Update on CEOS Solar Irradiance

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Outline

- Section 1: Background & Motivation
- Section 2: Brief Methodology Overview
- Section 3: TSIS-1 HSRS Update
  - Version 2 of the HSRS and extension to the full spectrum
- Section 4: Action Item: Comparisons to MODTRAN solar reference spectra
  - Including heritage, to the extent possible, of MODTRAN spectra
- Section 5: Conclusions

Background & Motivation

Solar reference spectra have broad applicability to Earth science applications.

- The Total and Spectral Solar Irradiance Sensor (TSIS-1) Spectral Irradiance Monitor (SIM) and the CubeSat Compact SIM (CSIM) instruments have observed the solar spectrum to higher accuracy across the spectrum.
- The TSIS-1 Hybrid Solar Reference Spectrum (HSRS) is a composite spectrum.
- CEOS/WGCV formally recognized the TSIS-1 HSRS as a new solar irradiance reference standard.

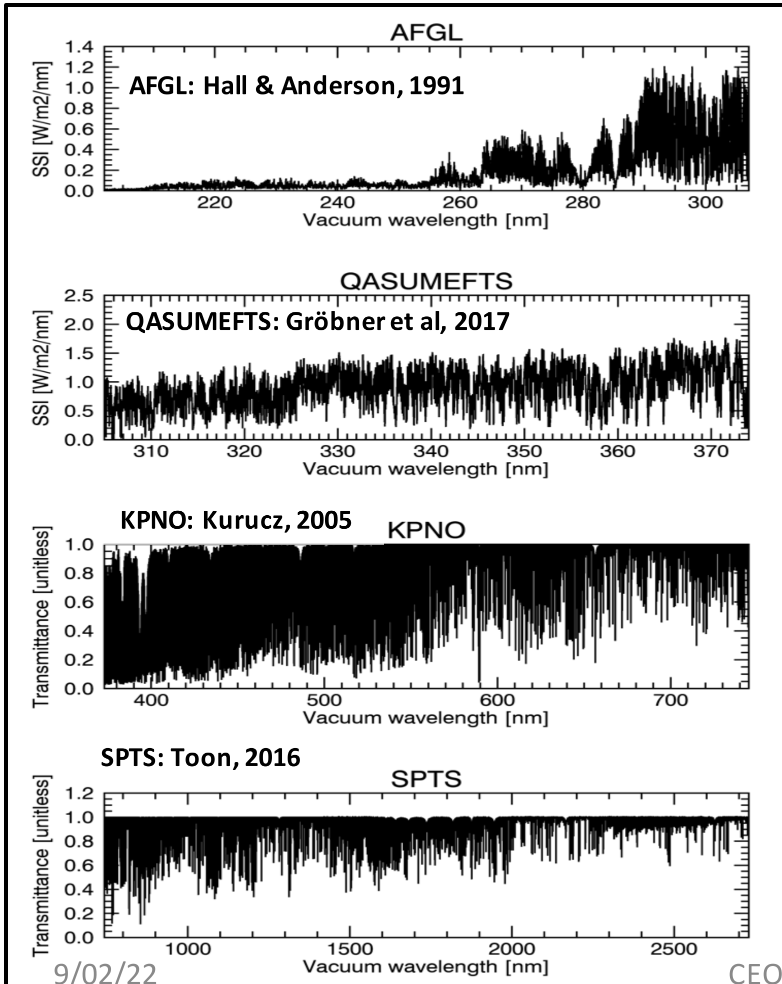
Extending the TSIS-1 HSRS to the full spectrum expands its utility for climate modeling, Earth energy budget science, and radiative transfer modeling.

- The magnitude of differences of the full spectrum TSIS-1 HSRS from MODTRAN solar reference spectra could hold implications for the above applications.

