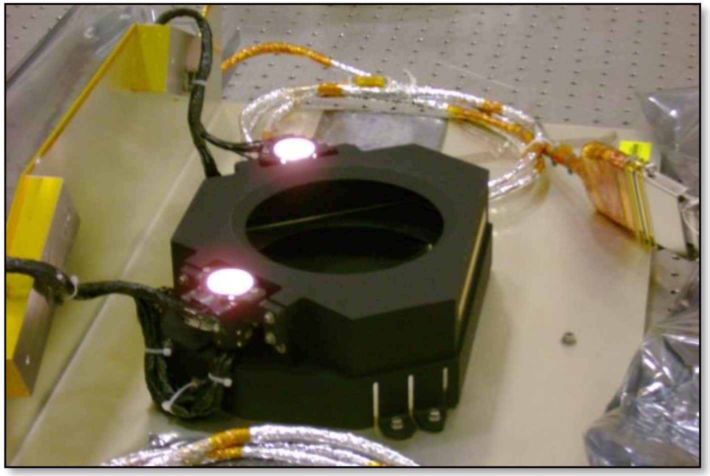
- **Two panels of space-grade Spectralon™**
  - **Act as near-Lambertian scatterers for incoming sunlight**
  - **One measured frequently, the other kept pristine**
- **Pre-launch, flight diffusers are illuminated using the heliostat**
- **Diffusers were characterized pre-launch at the University of Arizona, NIST Traceable**





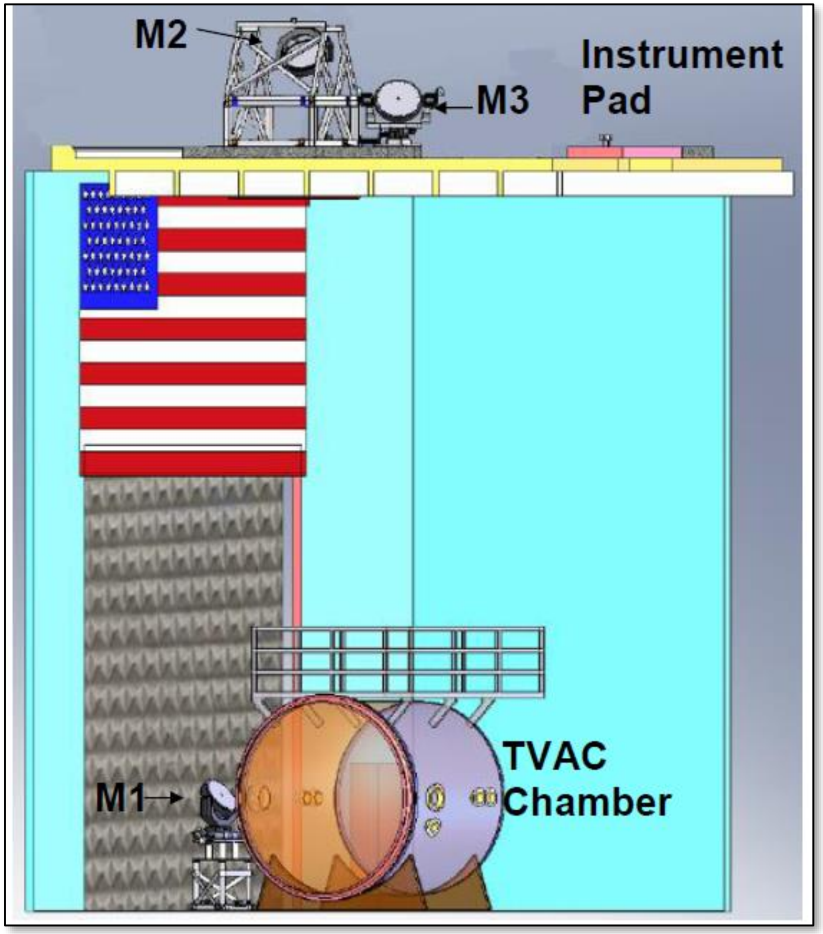
Stim Lamps

- **Three pairs of lamps are mounted in two assemblies on either side of the OLI-2 aperture**
- **Lamps are used frequently pre-launch to track performance, then used daily on-orbit as a secondary standard**



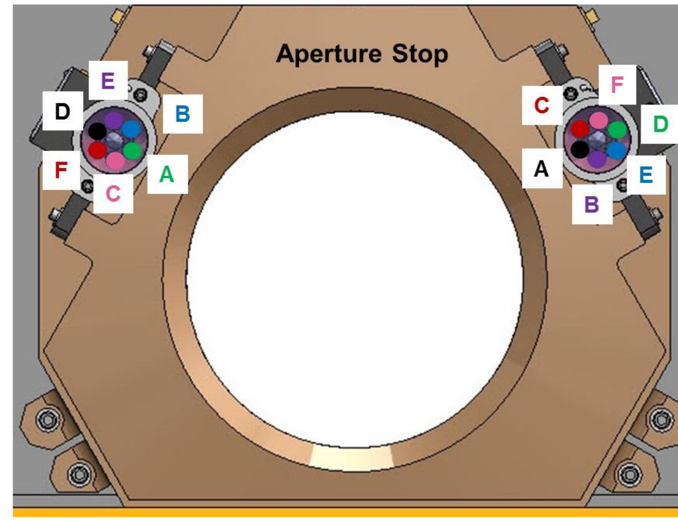
Diffuser Advantages and Disadvantages

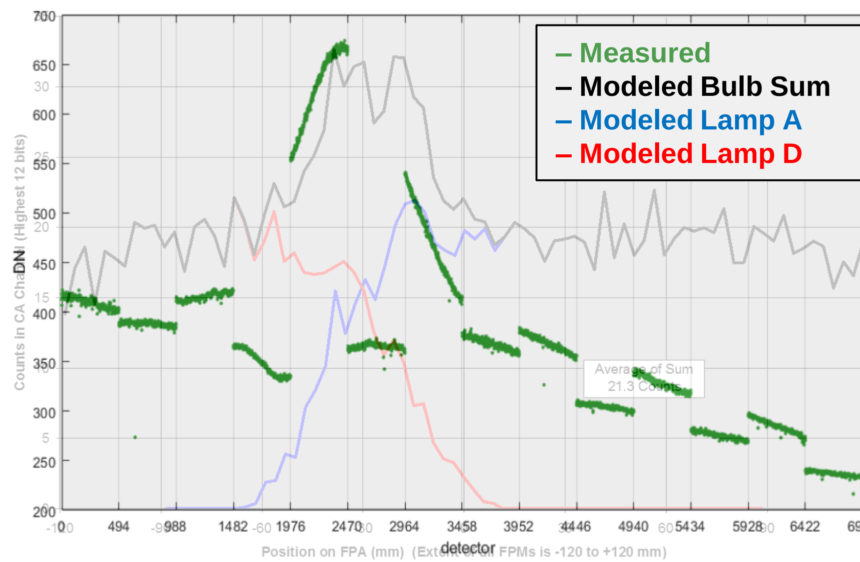
- **The diffuser acts as a stable transfer to orbit source for all non-Cirrus bands (VIS/SWIR bands)**
- **Pre-launch measurements are directly comparable to on-orbit measurements**
  - BRDF remains constant with attention to cleanliness
  - Infrequent use on-orbit minimizes degradation and maintains cleanliness
- **Diffuser observation replicates OLI-2 earth-viewing observation**
  - End-to-end illumination
  - Full field of view
  - Full aperture, equivalent AΩ



Stim Lamp Advantages and Disadvantages

- **Stim Lamps are required to validate Cirrus band calibration on-orbit.**
- **Stim lamp observation is similar to OLI-2 operation**
  - End-to-end illumination
  - With both bulbs, full field of view
  - AΩ is similar but not identical
- **Stim lamps images can be collected frequently**
  - On orbit, collect daily stim lamp images
  - Lamps can be used anywhere in orbit for extended durations
- **Stim lamps have predictable and repeatable patterns of illumination on the focal plane**
  - Anticipate bulb color temperature change on-orbit due to vacuum, instrument orientation and 0G environment





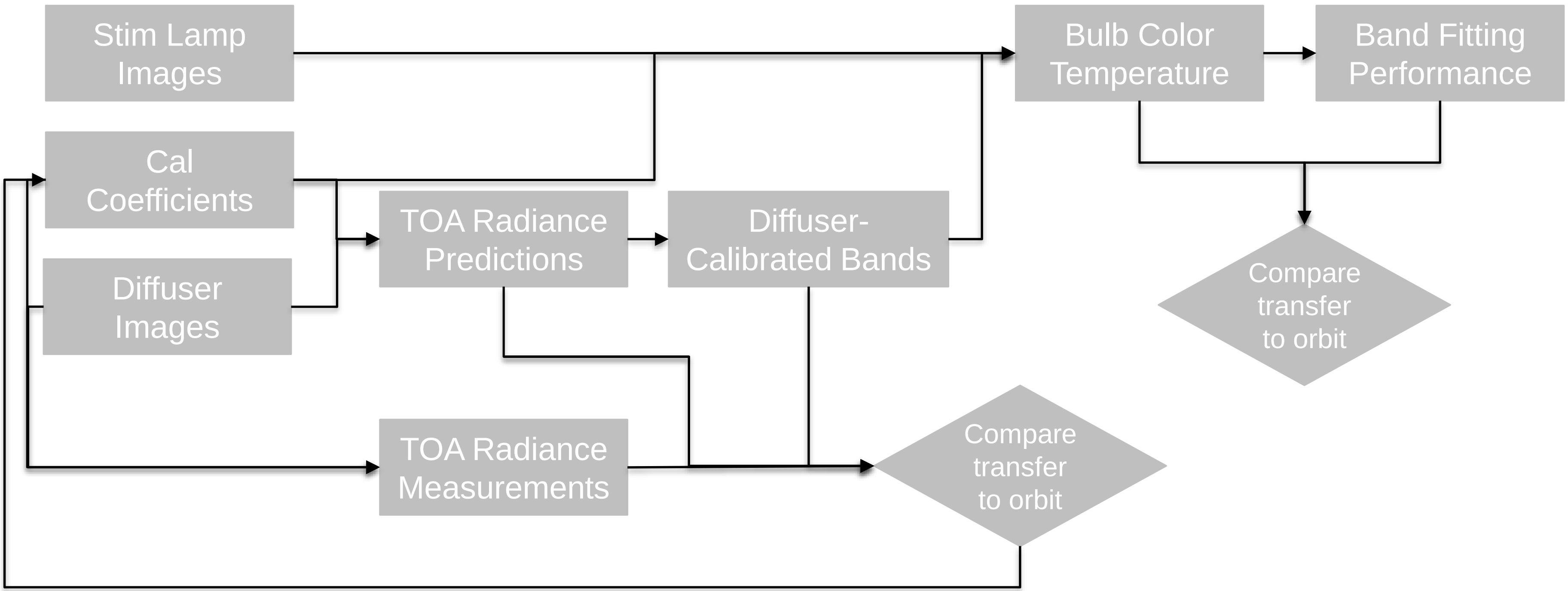
Transfer to Orbit Methodology

- **Two calibration sources allow us to harness advantages of each and compare measurements**
  - Diffuser is closest to actual OLI-2 AΩ, and BRDF should not change on orbit
  - Stim lamps are highly repeatable, have a simple spectral shape, and offer greater operational freedom
  - Use of both sources allows comparison across time scales

- **Original transfer-to-orbit method replicated OLI method**
  - Use diffuser to calibrate Bands 1 – 8; update calibration coefficients as needed
  - Use cal coefficients & stim lamp images to calibrate Band 9

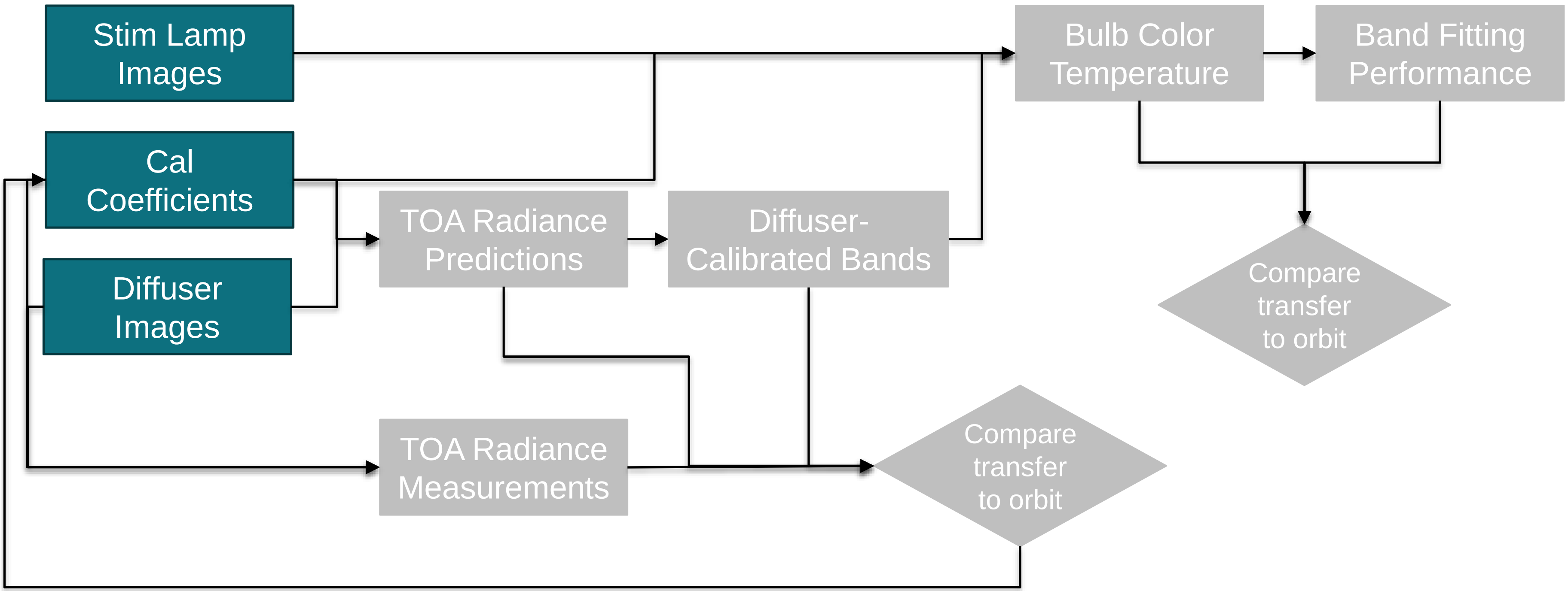
- **OLI-2 approach expands on the OLI approach and may offer improved calibration**
  - Use the diffuser to calibrate a <u>subset</u> of Bands 1 – 8; update calibration coefficients as needed
  - Use cal coefficients & stim lamp images to calibrate remaining bands

