Solar High-Spectral-Resolution Irradiance Model

Its Utilization and Applications

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Global Space-based Inter-Calibration System
GSICS VIS/NIR Meeting
September 10, 2026

Talk Overview

1) Background and Motivation

Lack of Standardized Implementation Approaches and Solar Spectral Irradiance Models

2) Solar Spectral Band Integration Framework

Relative Spectral Response (RSR) and RSR-weighted convolution

3) Methodology

Spectral Resampling Strategy: E(λ) vs RSR(λ)
Interpolation and Numerical Methods

5) Results and Key Findings

Sensitivity to Methodological Choices

6) Final Thoughts

Recommendations

Background and Motivation

Solar Spectral Irradiance Model

Question:

How sensitive is band-integrated solar irradiance derived from high-resolution irradiance spectra to the choice of spectral resampling and interpolation methods?

* The community has focused on model selection, but has overlooked how those models are numerically implemented

$$E_{band} = \frac{\int_0^\infty E_\lambda \times RSR_\lambda d\lambda}{\int_0^\infty RSR_\lambda \, d\lambda}$$

(spectral convolution)

Solar Spectral Band Integration Framework

Solar Spectral Irradiance Model

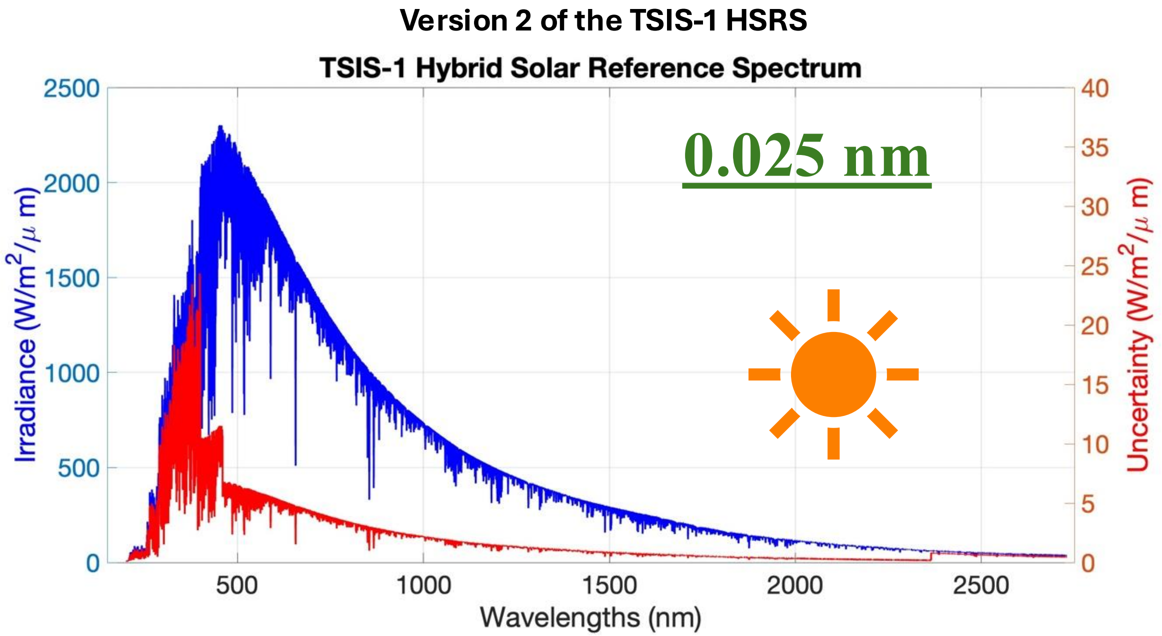
This might look straightforward, but in practice there are many ways to do it...

Key decisions include how to interpolate the irradiance data, which numerical integration method to apply (such as the trapezoidal rule, Simpson's rule, or more advanced techniques), whether to resample the finer-resolution data to match the coarser data or vice versa, and how to properly calculate the associated uncertainties.