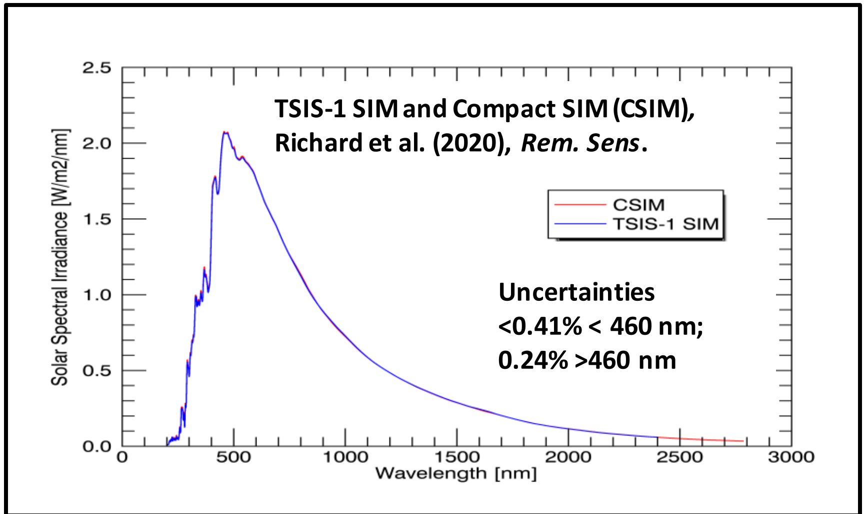
Methodology

The spectral ratio method is used to adjust high spectral-resolution solar line datasets to the absolute irradiance scale of a lower resolution, but higher accuracy, spectrum.

High Spectral Resolution Datasets, β



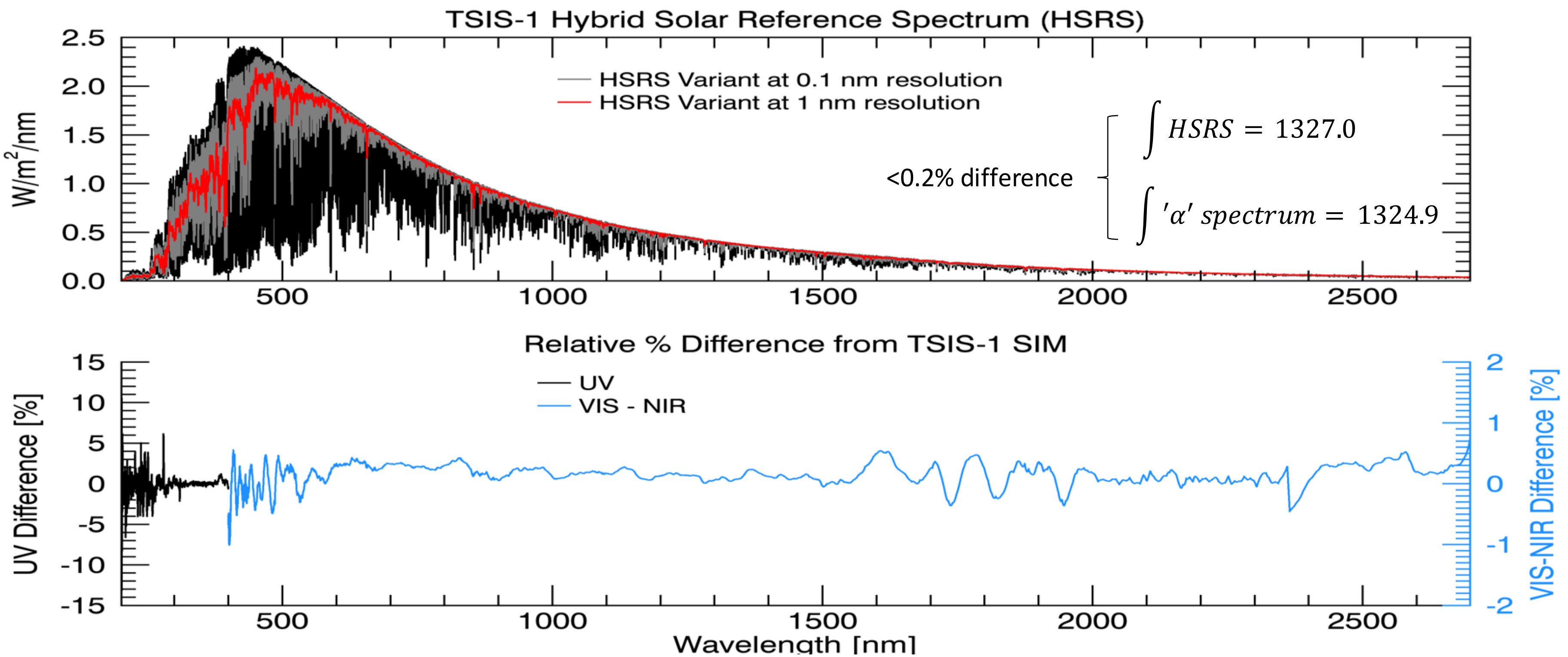
High-Accuracy Datasets, α



CSIM has an extended spectral range (200~2800 nm) relative to TSIS-1 SIM (200-2400 nm).