Transfer to Orbit Methodology



Measured on ground | Calculated with ground-based data | Measured on-orbit | Calculated with on-orbit data

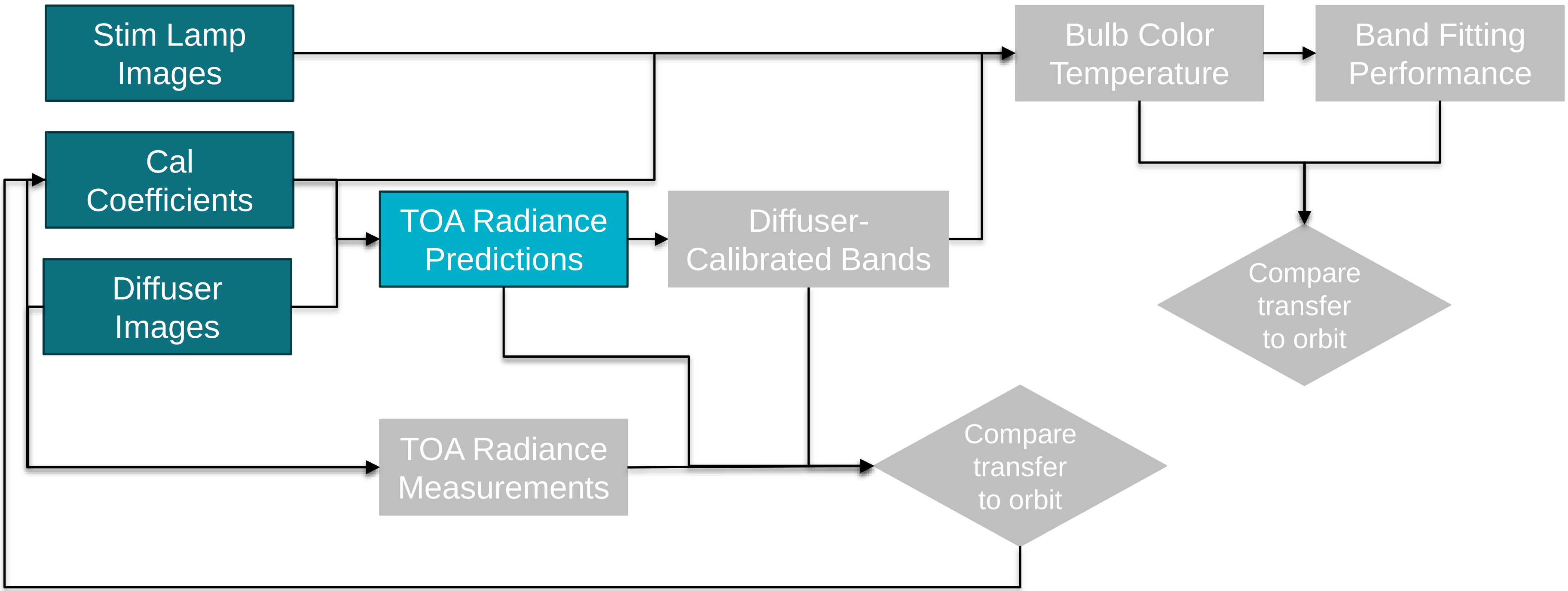
Transfer to Orbit Methodology



Calibration Alignment Test Station (CATS) measurements provided an integrated instrument-level observation of both calibration devices. Preliminary calibration coefficients have been calculated based on CATS data.

Measured on ground	Calculated with ground-based data	Measured on-orbit	Calculated with on-orbit data

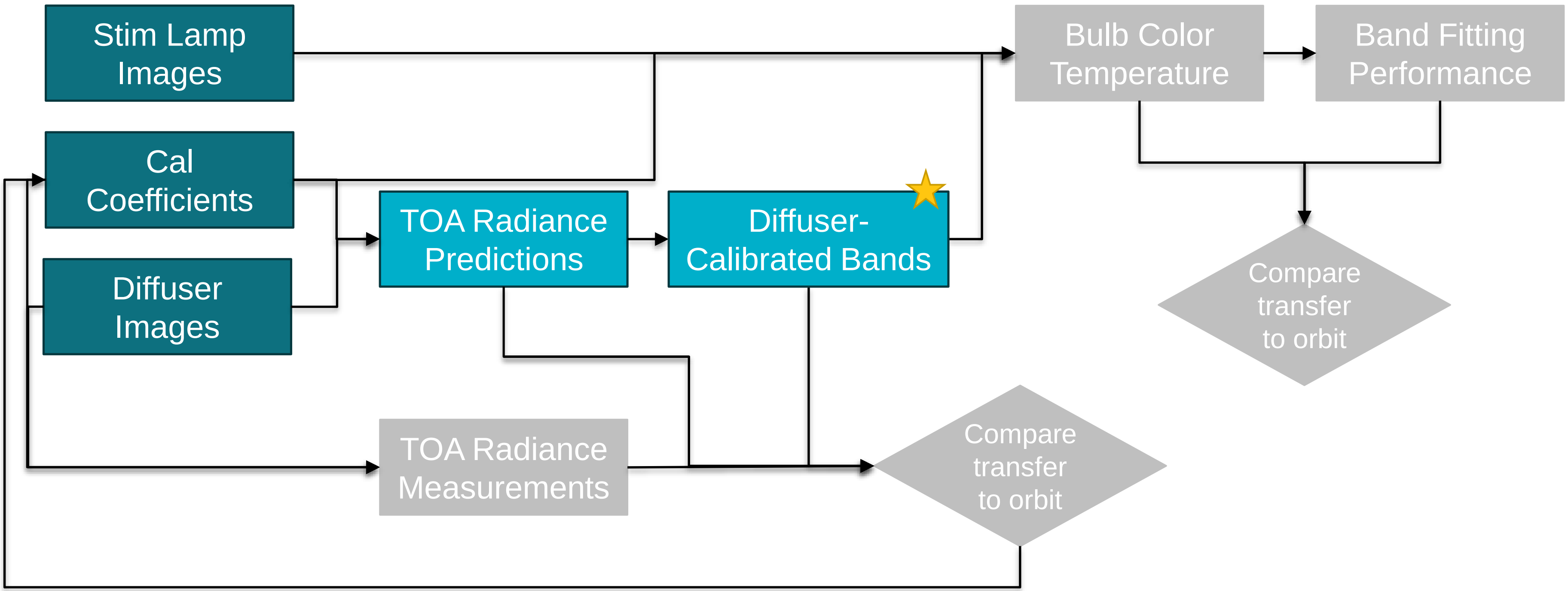
Transfer to Orbit Methodology



The diffuser and calibration coefficients, as well as CATS heliostat and atmospheric characterization data, are used to compute top of atmosphere (TOA) radiance predictions.

Measured on ground	Calculated with ground-based data	Measured on-orbit	Calculated with on-orbit data

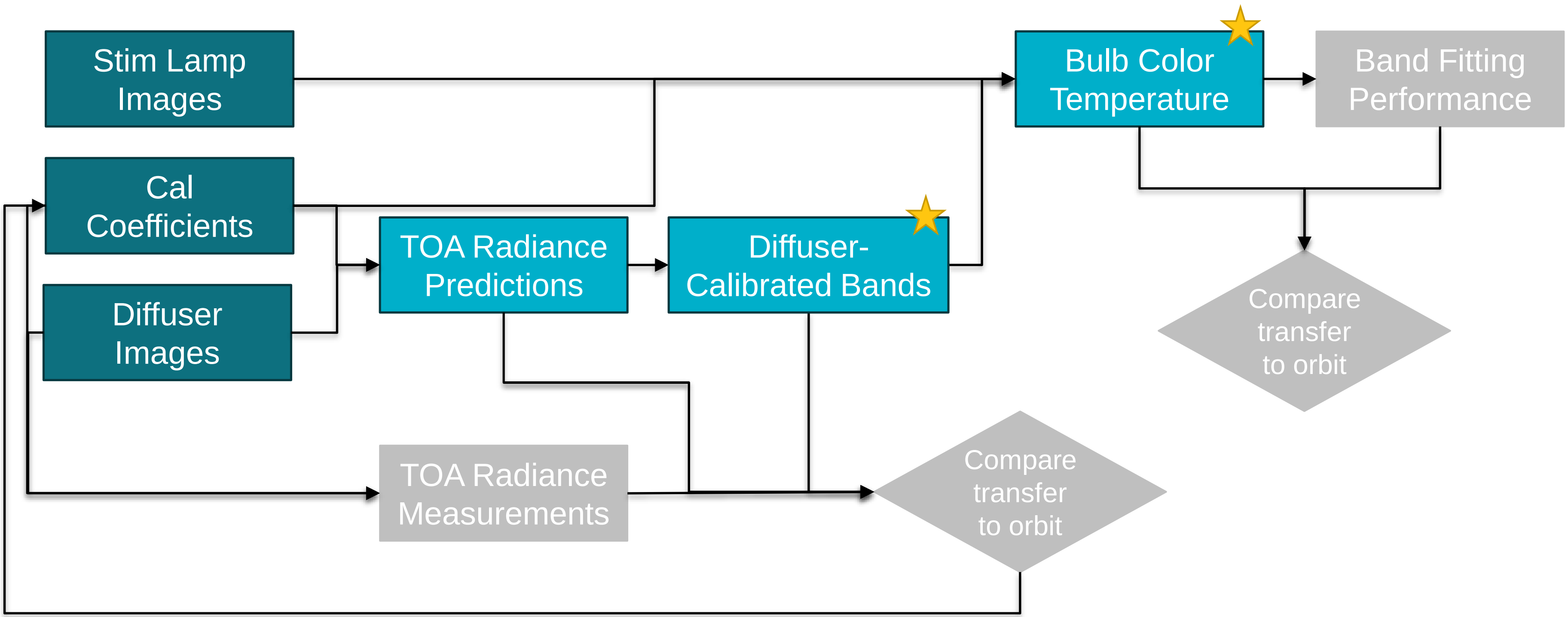
Transfer to Orbit Methodology



Original transfer-to-orbit method uses the diffuser for all VIS/SWIR bands. OLI-2 approach determines a subset of bands to be calibrated using the diffuser based on the radiance predictions.

Measured on ground | Calculated with ground-based data | Measured on-orbit | Calculated with on-orbit data

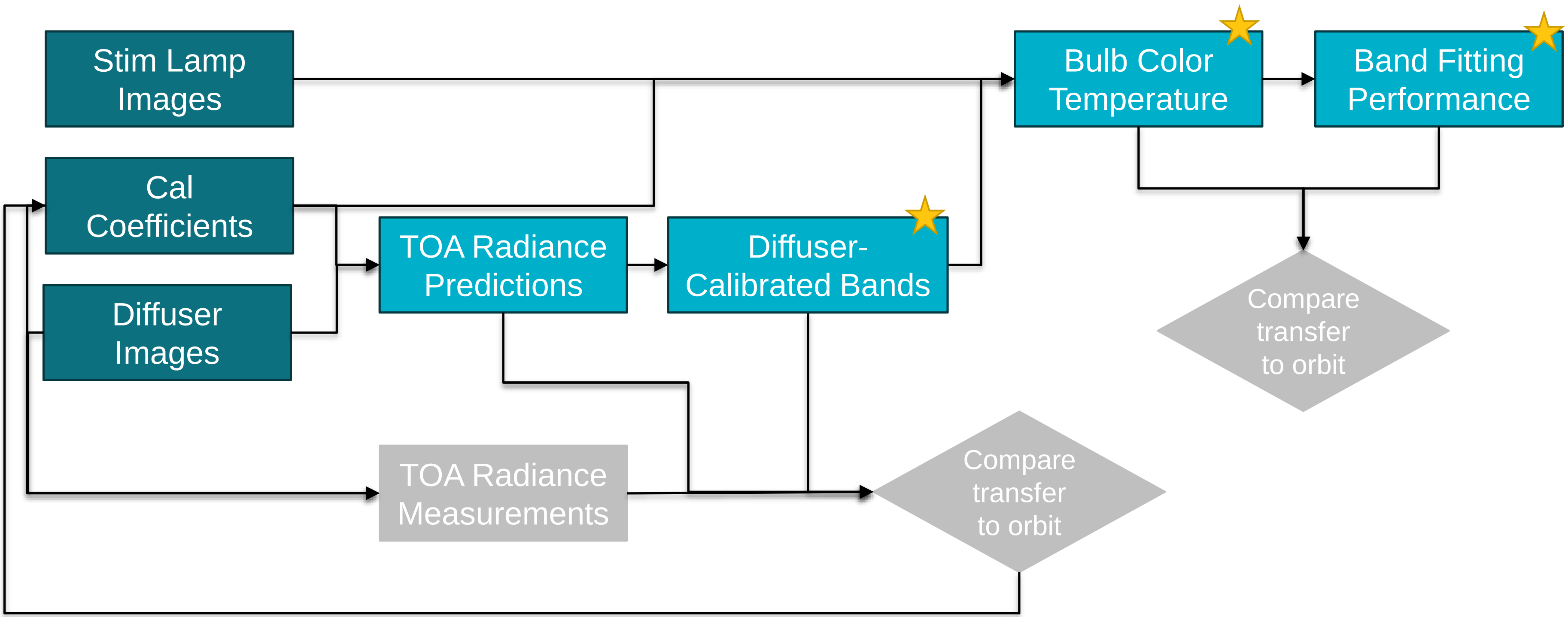
Transfer to Orbit Methodology



Stim lamp radiances are calculated. Radiance from each diffuser-calibrated bands is used to calculate a color temperature for each bulb.