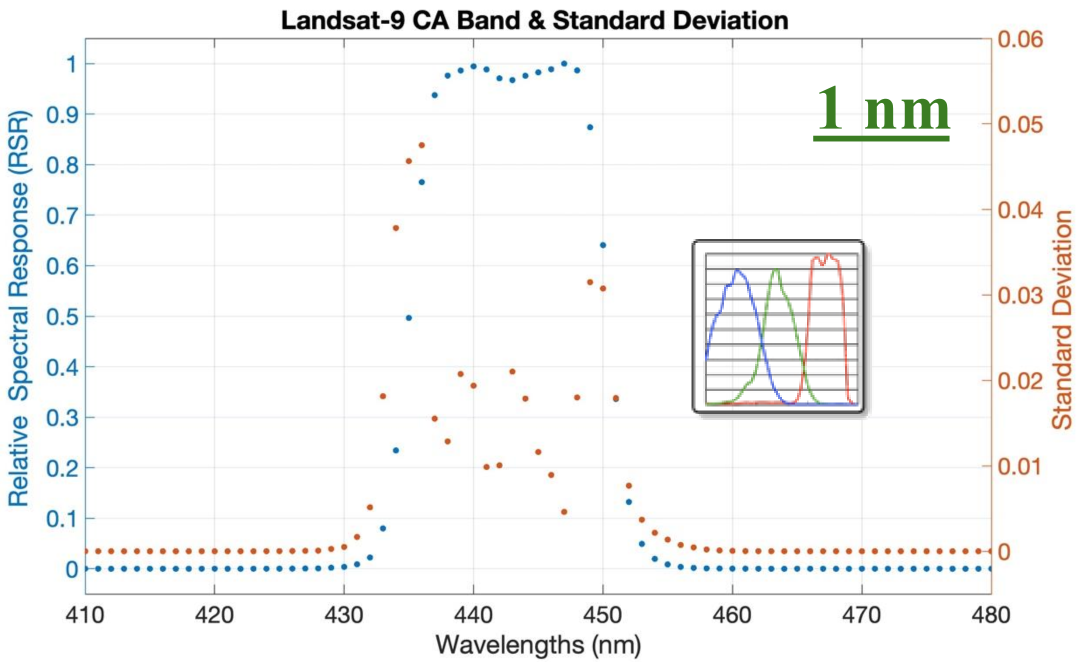
The numerical choices in spectral integration (including resampling direction and interpolation method) can introduce ERRORS that are larger than the intrinsic uncertainty of the solar spectral model.

Each of these choices influences the outcome...

Solar Spectral Band Integration Framework



Coddington et al. (2023)



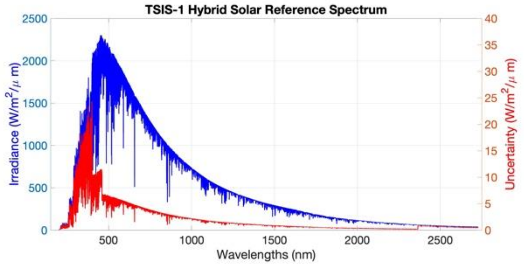
Landsat-9 OLI CA Band

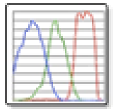
*Committee on Earth Observation Satellites (CEOS) formally recommended in March 2022 the TSIS-1

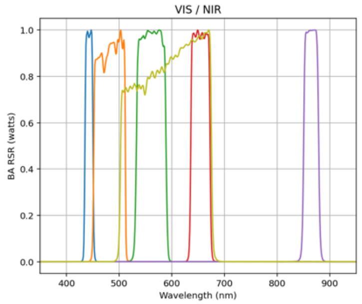
$$E_{band} = \frac{\int_0^{\infty} E_\lambda \times RSR_\lambda d\lambda}{\int_0^{\infty} RSR_\lambda \, d\lambda}$$

Methodology

Solar Spectral Irradiance (SSI)







Relative Spectral Response (RSR)

E(λ)

RSR(λ)

Resampling Strategy
(grid choice)

Interpolation Strategy
(numerical scheme choice)

$$E_{band} = \frac{\int_0^\infty E_\lambda \times RSR_\lambda d\lambda}{\int_0^\infty RSR_\lambda \, d\lambda}$$

Sensitivity Analysis
(results comparison)

Choice of spectral resampling direction:

→ $RSR(\lambda)$ onto the grid of $E(\lambda)$
0.025 nm spectral sampling

→ $E(\lambda)$ onto the grid of $RSR(\lambda)$
1 nm spectral sampling

Results and Key Findings

Spectral Resampling Strategy: E(λ) vs. RSR(λ)