The time period is specific to the solar cycle minimum between cycles 24 and 25 1-7 Dec 2019.

The TSIS-1 HSRS (202 – 2730 nm)



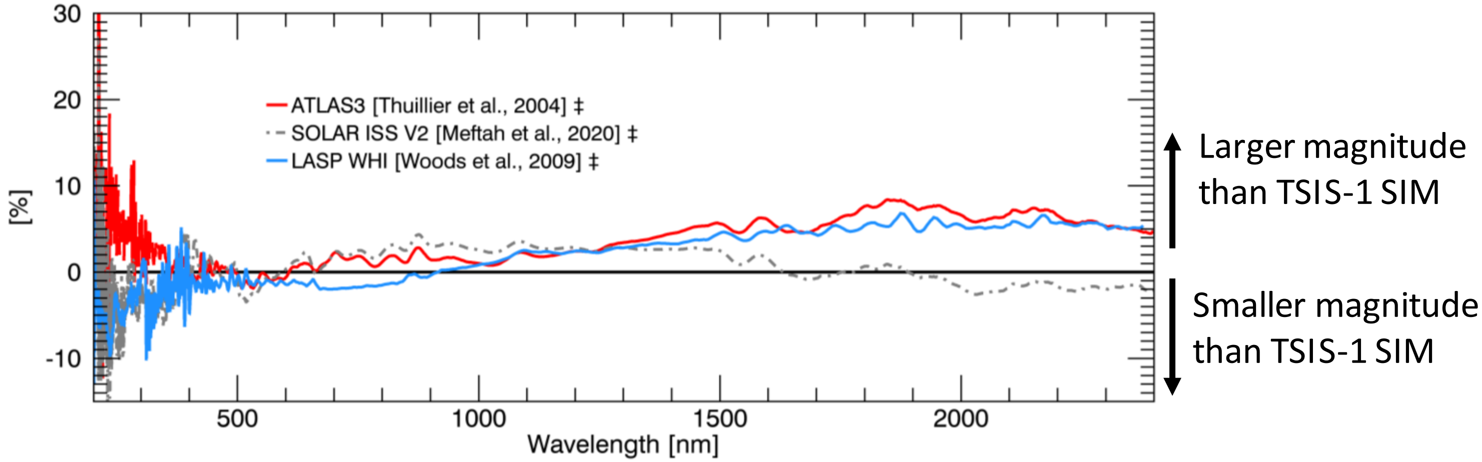
The TSIS-1 HSRS uncertainty is the root-sum-square of the SIM total measurement uncertainty and the 1-σ standard deviation of the relative percent difference from the SIM instruments.

Data Access: https://lasp.Colorado.edu/lisird/data/tsis1_hsrs

Coddington, O., Richard, E., Harber, D., Pilewskie, P., Woods, T., Chance, K., Liu, X., and Sun, K, (2021), "**The TSIS-1 Hybrid Solar Reference Spectrum**", *Geophysical Research Letters*, 48, e2020GL091709. https://doi.org/10.1029/2020GL091709

TSIS-1 SIM Comparison to other Solar Reference Spectra

Relative percent difference between TSIS-1 SIM and several other commonly used reference spectra.