Measured on ground	Calculated with ground-based data	Measured on-orbit	Calculated with on-orbit data

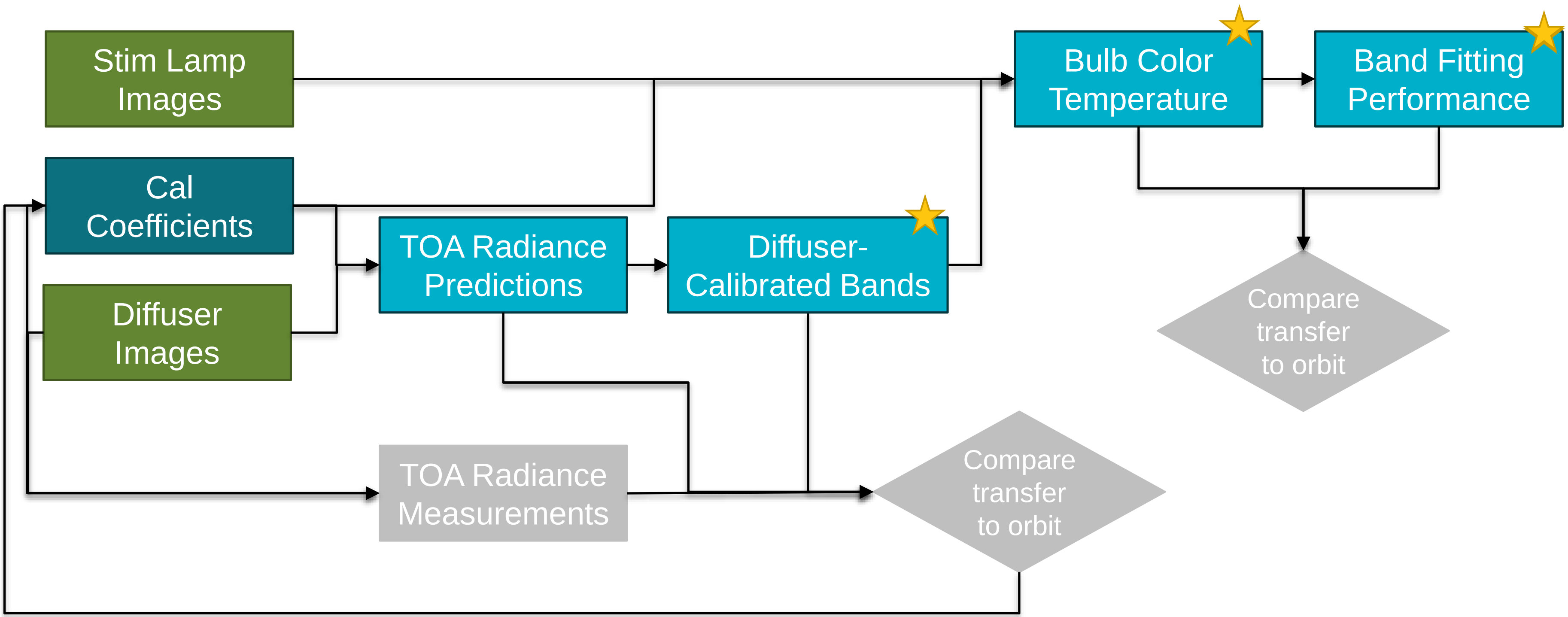
Transfer to Orbit Methodology



The error between the temperature fitting curve and radiance in each band is calculated. This error (the **Stim Lamp Fit Metric**) should be stable between ground measurements and orbit.

Measured on ground | Calculated with ground-based data | Measured on-orbit | Calculated with on-orbit data

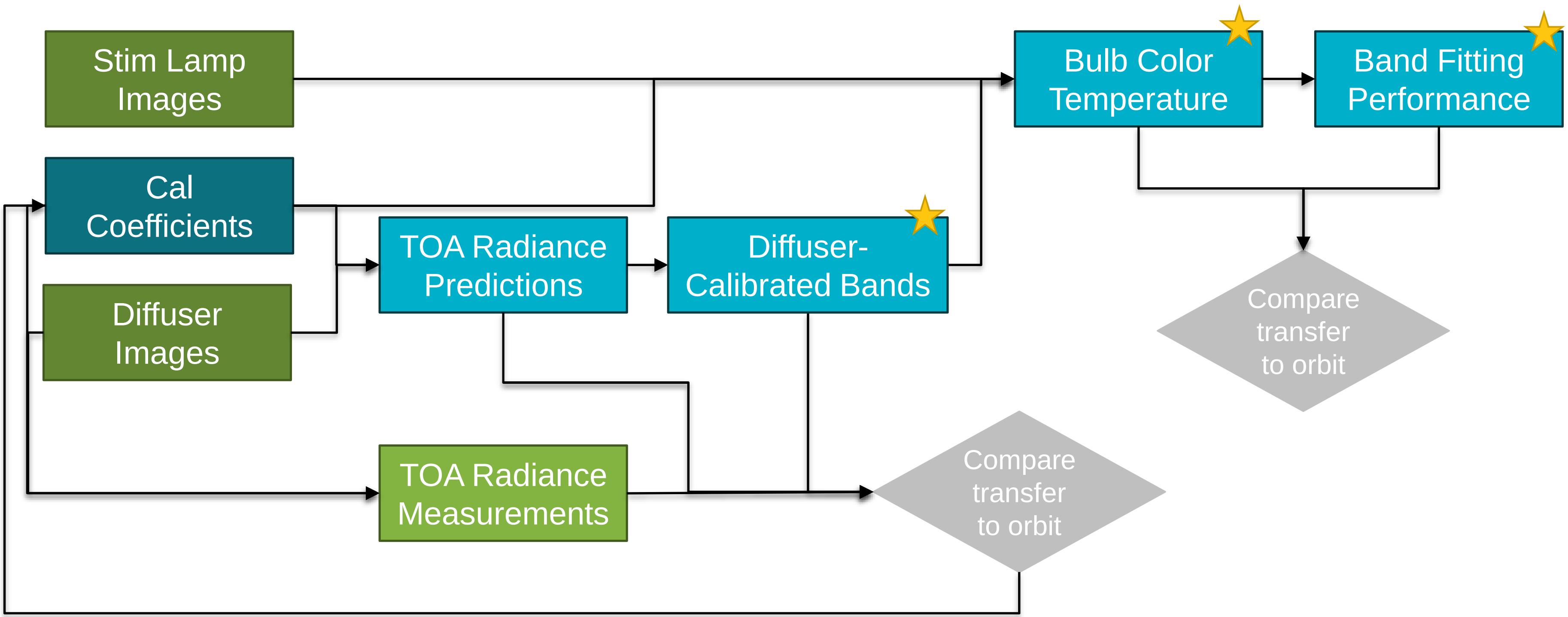
Transfer to Orbit Methodology



On orbit, stim lamp and diffuser images are collected.

Measured on ground | Calculated with ground-based data | Measured on-orbit | Calculated with on-orbit data

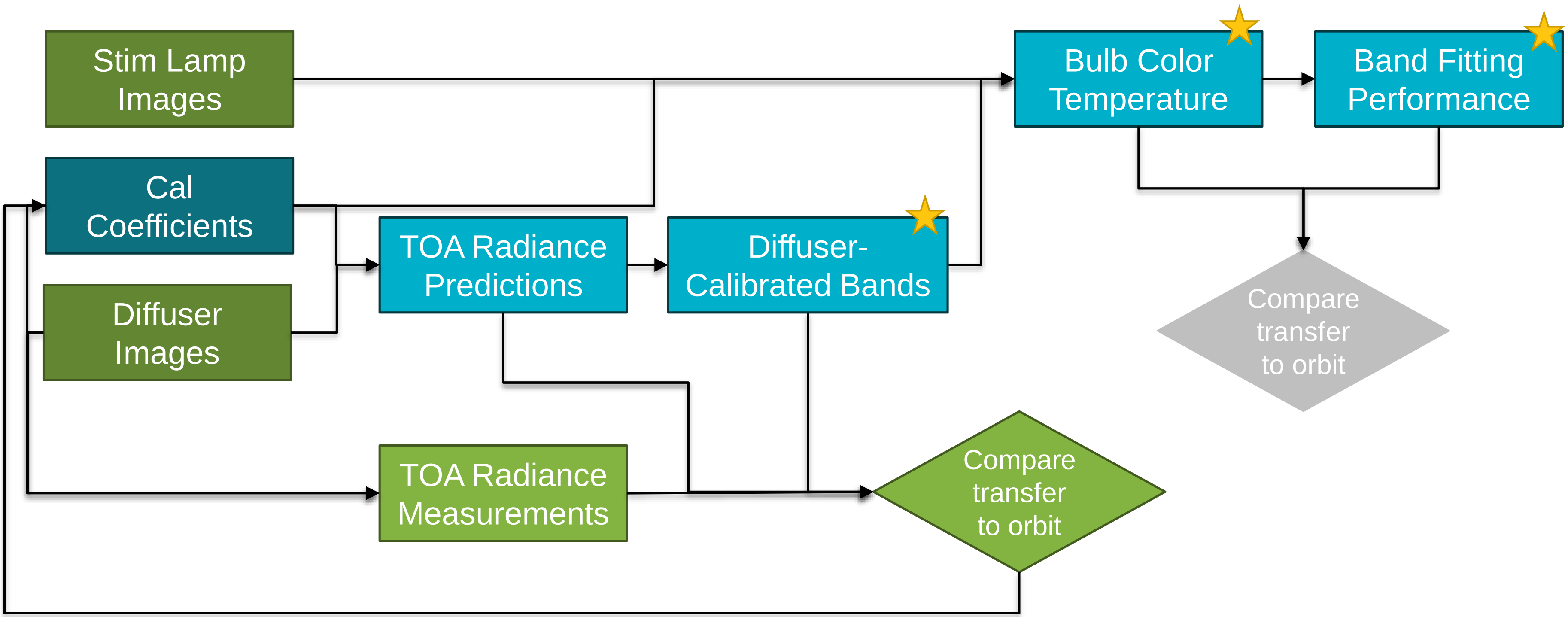
Transfer to Orbit Methodology



The ground-based calibration coefficients and the on-orbit diffuser images are used to measure the TOA radiance.

Measured on ground	Calculated with ground-based data	Measured on-orbit	Calculated with on-orbit data

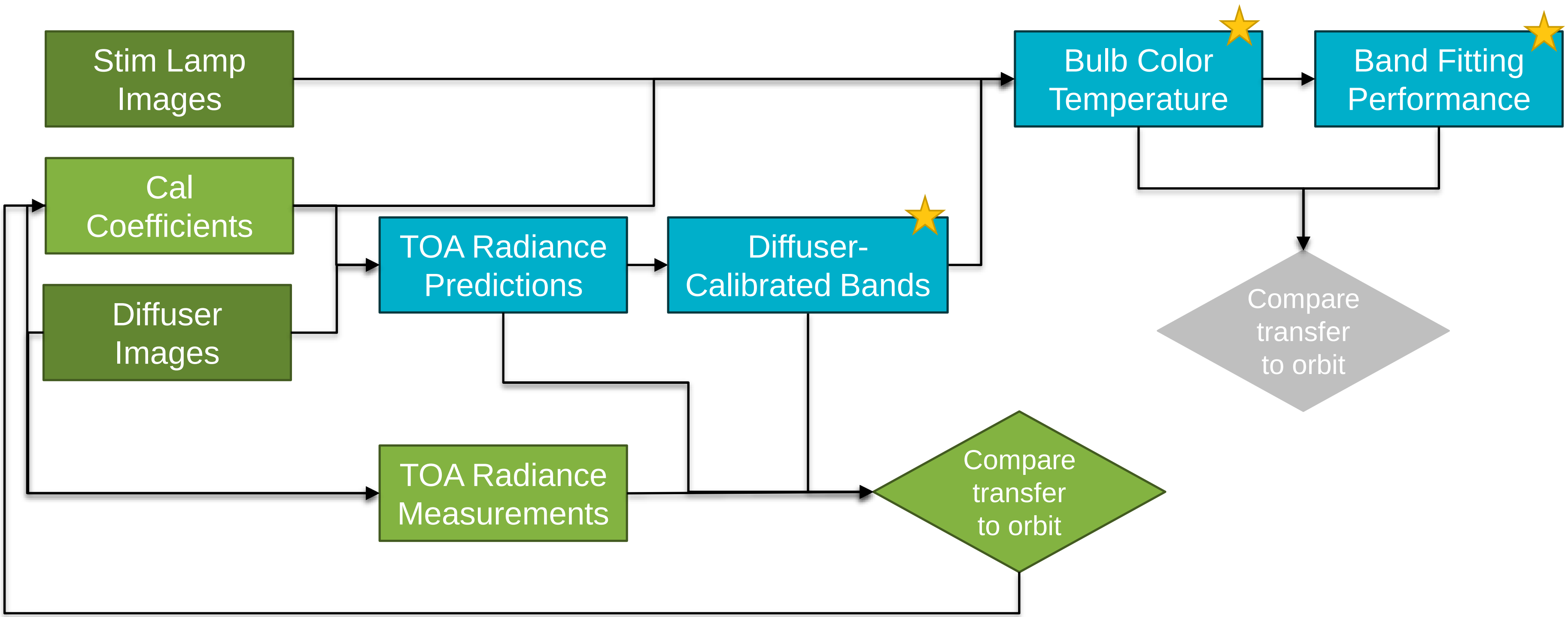
Transfer to Orbit Methodology



The TOA radiance measurements are compared to the TOA predictions for the diffuser-calibrated bands.