* TSIS-1 HSRS

Interpolation of the RSR to match the Solar Model **X** Interpolation of the Solar Model to match the RSR

0.025 nm spectral sampling				1 nm spectral sampling		
Landsat-9 Spectral Bands	Irradiance [W/m²/μm]	TSIS Uncertainty %	DIFF	Landsat-9 Spectral Bands	Irradiance [W/m²/μm]	TSIS Uncertainty %
Coastal	1906.10 ± 9.53	0.50	-3.83%	Coastal	1979.02 ± 9.90	0.50
Blue	2015.57 ± 6.60	0.33	0.86%	Blue	1998.33 ± 6.59	0.33
Green	1866.83 ± 5.60	0.30	0.06%	Green	1865.77 ± 5.60	0.30
Red	1564.44 ± 4.69	0.30	-0.51%	Red	1572.48 ± 4.72	0.30
NIR	947.720 ± 2.84	0.30	-0.59%	NIR	953.279 ± 2.86	0.30
SWIR1	238.793 ± 0.72	0.30	0.22%	SWIR1	238.257 ± 0.71	0.30
SWIR2	81.3761 ± 0.24	0.30	0.11%	SWIR2	81.2879 ± 0.24	0.30
PAN	1749.74 ± 5.25	0.30	0.02%	PAN	1749.38 ± 5.25	0.30
Cirrus	357.924 ± 1.07	0.30	-0.06%	Cirrus	358.146 ± 1.07	0.30

* For this initial testing phase, a simple linear interpolation scheme was employed. The effects of alternative interpolation methods will be evaluated subsequently to assess their impact on the results.

Results and Key Findings

* TSIS-1 HSRS

Spectral Resampling Strategy: E(λ) vs. RSR(λ)

0.025 nm spectral sampling x **1 nm** spectral sampling

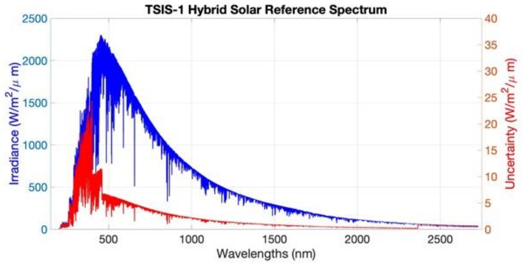
DIFF
-3.83%
0.86%
0.06%
-0.51%
-0.59%
0.22%
0.11%
0.02%
-0.06%

This difference is quite significant (uncertainty associated with the TSIS-1 HSRS is reported ~ 0.3% to 0.5% for OLI bands).
This indicates that the observed discrepancy is not dominated by solar model uncertainty, but rather by methodological choices in the resampling procedure.

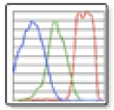
What are the effects of employing alternative interpolation methods?

Methodology

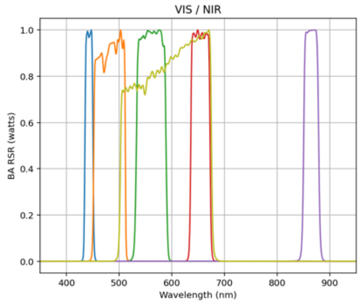
Solar Spectral Irradiance (SSI)



$E(\lambda)$



$RSR(\lambda)$



Relative Spectral Response (RSR)

0.025 nm
spectral sampling

Interpaled the RSR to match with the Solar Model

Resampling Strategy
(grid choice)

Interpolation Strategy
(numerical scheme choice)

$$E_{band} = \frac{\int_0^\infty E_\lambda \times RSR_\lambda d\lambda}{\int_0^\infty RSR_\lambda \, d\lambda}$$

Sensitivity Analysis
(results comparison)

The initial action requested of the members was to perform band-averaging of the TSIS-1 HSRS data at **0.025 nm** sampling to the Landsat-9 OLI RSR bands.

Cibele Teixeira Pinto
Norvik Voskanian
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Larry Leigh
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Results and Key Findings

Interpolation and Numerical Methods

The results were consistency when using TSIS data with a fine wavelength grid of 0.025 nm.