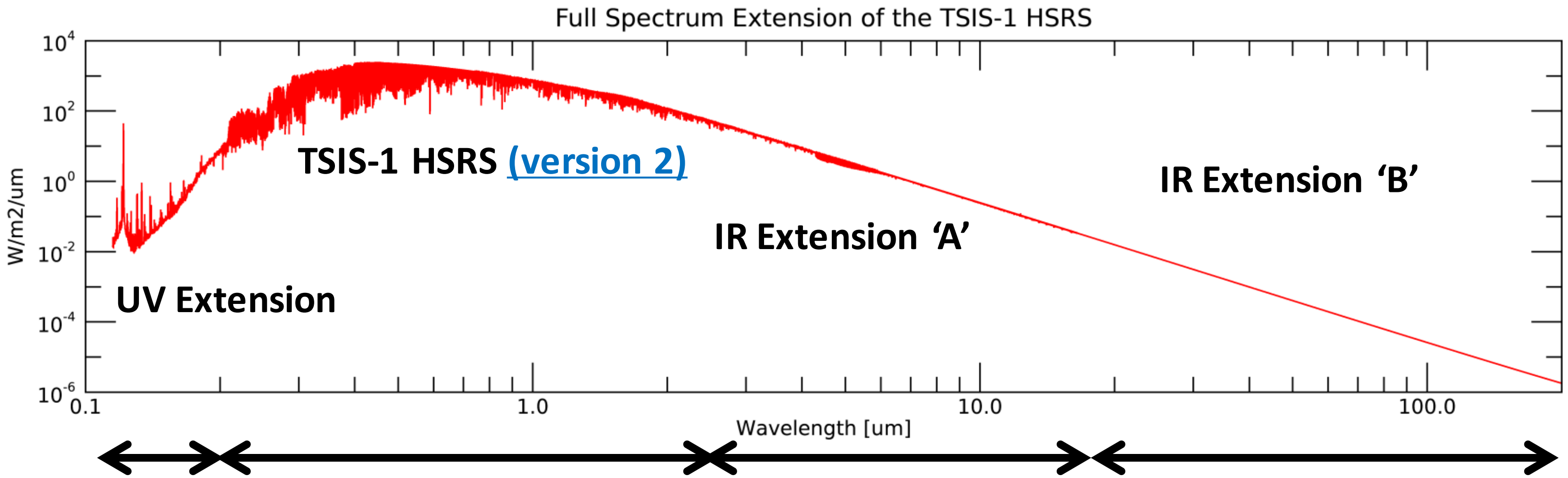
Scalar offset: i.e., the unmeasured part of spectrum

Spectrum	205-2390 (W/m^2)	+ 52 (W/m^2)*	Adopted TSI value (W/m^2)	Diff from TSI (W/m^2)	% Diff.
ATLAS3 ‡	1333.6	1385.6	1361	+ 24.6	+ 1.8
LASP-WHI ‡	1321.0	1373	1361	+ 12.0	+ 0.9
SOLAR-ISS	1320.8	1372.8	1361	+ 11.8	+ 0.9
TSIS-1 SIM	**1309**	**1361.0**	**1361.5**	**- 0.5**	**- 0.04**

‡ Excludes normalization to TSI.

The ‘Full-Spectrum’ TSIS-1 HSRS

Extending the TSIS-1 HSRS to the full spectrum expands its utility for climate modeling, Earth energy budget science, radiative transfer modeling, and solar irradiance variability modeling.



> 9 orders of magnitude in irradiance

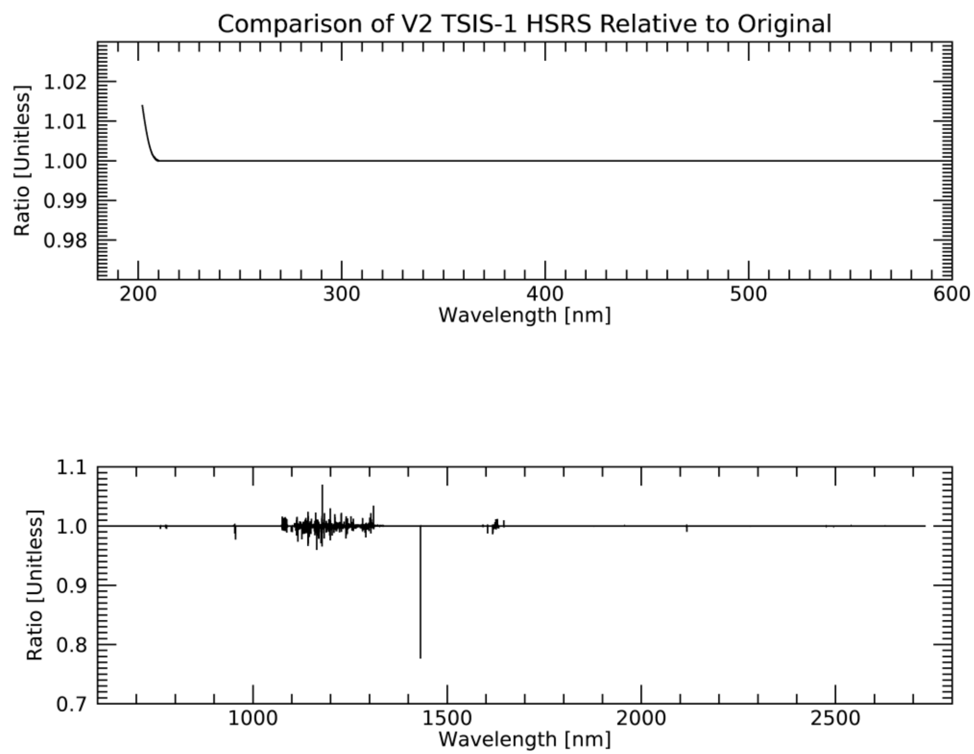
> 3 orders of magnitude in wavelength from 115 nm to 200 μm.