Measured on ground	Calculated with ground-based data	Measured on-orbit	Calculated with on-orbit data

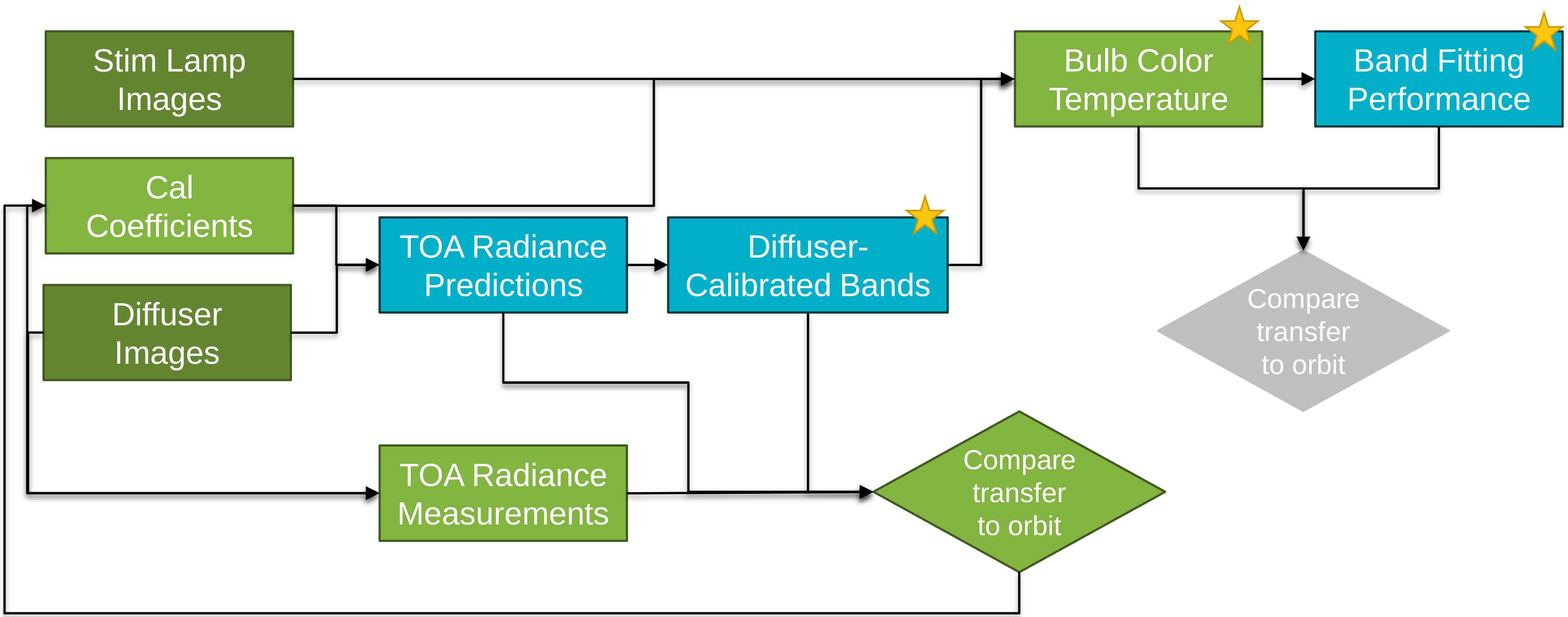
Transfer to Orbit Methodology



If necessary, the calibration coefficients are updated for the diffuser-calibrated bands.

Measured on ground	Calculated with ground-based data	Measured on-orbit	Calculated with on-orbit data

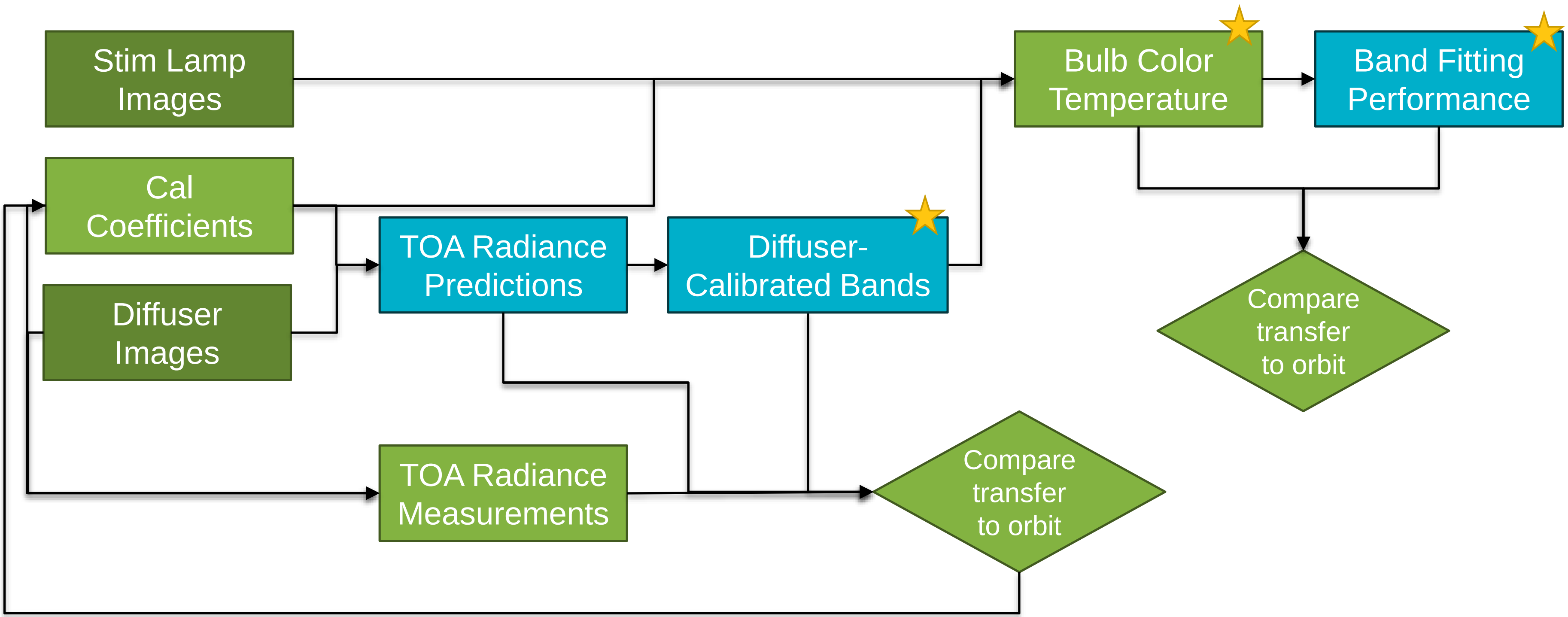
Transfer to Orbit Methodology



Updated calibration coefficients and on-orbit stim lamp data are used to calculate stim lamp radiance, and the bulb color temperatures using the diffuser-calibrated bands.

Measured on ground	Calculated with ground-based data	Measured on-orbit	Calculated with on-orbit data

Transfer to Orbit Methodology



The **Stim Lamp Fit Metric** will be used to re-calibrate remaining bands.

Measured on ground | Calculated with ground-based data | Measured on-orbit | Calculated with on-orbit data

Two methods to predict diffuser top of atmosphere spectral radiance

- **Method 1: Spectral Irradiance from Literature**

$$L_{bw,b,d}(t) = \frac{\int_0^\infty E_{\lambda,sun}(\lambda) * BRDF_b * NU_{b,d}(t_{CATS}) * R_b(\lambda) * cos(\theta)d\lambda}{D^2(t)\int_0^\infty R_b(\lambda)d\lambda}$$

- **Method 2: Measured Solar Diffuser Radiance from Heliostat Experiment**

$$L_{bw,b,d}(t) = \frac{L_{bw,b,d}(t_{CATS})}{\tau_{helio,b}\tau_{atm,b}} \frac{D^2(t_{CATS})}{D^2(t)}$$

Method 1: Irradiance-Based Calculation

Solar spectral irradiances from literature $(W\ m^{-2}\ \mu m^{-1})$

BRDF (sr^{-1})

Non-Uniformity $(\#)$

Measured RSR $(\#)$

Incidence angle on diffuser (rad)

$$L_{bw,b,d}(t) = \frac{\int_0^\infty E_{\lambda,sun}(\lambda) * BRDF_b * NU_{b,d}(t_{CATS}) * R_b(\lambda) * \cos(\theta) d\lambda}{D^2(t) \int_0^\infty R_b(\lambda) d\lambda}$$

Band-weighted spectral radiance $(W\ m^{-2}\ \mu m^{-1}\ sr^{-1})$

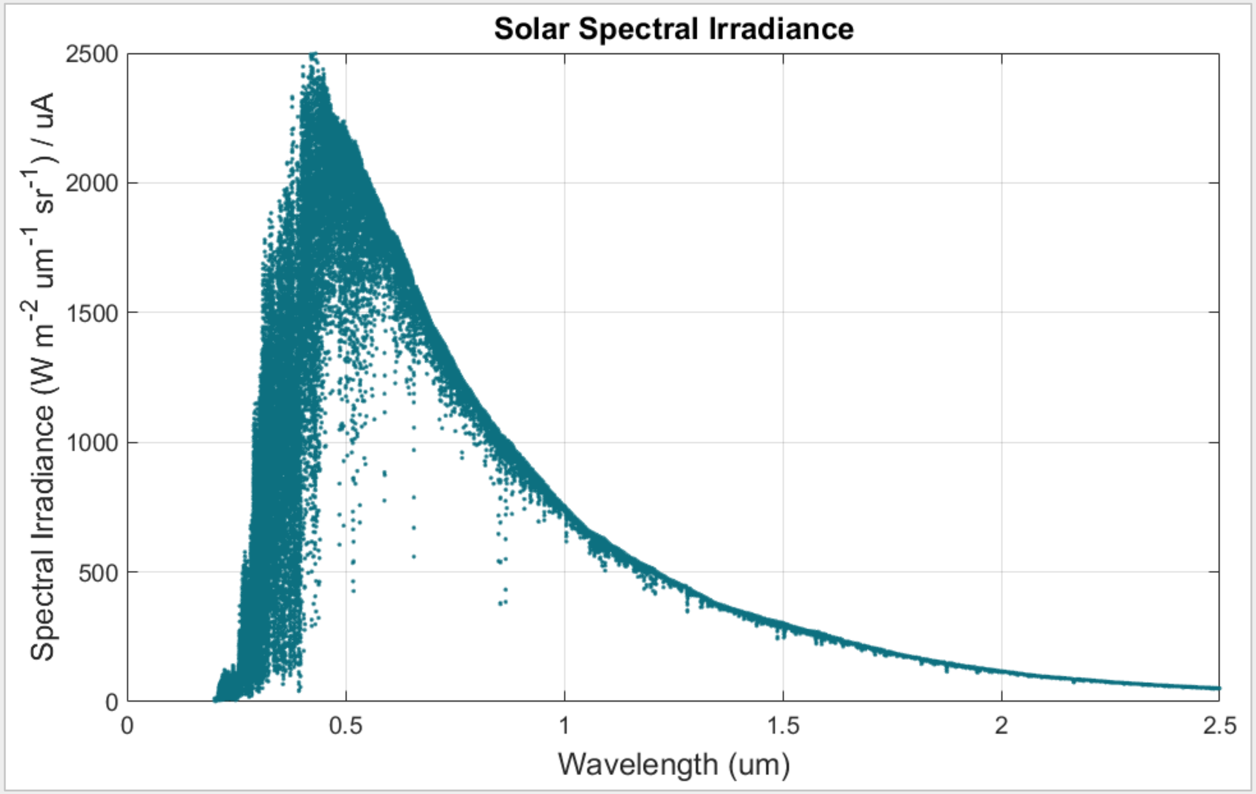
Earth-Sun Distance $(\#)$

Method 1: Irradiance-Based Calculation

Solar Irradiance

$$L_{bw,b,d}(t) = \frac{\int_0^{\infty} \boldsymbol{E_{\lambda,sun}(\lambda)} * BRDF_b * NU_{b,d}(t_{CATS}) * R_b(\lambda) * cos(\theta)d\lambda}{D^2(t)\int_0^{\infty} R_b(\lambda)d\lambda}$$

- Examining three solar irradiance spectra
  - CHKUR
  - CEOS
  - Thuillier 2002 (used on OLI)

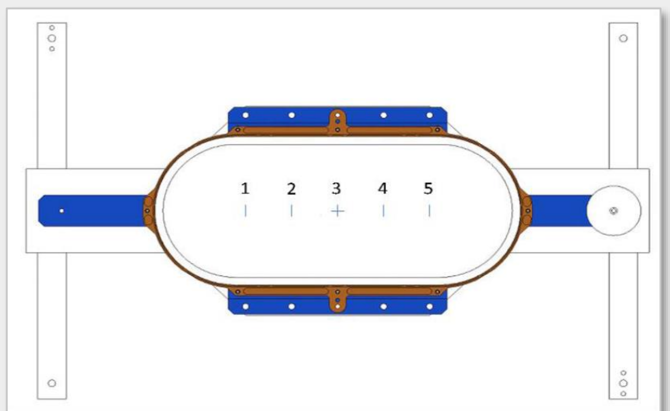


Method 1: Irradiance-Based Calculation

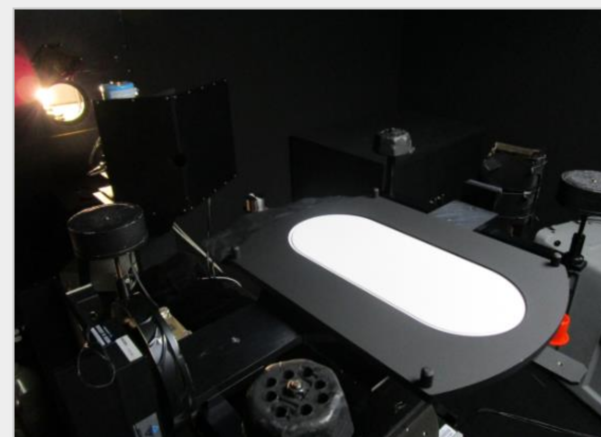
BRDF

$$L_{bw,b,d}(t) = \frac{\int_0^\infty E_{\lambda,sun}(\lambda) * \boldsymbol{BRDF_b} * NU_{b,d}(t_{CATS}) * R_b(\lambda) * cos(\theta)d\lambda}{D^2(t)\int_0^\infty R_b(\lambda)d\lambda}$$

- Witness Samples were cut from the same block of material as the flight diffusers; used to monitor contamination
- Diffuse reflectance standard panels in test were calibrated at NIST
- University of Arizona measured multiple panel locations at various wavelengths