0.025 nm
spectral sampling

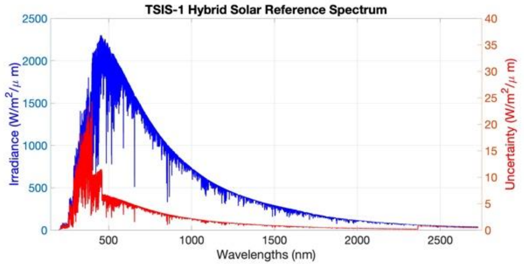
Interpaled the RSR to match with the Solar Model

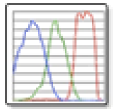
Landsat-9 Spectral Bands	Irradiance [W/m²/μm] Member/Team 1	Irradiance [W/m²/μm] Member/Team 2	Irradiance [W/m²/μm] Member/Team 3	Irradiance [W/m²/μm] Member/Team 4
Coastal	1906.10 ± 9.53	1906.10	1906.1	1907.46
Blue	2015.57 ± 6.60	2015.57	2015.6	2017.09
Green	1866.83 ± 5.60	1866.83	1866.8	1868.19
Red	1564.44 ± 4.69	1564.44	1564.4	1565.59
NIR	947.720 ± 2.84	947.720	947.70	948.42
SWIR1	238.793 ± 0.72	238.793	238.80	238.57
SWIR2	81.3761 ± 0.24	81.376	81.400	81.48
PAN	1749.74 ± 5.25		1749.7	1751.02
Cirrus	357.924 ± 1.07		357.90	

the variability across member results is low (standard deviation below 0.04%)

Methodology

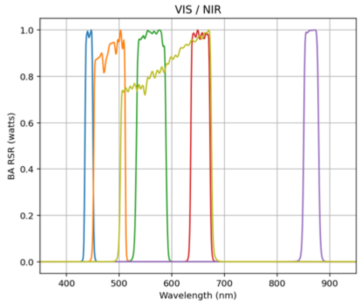
Solar Spectral Irradiance (SSI)





E(λ)

RSR(λ)



Relative Spectral Response (RSR)

1 nm

spectral sampling

Interpolation of the Solar Model to match the RSR

Resampling Strategy
(grid choice)

Interpolation Strategy
(numerical scheme choice)

$$E_{band} = \frac{\int_0^{\infty} E_\lambda \times RSR_\lambda d\lambda}{\int_0^{\infty} RSR_\lambda \, d\lambda}$$

Sensitivity Analysis
(results comparison)

The next action requested of the members was to perform band-averaging of the TSIS-1 HSRS data at **1 nm** sampling to the Landsat-9 OLI RSR bands.

Cibele Teixeira Pinto
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Results and Key Findings

Interpolation and Numerical Methods

In contrast, the results show a marked sensitivity when the resampling direction is reversed, when $E(\lambda)$ is interpolated onto the coarser $RSR(\lambda)$ grid - with discrepancies reaching nearly 4%

1 nm

spectral sampling

Interpolation of the Solar Model to match the RSR

Landsat-9 Spectral Bands	Irradiance [W/m²/μm] Member/Team 1	Irradiance [W/m²/μm] Member/Team 2	Irradiance [W/m²/μm] Member/Team 3	Irradiance [W/m²/μm] Member/Team 4
Coastal	1907.13	1979.02	1979.00	1979.95
Blue	2015.50	1998.33	1998.30	2000.07
Green	1866.84	1865.77	1865.80	1867.01
Red	1564.45	1572.48	1572.50	1573.62
NIR	947.806	953.279	953.30	953.94
SWIR1	238.788	238.257	238.30	238.44
SWIR2	81.3758	81.288	81.30	81.35
PAN	1749.75		1749.40	1750.68
Cirrus	357.938		358.10	

standard deviation across ensemble member results is up to 2%

Results and Key Findings

Interpolation and Numerical Methods

After reviewing the results provided by the members and discussing them with the respective contributors, I infer that the observed issue may be associated with the **interpolation methods employed**.

Regular interpolation: Up to **4% errors** when downsampling to 1 nm

The choice of integration approach may introduce greater ERROR than the uncertainty inherent in the solar model itself.

Why “regular” Interpolation Fails

Why “regular” Interpolation Fails (when down-sampling)

- ✓ **Interpolation** (like linear, bilinear, or bicubic) estimates values **between** known data points. It's great for upscaling or smooth visualization, but it's not designed to **preserve the integral** of sharp or rapidly changing data (e.g., the integral or area under a curve);

- ✓ When you use interpolation just to **fill in values**, you may change the shape of the curve and distort the total area.