Coddington, O., Richard, E., Harber, D., Pilewskie, P., Woods, T., Snow, M., Chance, K., Liu, X., and Sun, K, “**Version 2 of the TSIS-1 Hybrid Solar Reference Spectrum and Extension to the Full Spectrum** ”, **in preparation** - to be submitted to *Geophysical Research Letters*

Version 2 of the TSIS-1 HSRS

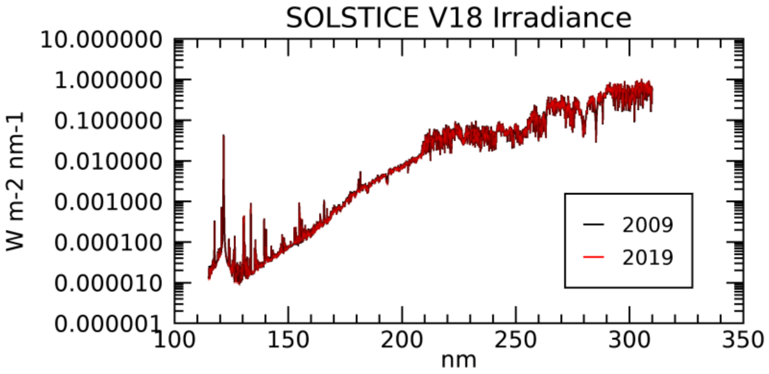
- …is an incremental update.
  - A reprocessing changes the radiometric baseline between 202 and 210 nm.
  - Updates the JPL SPTS high spectral resolution lines to the latest version

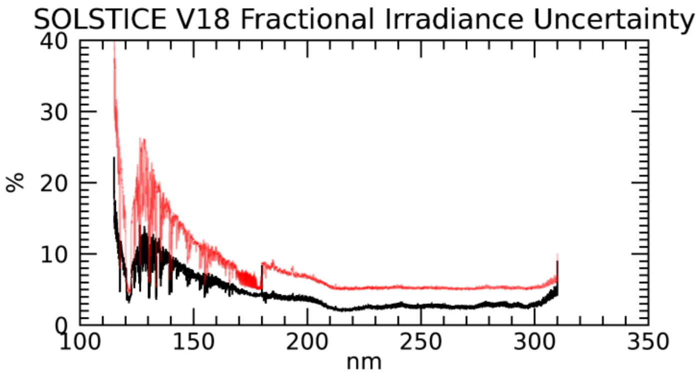
  [G. Toon, https://mark4sun.jpl.nasa.gov/toon/solar/solar_spectrum.html]



UV Extension

- Spans 115-202 nm; <0.01% of TSI
- Final (v18) SORCE SOLSTICE data
  [Snow et al., *Sol. Phys.*, 2022]
- Time period is the 2009 solar minimum.
  - 2009 and 2019 solar minimum irradiance indistinguishable, within measurement uncertainty.
  - Smaller measurement uncertainties in 2009.