Diffuser test locations

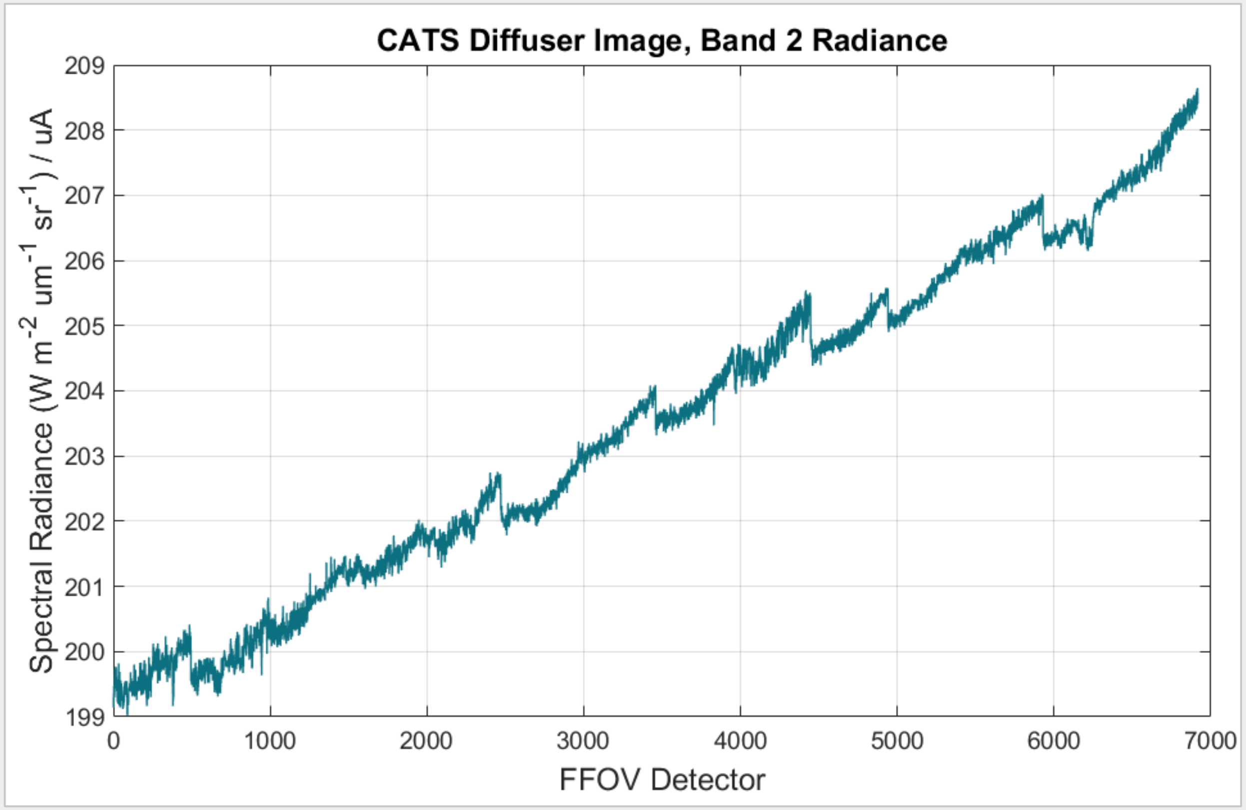

Flight diffuser BRDF testing at the University of Arizona

Method 1: Irradiance-Based Calculation

Non-uniformity

$$L_{bw,b,d}(t) = \frac{\int_0^\infty E_{\lambda,sun}(\lambda) * BRDF_b * \boldsymbol{NU_{b,d}(t_{CATS})} * R_b(\lambda) * cos(\theta) d\lambda}{D^2(t) \int_0^\infty R_b(\lambda) d\lambda}$$

- Non-uniformity is a result of illumination angle
- See ~5% change in radiance across full field of view (FFOV)

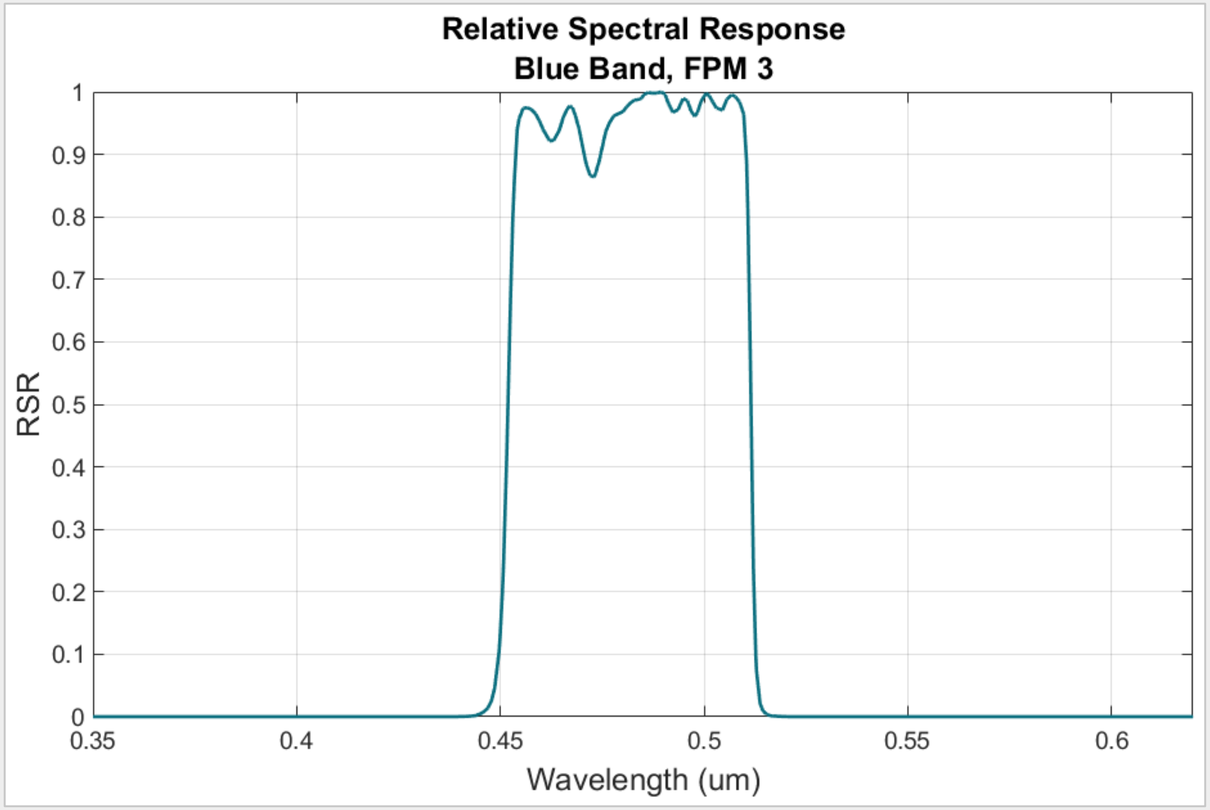


Method 1: Irradiance-Based Calculation

Measured RSR

$$L_{bw,b,d}(t) = \frac{\int_0^\infty E_{\lambda,sun}(\lambda) * BRDF_b * NU_{b,d}(t_{CATS}) * \boldsymbol{R_b(\lambda)} * cos(\theta) d\lambda}{D^2(t) \int_0^\infty \boldsymbol{R_b(\lambda)} d\lambda}$$

- Measured during CATS spectral testing
- This is averaged over all detectors and focal plane modules (FPMs) within each band

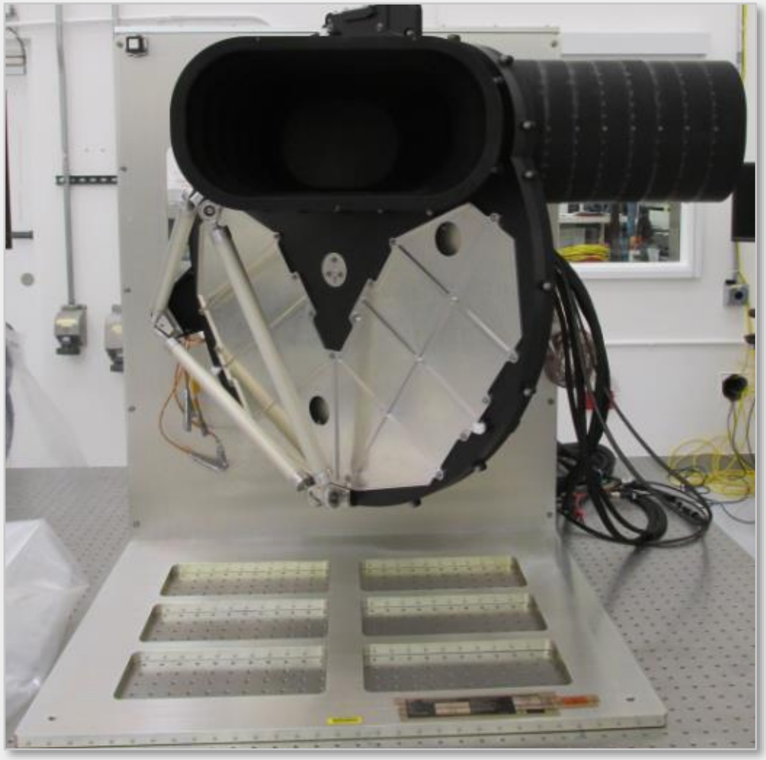


Method 1: Irradiance-Based Calculation

Incidence Angle

$$L_{bw,b,d}(t) = \frac{\int_0^\infty E_{\lambda,sun}(\lambda) * BRDF_b * NU_{b,d}(t_{CATS}) * R_b(\lambda) * \boldsymbol{cos(\theta)d\lambda}}{D^2(t)\int_0^\infty R_b(\lambda)d\lambda}$$

- Light is incident on the diffuser at an angle of 45° by design of solar calibration subsystem



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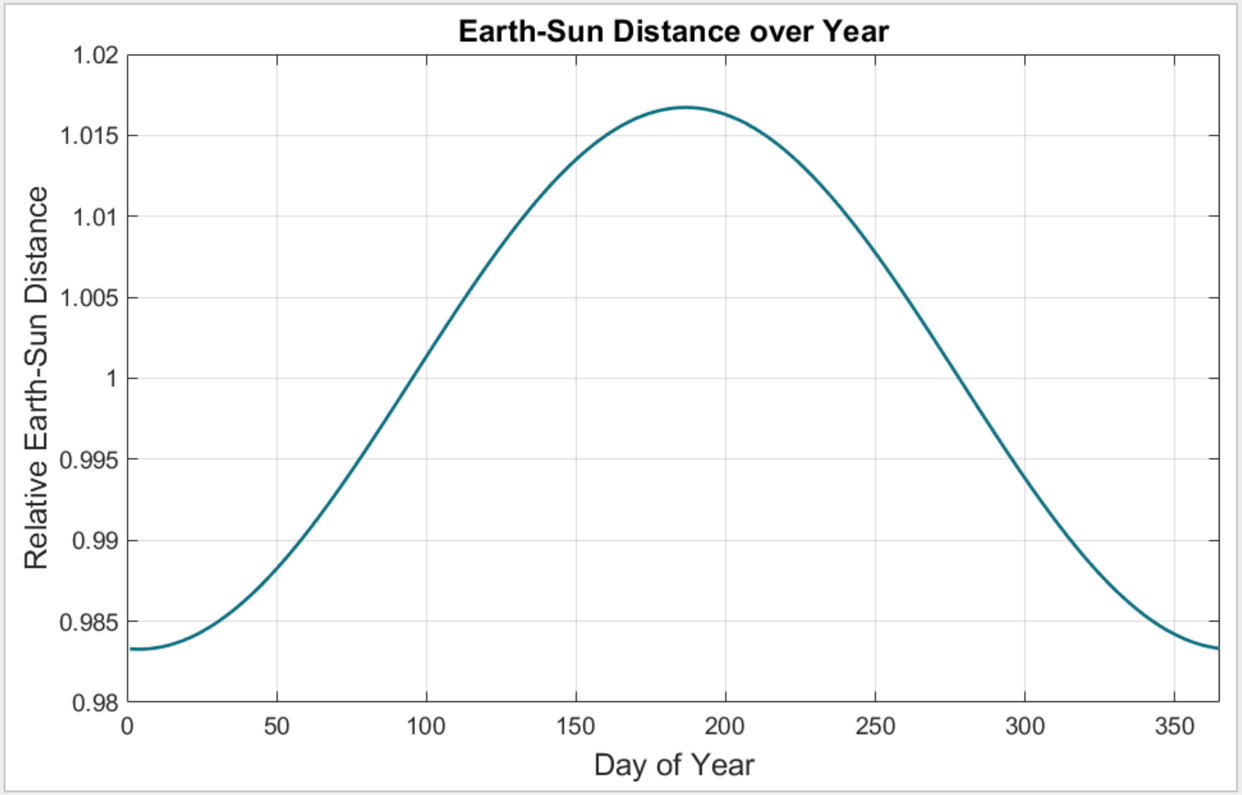
Earth Sun Distance

- Day of year is used to calculate earth-sun distance to correct solar irradiance



Method 2: Radiance-Based Calculation

$$L_{bw,b,d}(t) = \frac{L_{bw,b,d}(t_{CATS})}{\tau_{helio,b}\tau_{atm,b}} \frac{D^2(t_{CATS})}{D^2(t)}$$

Band-weighted spectral radiance $(W\ m^{-2}\ \mu m^{-1}\ sr^{-1})$

Measured Diffuser Radiance during CATS $(W\ m^{-2}\ \mu m^{-1}\ sr^{-1})$

Earth-Sun Distance at CATS test $(\#)$

Heliostat Transmittance $(\#)$

Atmospheric Transmittance $(\#)$

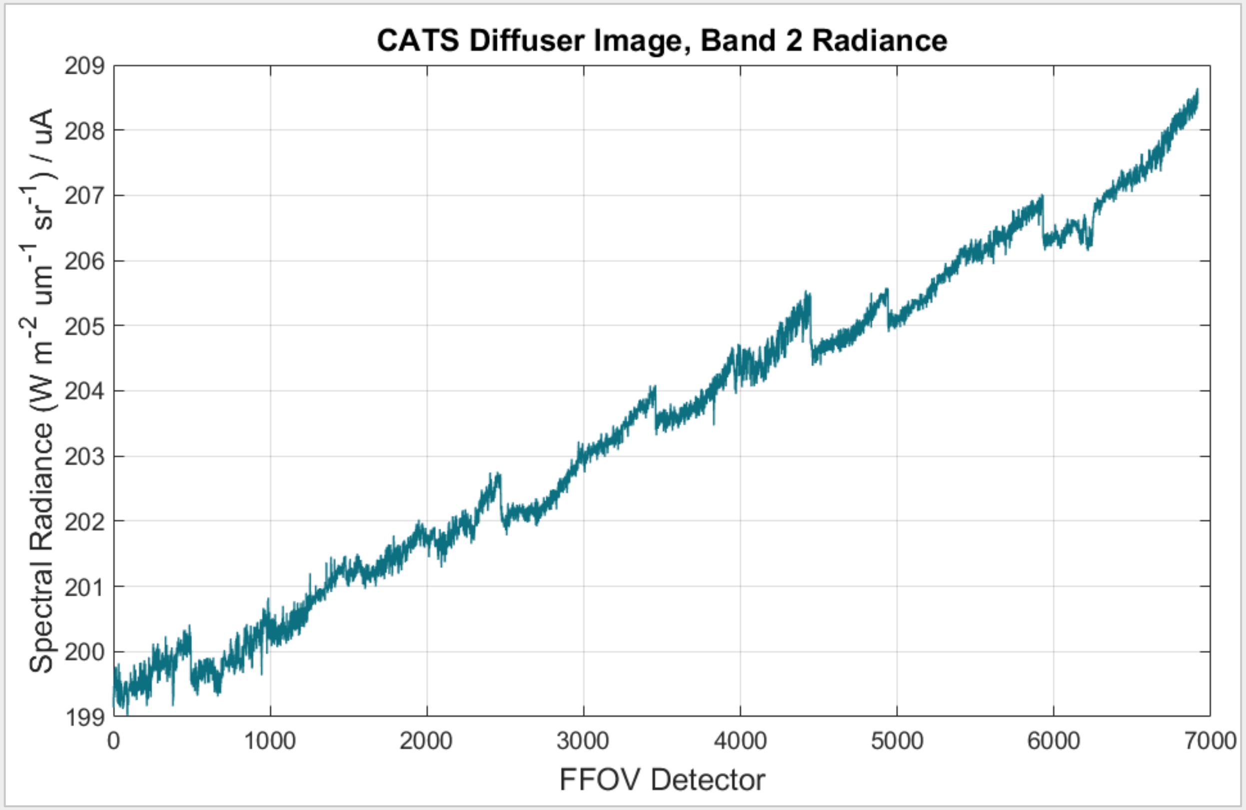
Earth-Sun Distance $(\#)$

Method 2: Radiance-Based Calculation

Measured Diffuser Radiance

$$L_{bw,b,d}(t) = \frac{L_{bw,b,d}(t_{CATS})}{\tau_{helio,b}\tau_{atm,b}} \frac{D^2(t_{CATS})}{D^2(t)}$$