If our goal is to maintain an accurate total quantity we must preserve the integral of the data. This requires using **integration-preserving downsampling methods.**

Flux-conserving (area-preserving) resampling :

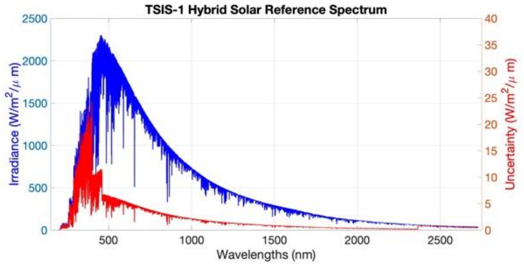
→ **Trapezoidal Rule**

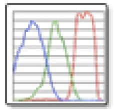
→ **Gaussian Kernel**

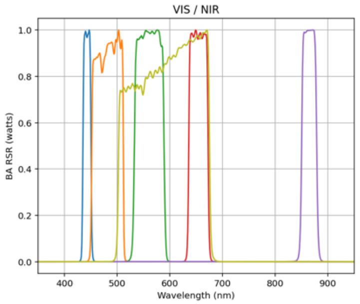
*while the Trapezoidal rule is intrinsically flux-conserving, the Gaussian kernel requires explicit normalization and consistent treatment of spectral sampling to ensure flux preservation during interpolation.

Methodology

Solar Spectral Irradiance (SSI)







Relative Spectral Response (RSR)

$E(\lambda)$

$RSR(\lambda)$

1 nm
spectral sampling

Interpolation of the Solar Model to match the RSR

Resampling Strategy
(grid choice)

Interpolation Strategy
(numerical scheme choice)

Members were subsequently asked to band-average TSIS-1 HSRS data, resampled to **1 nm**, to the Landsat-9 OLI RSR bands using **integration-preserving downsampling methods**.

$$E_{band} = \frac{\int_0^{\infty} E_\lambda \times RSR_\lambda d\lambda}{\int_0^{\infty} RSR_\lambda \, d\lambda}$$

Sensitivity Analysis
(results comparison)

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Results and Key Findings

Interpolation and Numerical Methods

instructing the members to adopt **integration-preserving downsampling methods**.

1 nm

spectral sampling

Interpolation of the Solar Model to match the RSR

Integration-Preserving Downsampling Methods

Landsat-9 Spectral Bands	Irradiance [W/m²/μm] Member/Team 1	Irradiance [W/m²/μm] Member/Team 2	Irradiance [W/m²/μm] Member/Team 3	Irradiance [W/m²/μm] Member/Team 4
Coastal	1907.13	1907.131	1907.8	$\boxed{1914.94}$
Blue	2015.50	2015.502	2015.4	2015.07
Green	1866.84	1866.841	1866.9	1866.01
Red	1564.45	1564.446	1564.7	1563.19
NIR	947.806	947.806	948	947.36
SWIR1	238.788	238.7881	238.8	238.47
SWIR2	81.3758	81.37578	81.4	81.41
PAN	1749.75	1749.753	1749.9	1749.01
Cirrus	357.938	357.9378	357.9	

When using interpolation approaches that preserve the integrated quantity, the results began to converge. However, for some spectral bands and for certain members, discrepancies up to 0.5% remained

Results and Key Findings

Interpolation and Numerical Methods

instructing the members to adopt **integration-preserving downsampling methods**.

All bands exhibit deviations of **≤0.1%,** with the exception of the CA band for one member, which shows a deviation of **0.46%**. I consider this difference significant, given that the TSIS uncertainty value for this band is only **0.5%**

After further analysis, it was determined that the underlying issue was related to the bin boundary (edge) effects in spectral resampling.

✓ Small shifts in bin boundaries can introduce systematic wavelength offsets or subtle distortions in the integrated flux, which propagate into the final band-averaged results.

Results and Key Findings

Interpolation and Numerical Methods

instructing the members to adopt **integration-preserving downsampling methods**.