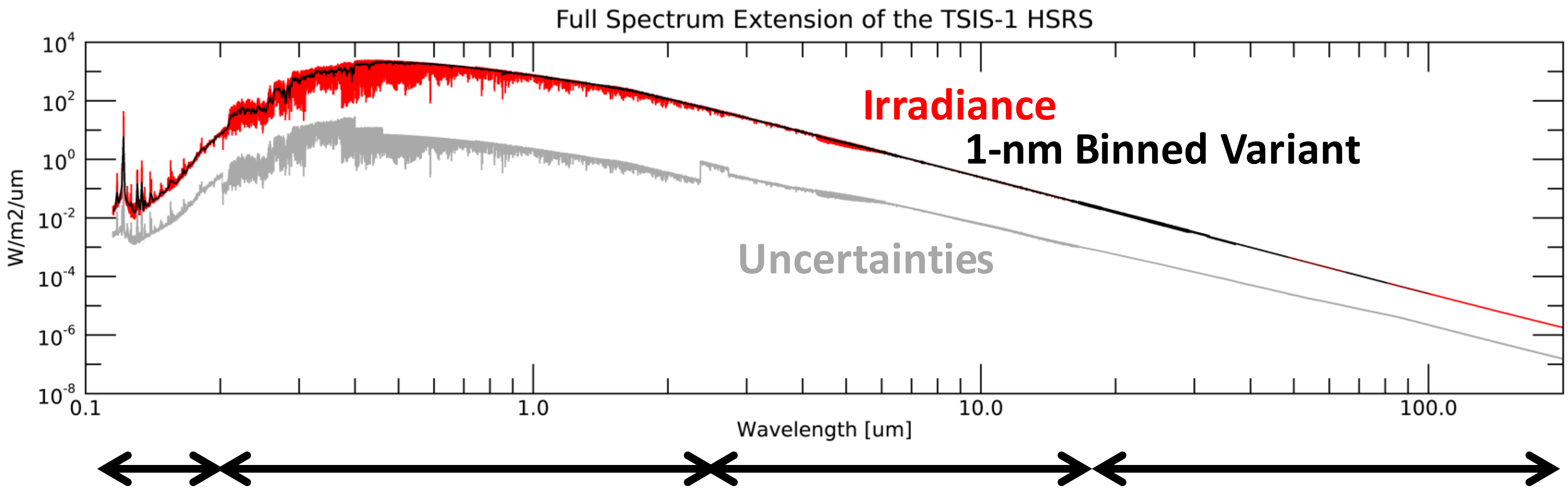




IR Extensions “A” & “B”

- Extension A
  - Spans 2.73 to 16.5 µm; 2.6% of TSI
  - The spectral ratio method normalizes the JPL/SPTS observed solar line data to the Kurucz (1995) irradiance scale.
  - An overall ~0.6% reduction merges the extension to the TSIS-1 HSRS. This preserves the shape of the Kurucz continuum irradiance.
- Extension B
  - Spans 16.5 to 200 µm; 0.01% of TSI
  - Solely the Kurucz (1995) irradiance.
  - An overall ~0.6% reduction merges the IR extensions together

The ‘Full-Spectrum’ TSIS-1 HSRS



SORCE SOLSTICE (version 18)
0.115-0.202 µm
∑SSI = 0.12 W/m²
(<0.01% of TSI)

SORCE SOLSTICE direct measurement uncertainty

TSIS-1 HSRS (version 2)

∑SSI .202-2.73 µm [W/m²]	∑SSI .115-200 µm [W/m²]	TSIS-1 TSI [W/m²]	Difference from TSI [%]
1327.0	1362.8	1361.5	<0.1

original, v1)

IR Extension ‘A’

Uncertainty Estimated
Equal to the relative difference between Kurucz [1995] and one Fontenla irradiance model [current MODTRAN default solar spectrum]; ranges from ~1-8%

IR Extension ‘B’
urucz [1997] irradiance model
.5-200 µm
aled (reduced) by ~0.6%
SSI = 0.19 W/m²
.01% of TSI)

Coddington, O., Richard, E., Harber, D., Pilewskie, P., Woods, T., Snow, M., Chance, K., Liu, X., and Sun, K, “**Version 2 of the TSIS-1 Hybrid Solar Reference Spectrum and Extension to the Full Spectrum**”, in preparation - to be submitted to *Geophysical Research Letters*