- On-ground diffuser radiance is taken as the average of the two most spatially similar images



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Heliostat Transmittance

- Heliostat transmission was measured with two spectrometers mounted on the calibration panel
- Used Automated Solar Radiometer (ASR) during heliostat characterization to correct atmospheric transmittance changes
- Transmission calculation includes chamber window transmission measured with Cary spectrometer

ASR was set up on test roof to get real-time atmospheric measurements

Heliostat calibration panel, with U of A ASD attached

Method 2: Radiance-Based Calculation

$$L_{bw,b,d}(t) = \frac{L_{bw,b,d}(t_{CATS})}{\tau_{helio,b}\tau_{atm,b}} \frac{D^2(t_{CATS})}{D^2(t)}$$

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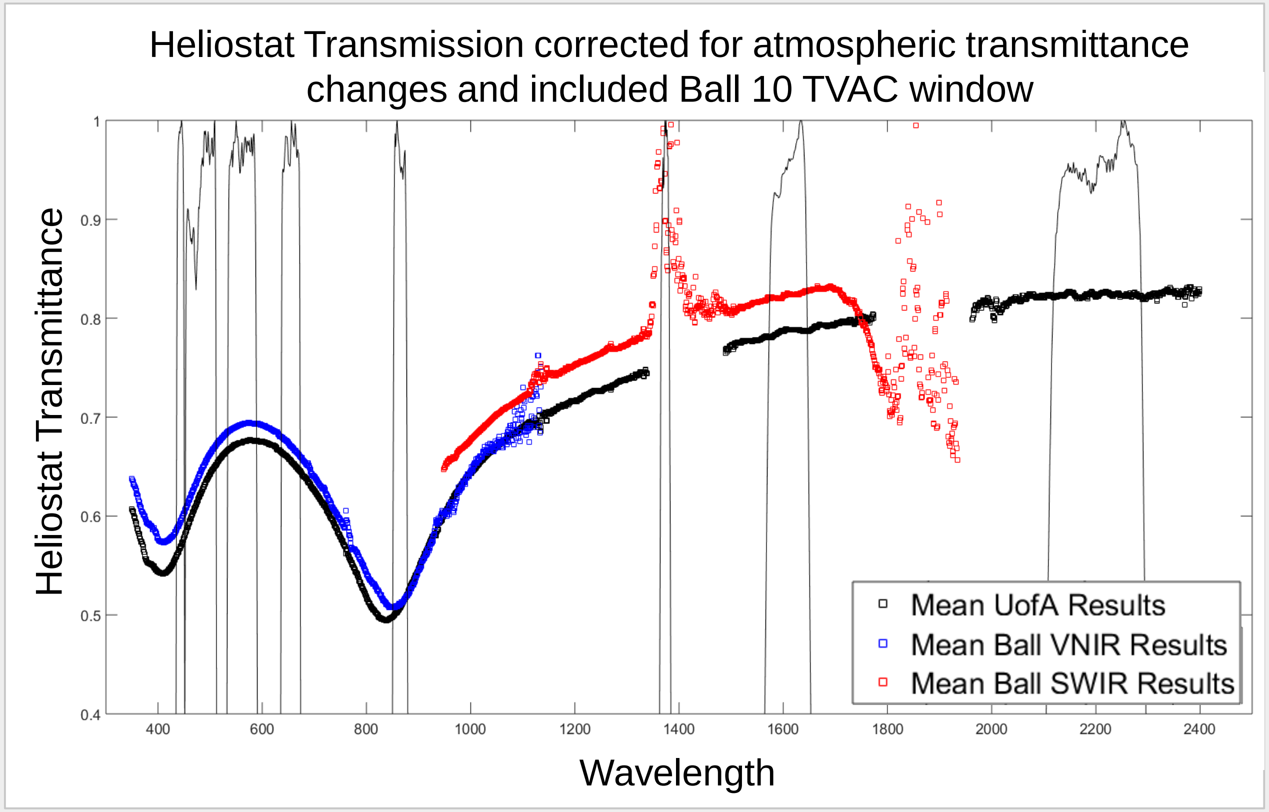

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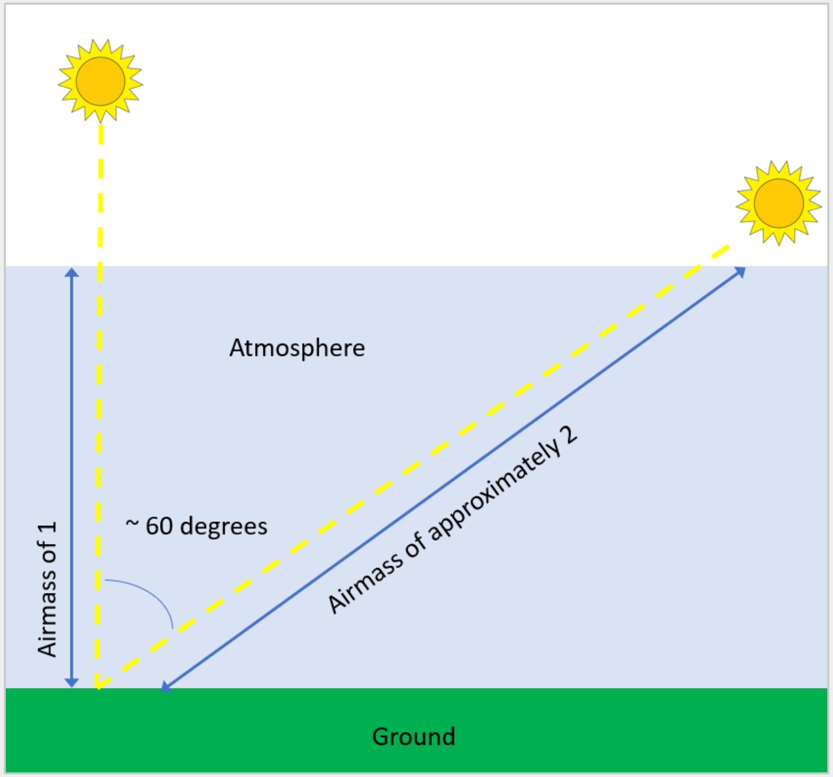
Atmospheric Transmittance

- ASR was collected during heliostat operation because solar transmittance changes based on pathlength and air column clarity



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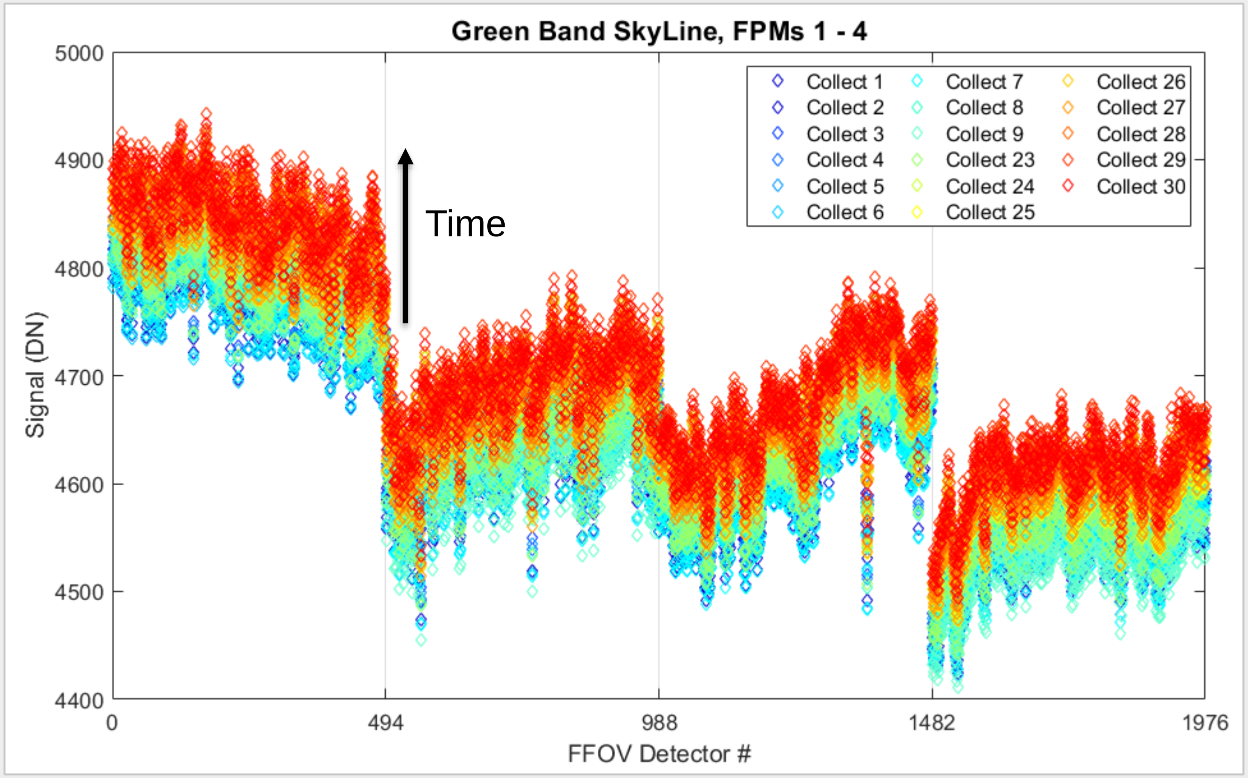

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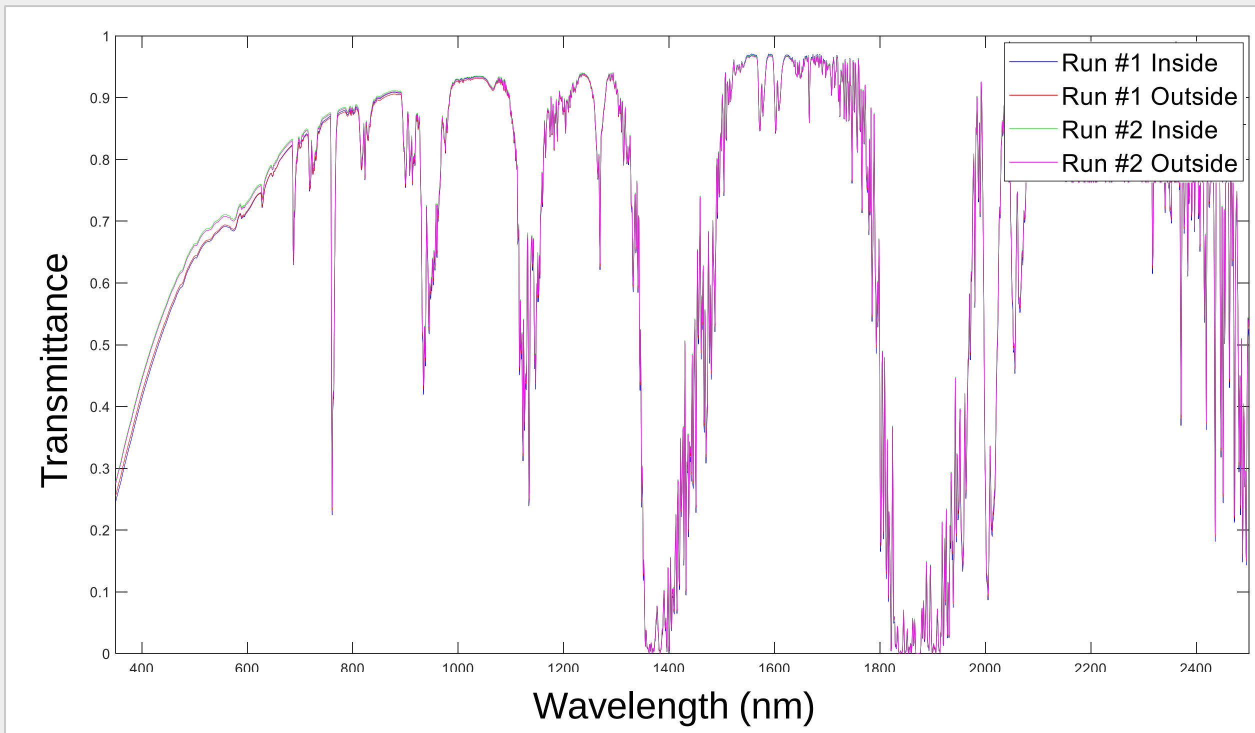
Atmospheric Transmittance

- Atmospheric transmittance was calculated for the times of the most similar diffuser images by the University of Arizona