1 nm

spectral sampling

Interpolation of the Solar Model to match the RSR

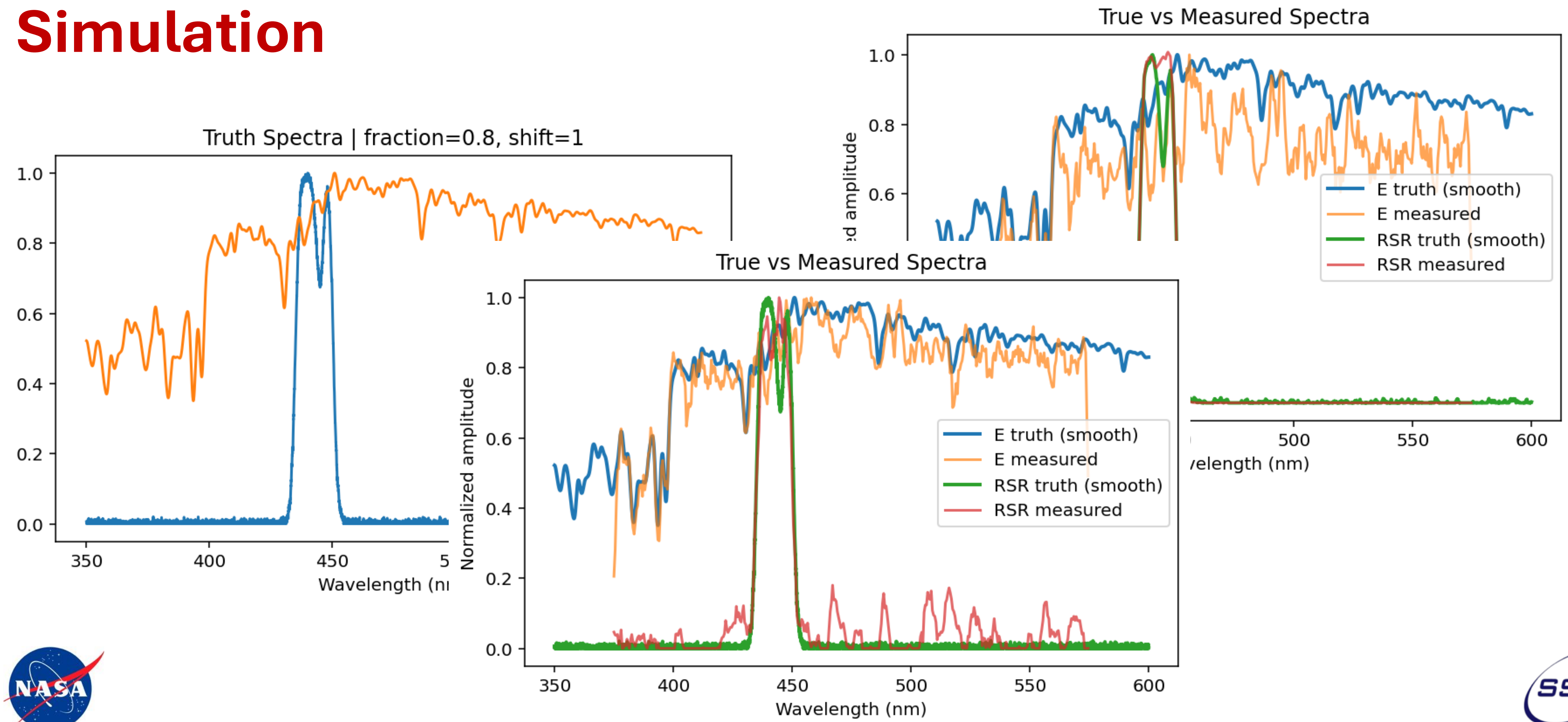
Integration-Preserving Downsampling Methods

Landsat-9 Spectral Bands	Irradiance [W/m²/μm] Member/Team 1	Irradiance [W/m²/μm] Member/Team 2	Irradiance [W/m²/μm] Member/Team 3	Irradiance [W/m²/μm] Member/Team 4
Coastal	1907.13	1907.131	1907.8	1905.88
Blue	2015.50	2015.502	2015.4	2015.02
Green	1866.84	1866.841	1866.9	1866.58
Red	1564.45	1564.446	1564.7	1564.26
NIR	947.806	947.806	948	947.918
SWIR1	238.788	238.7881	238.8	238.584
SWIR2	81.3758	81.37578	81.4	81.4474
PAN	1749.75	1749.753	1749.9	1749.61
Cirrus	357.938	357.9378	357.9	1905.88

After adjusting the spectral bin definition, the results show clear convergence: the standard deviation across ensemble members ranging from 0.005% to 0.037% across the spectral bands.