Comparisons to MODTRAN solar reference spectra

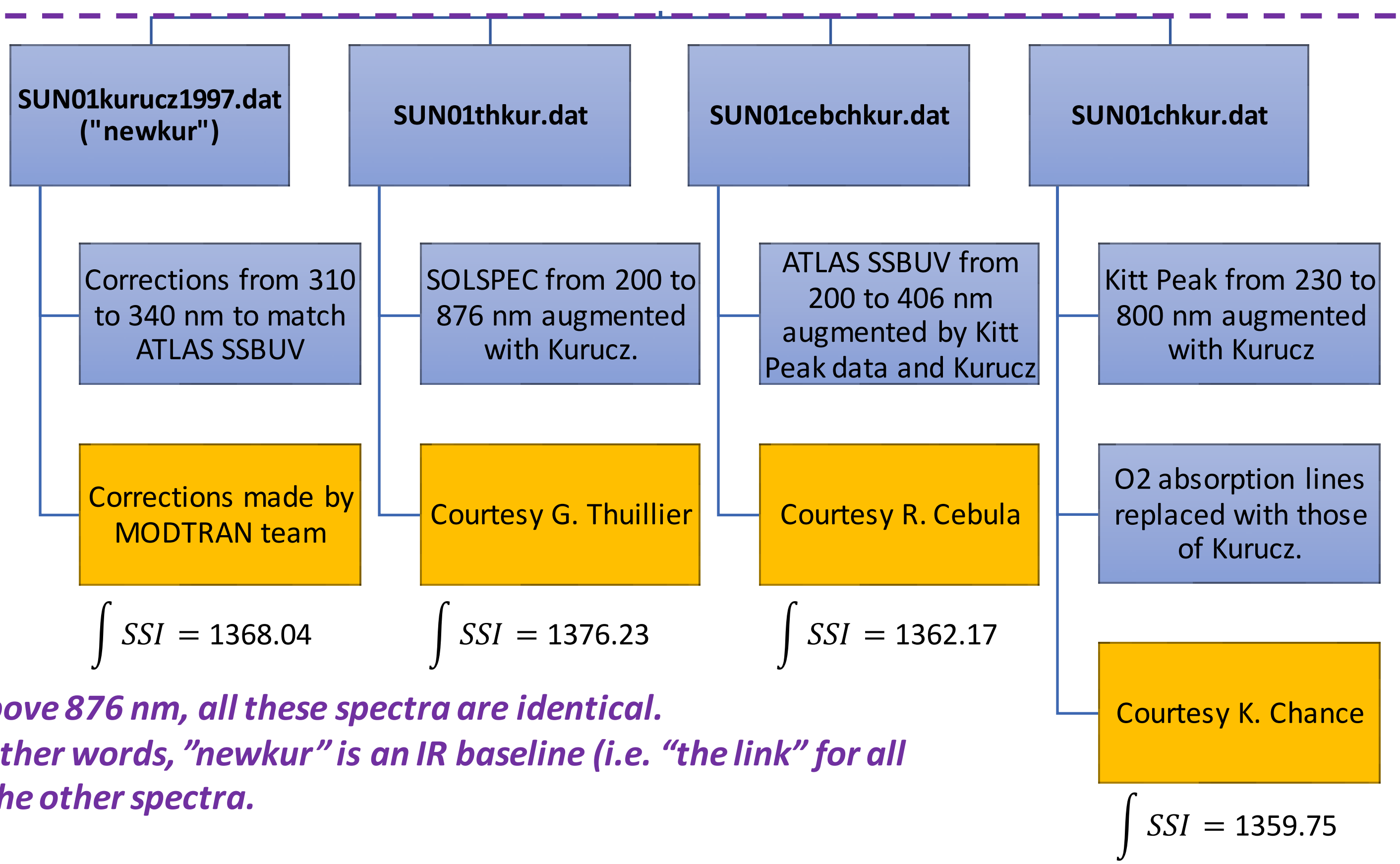
13 MODTRAN solar reference spectra obtained courtesy of Lex Berk, who attributes other colleagues (Gail Anderson and Prab Acharya) for their efforts over the years

MODTRAN has 6 solar spectra of “Kurucz heritage” and an additional 7 solar spectra of Fontenla.

MODTRAN Solar spectra “linked” to Kurucz

The “link” to Kurucz is implicated by filename, but R. Kurucz was not personally involved in the development of any of these spectra (personal communication).

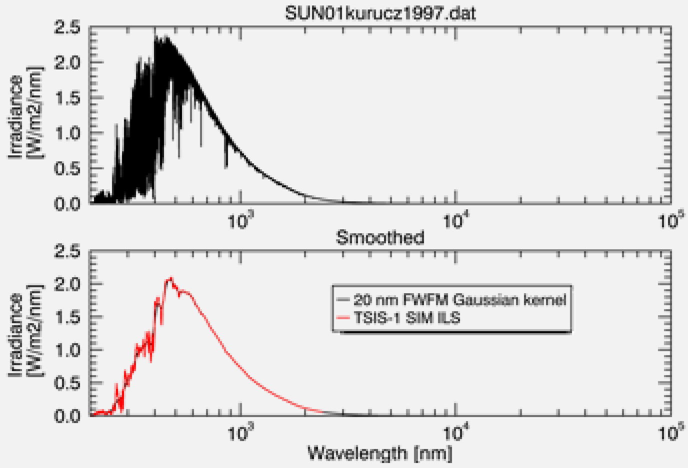
These MODTRAN spectra all span 0-50000 cm^{-1} (0.2 to > 200 μm)



Above 876 nm, all these spectra are identical.
In other words, ”newkur” is an IR baseline (i.e. “the link” for all of the other spectra.