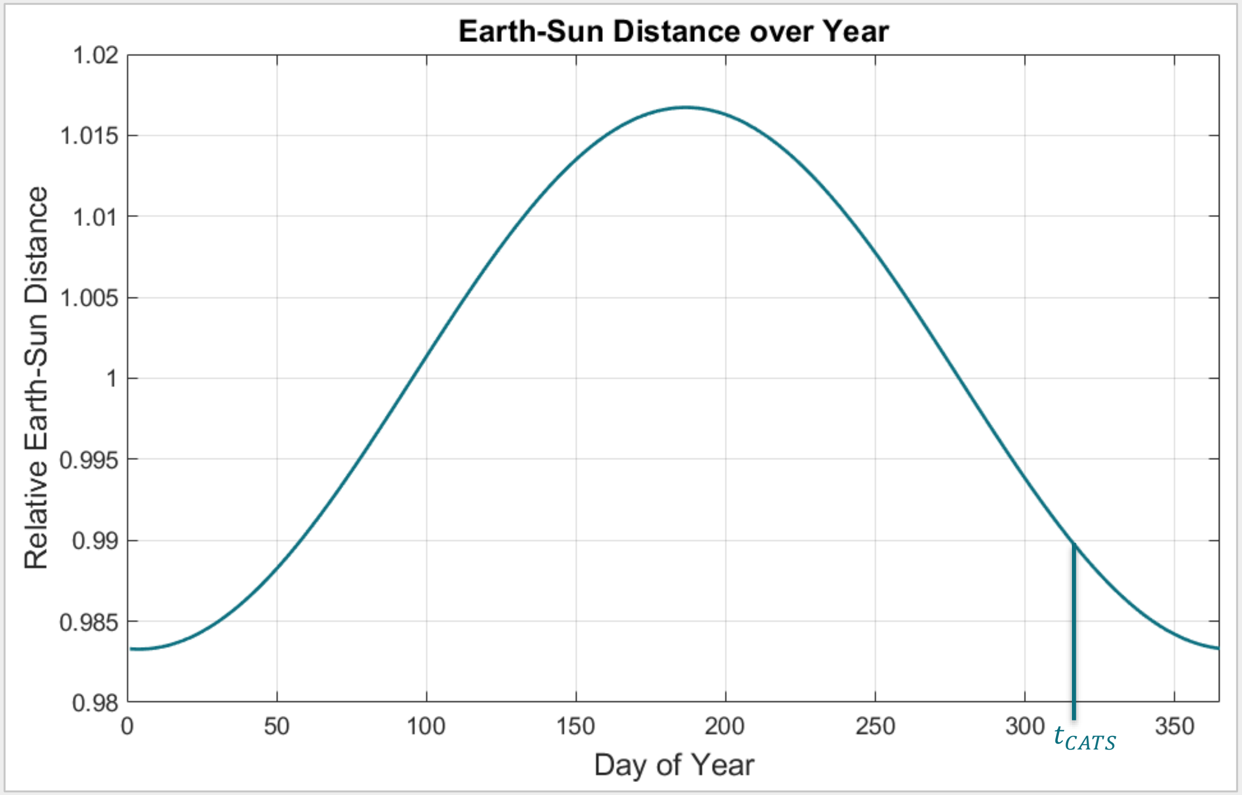
Method 2: Radiance-Based Calculation

$$L_{bw,b,d}(t) = \frac{L_{bw,b,d}(t_{CATS})}{\tau_{helio,b}\tau_{atm,b}} \frac{D^2(t_{CATS})}{D^2(t)}$$

Earth Sun Distance at CATS testing

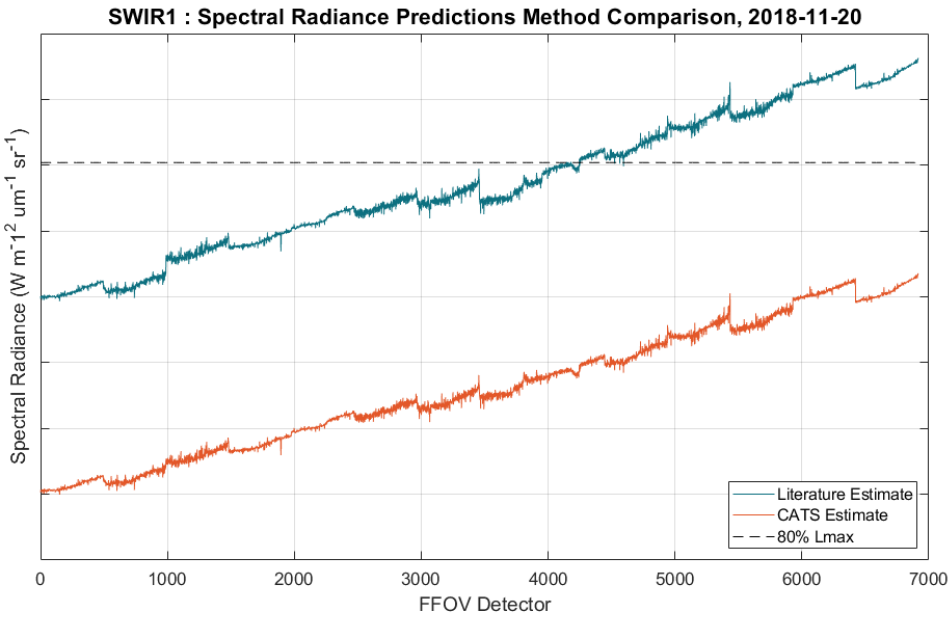
Earth Sun Distance

- Day of year is used to calculate earth-sun distance to correct solar irradiance

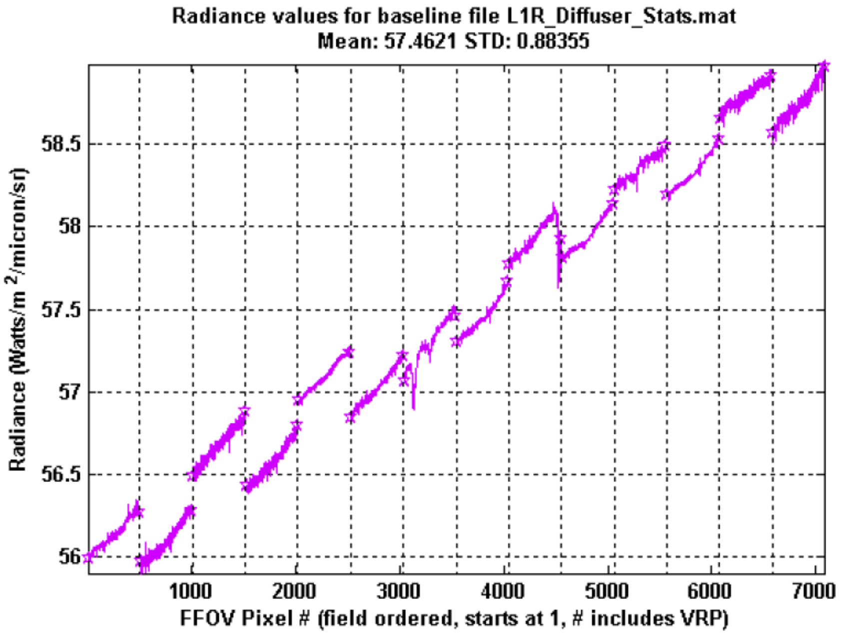


TOA Prediction Preliminary Results

OLI-2



OLI



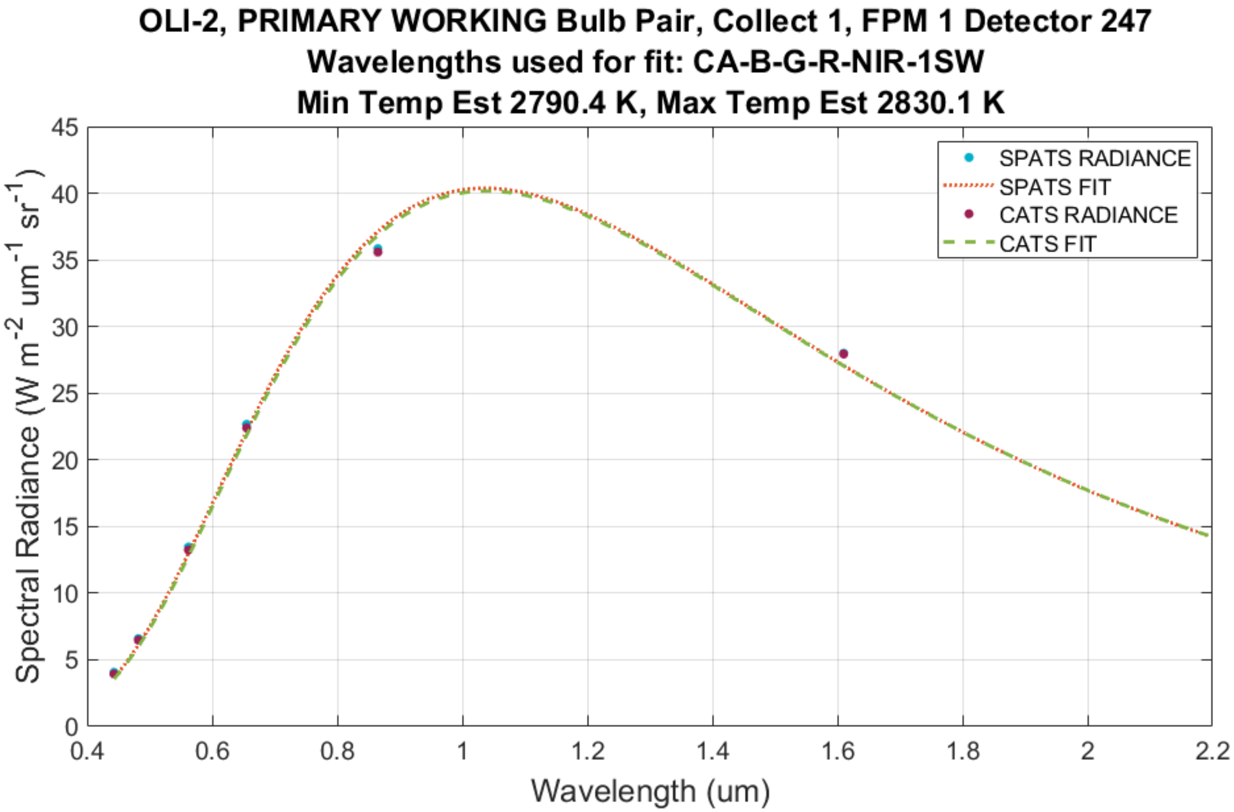
- **See a preliminary agreement of up to 5% between the two TOA calculation methods**
- **See a preliminary agreement of up to 5% between OLI and OLI-2 data**
- **We will continue to refine these predictions**

Determine diffuser-calibrated bands

- **The subset of diffuser-calibrated bands can be determined by:**
  - **Similar predictions from the two diffuser TOA radiance methods**
  - **Similar predicted and on-orbit radiance measurements reported on OLI**

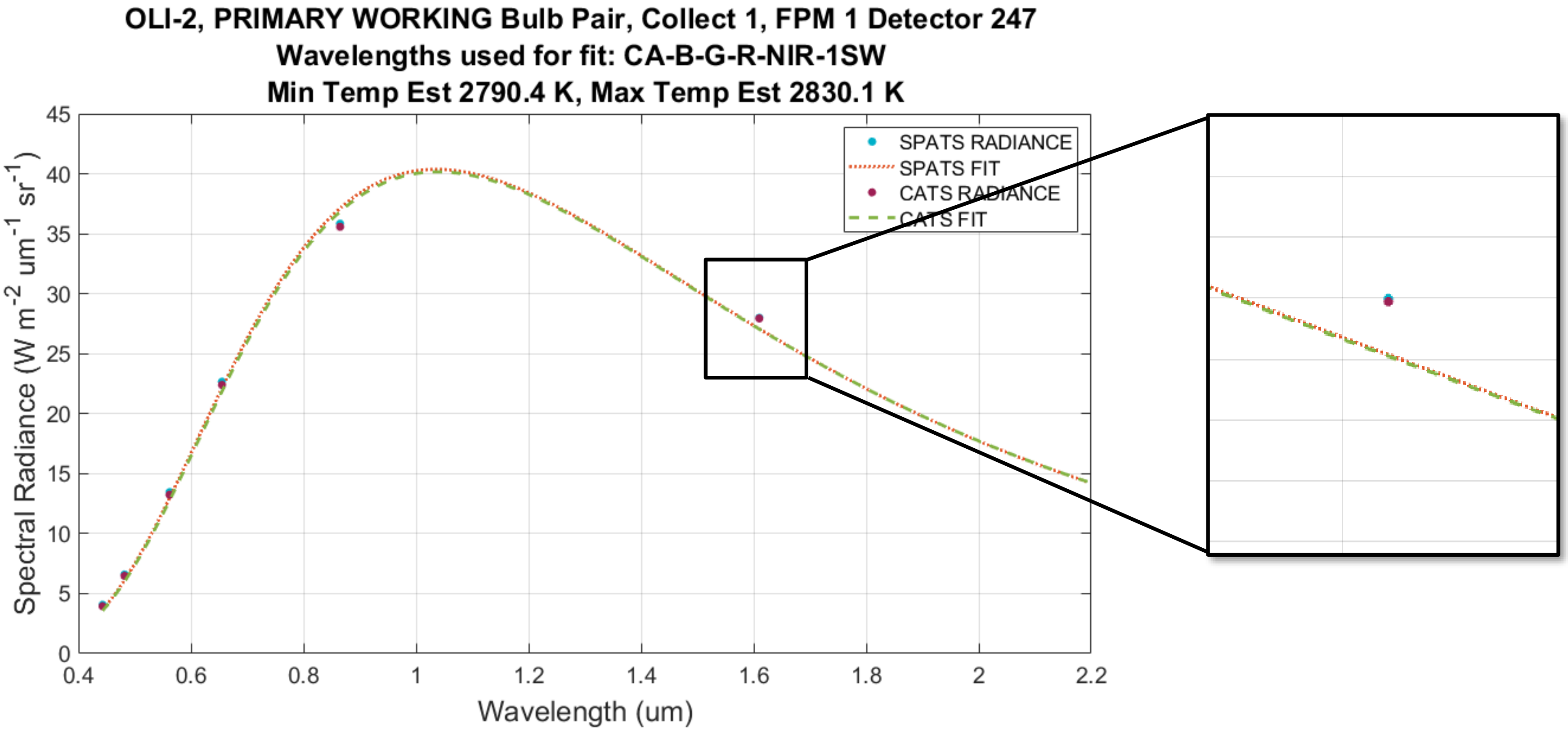
- **May also be informed by**
  - **Quality of *Stim Lamp Fit Metric***
  - **Agreement of different solar spectra**
  - **Similarity between OLI and OLI-2**