Next Steps...

Simulation



Results and Key Findings

Motivation:

The community has focused on model selection, but has overlooked how those models are numerically implemented.

The results identify three primary sources of numerical variability:

- the spectral mapping direction between $E(\lambda)$ and $RSR(\lambda)$
  key choice that prioritizes preserving data and numerical stability
- the interpolation scheme used during resampling; and
  avoidable errors of up to ~4%
- spectral edge effects associated with bin definition and boundary placement.
  avoidable errors of up to ~0.5%

Final Thoughts: Conclusions and Recommendations

Recommendation → Core Guideline

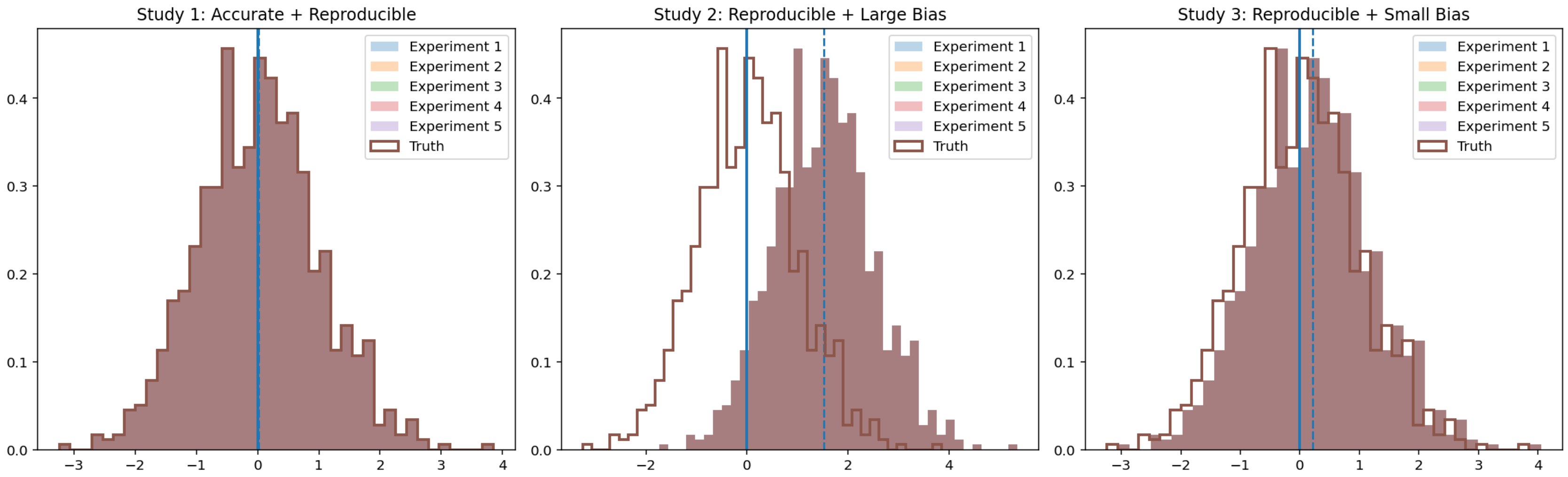
- ✓ The fundamental rule for evaluating band-integrated irradiance is that the integration grid must resolve the spectral structure of the product E(λ) × RSR(λ).

Interpolate the **lower-resolution (coarse) data onto the higher-resolution (fine)** grid. Assuming standard, good-quality data for both the RSR and Irradiance (E), the **coarse-to-fine approach is the safer and more numerically stable choice**, as it preserves structural consistency and reduces the risk of aliasing-induced errors, thereby improving robustness and maintaining controlled error.

Final Thoughts: Conclusions and Recommendations

Implementation must be standardized to ensure reproducibility

→ reproducibility is the ability of an entire study, experiment, or calculation to be duplicated with consistent results.



When implemented correctly (best practices), variability drops below 0.04% — well below the ~0.3–0.5% uncertainty of the TSIS-1 HSRS model.

Final Thoughts: Conclusions and Recommendations

for more information:

SPIE. OPTICS+ PHOTONICS

26 August 2026

Best Practices for use of High-Spectral Resolution Solar Irradiance

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Solar High-Spectral-Resolution Irradiance Model

Its Utilization and Applications

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Thank you!

Global Space-based Inter-Calibration System

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