Calculate the Stim Lamp Bulb Color Temperature Fit



$$P_\lambda(\lambda, T) = \frac{c_1}{\lambda^5 \cdot e^{[(c_2/\lambda \cdot T)-1]}}$$

Calculate the Stim Lamp Bulb Color Temperature Fit



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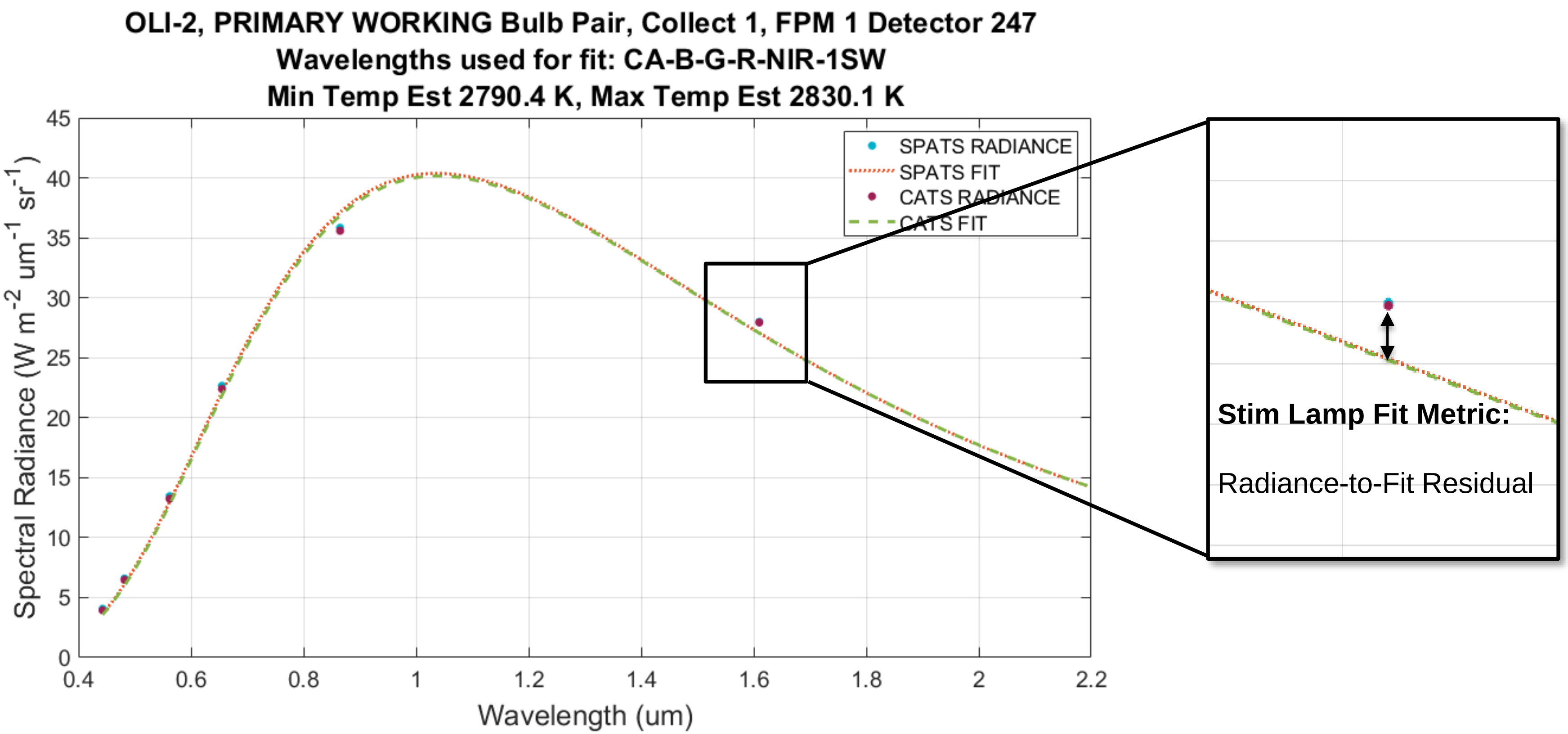
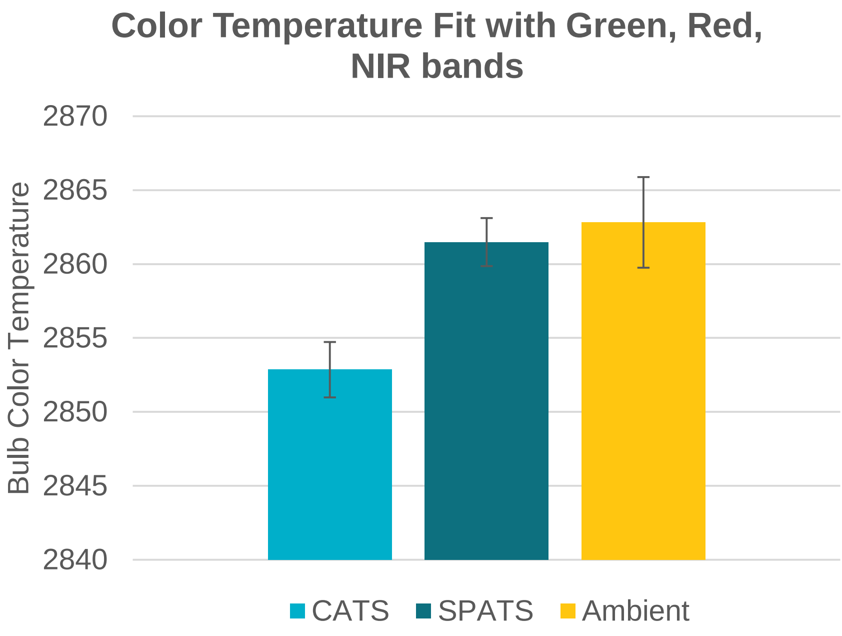
Calculate the Stim Lamp Bulb Color Temperature Fit



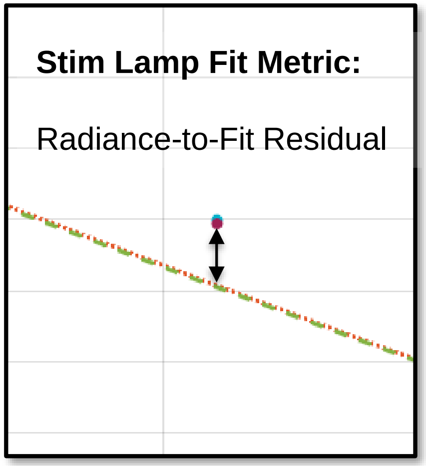
$$P_\lambda(\lambda, T) = \frac{c_1}{\lambda^5 \cdot e^{[(c_2/\lambda \cdot T) - 1]}}$$

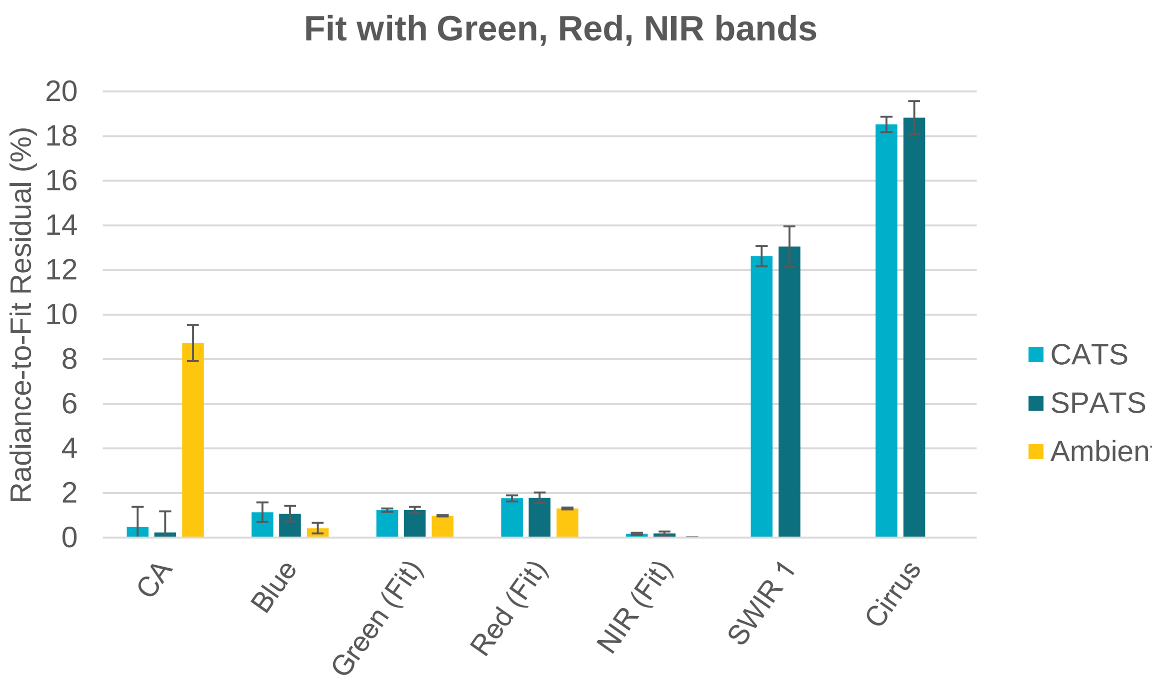
Color temperature fitting should be stable

- **Expect the color temperature to change on orbit due to vacuum, instrument orientation, and 0G**
  - **Calibration Alignment Test Station (CATS) and Spatial Performance Test Station (SPATS) used different instrument orientation**
  - **SPATS/CATS were completed in vacuum while other collects were completed in ambient environments**
  - **See anticipated changes between different test campaigns**
- **Expect the band fitting (Stim Lamp Fit Metric) to perform the same relative to the collected signal regardless of the environmental changes**
- **Cal coefficients are preliminary**



The residuals of each band relative to the fit remain consistent despite the changes

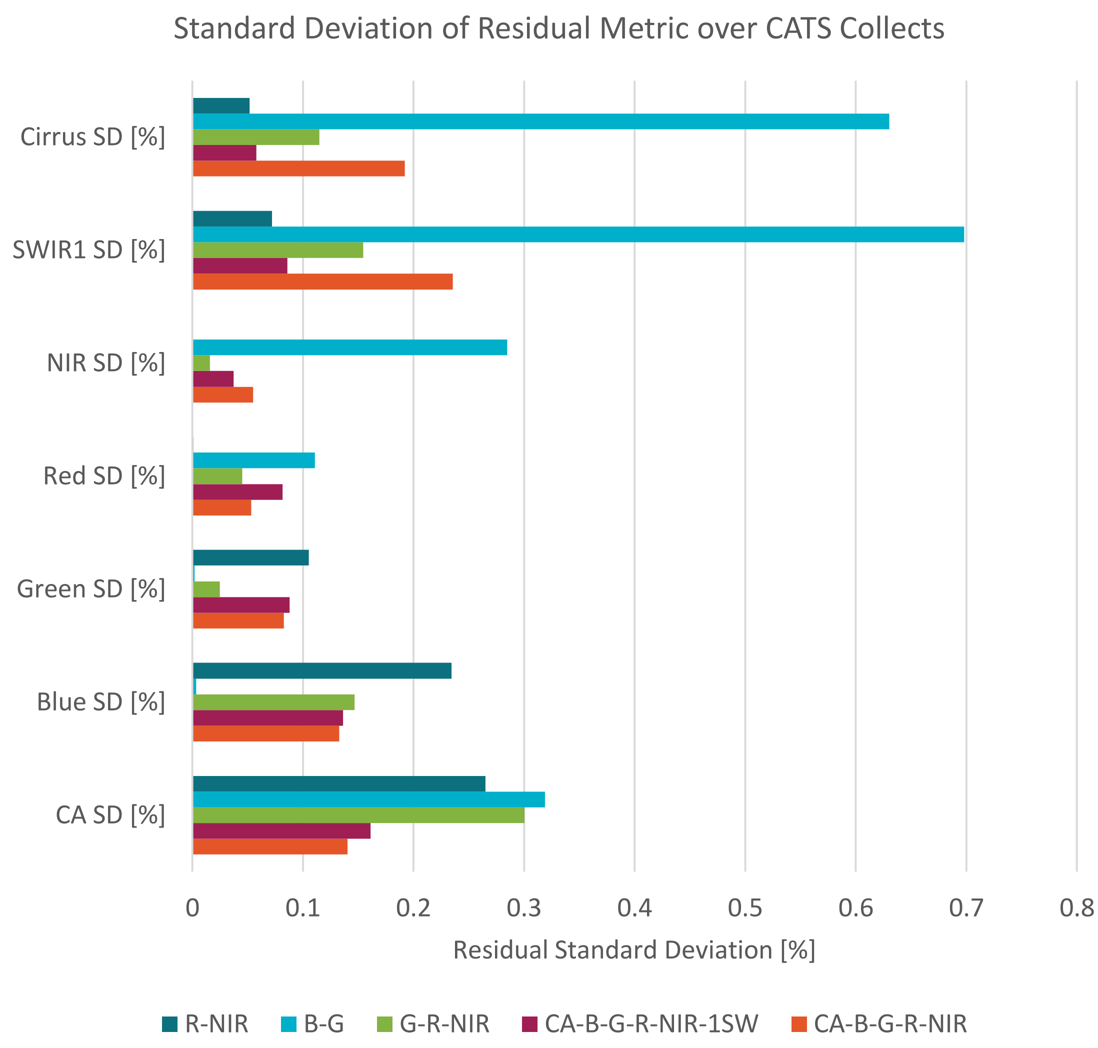




- Both between test campaigns and within test campaign, the fitting method is repeatable
- This residual can be used as a metric to fit bands relative to one another
- The residuals may offer an evaluation of the cal coefficients

Bulb color temperature is highly repeatable with as few as 2 bands

- **Choice of diffuser-calibration bands affects the quality of the bulb color temperature fit**
- **The quality of the fit can be highly repeatable**
- **Using more bands for the fit does not imply a better fit**
  - **Fit quality is measured by both magnitude and repeatability of residual**



Summary

- The data we have collected through ground tests give us enough information to determine:
  - Diffuser-calibrated band subset through the diffuser measurements
  - Bulb temperature fitting parameters through the stim lamp measurements
- We will continue to refine the metrics for determining which subset of bands to use and coming up with these final parameters
- On orbit, we will collect data to
  - Compare diffuser TOA radiance measurements to predictions
  - Determine whether the cal coefficients changed
  - Use updated cal coefficients to fit the on orbit stim lamp images for all bands

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