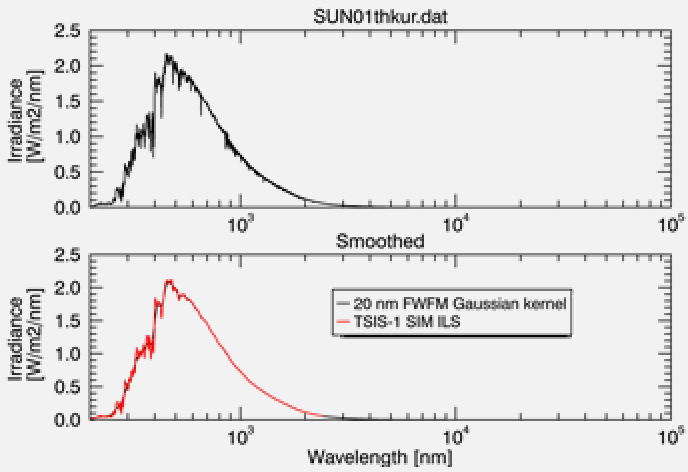
SUN01kurucz1997.dat
“newkur”

- “Corrected” theoretical spectrum between 310 and 340 nm based on SSBUV observations. SSBUV measures TOA solar UV irradiance.



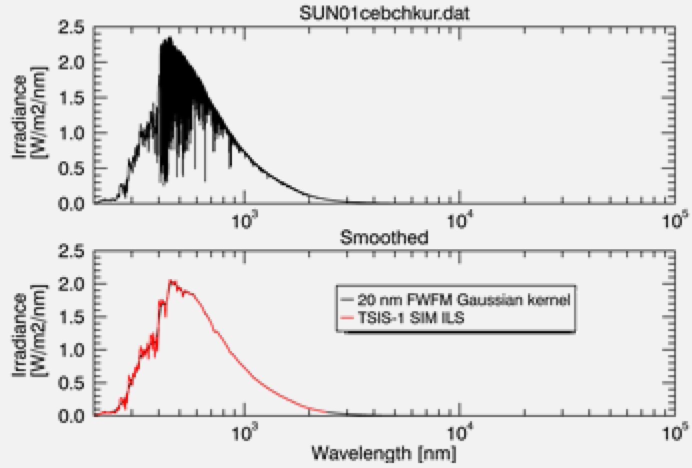
SUN01thkur.dat

- SOLSPEC data < 876 nm, augmented with Kurucz theoretical spectrum. SOLSPEC is a French instrument measuring TOA solar irradiance.



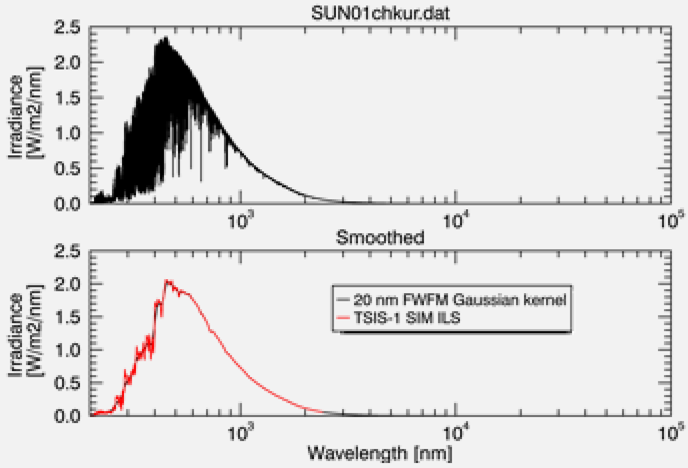
SUN01cebchkur.dat

- SSBUV data from 200 to 406 nm, augmented with Kitt Peak ground observations and the Kurucz theoretical spectrum. SSBUV measures TOA solar UV irradiance.



SUN01chkur.dat

- Kitt Peak ground-based observations from 230-800 nm, augmented with Kurucz theoretical spectrum.



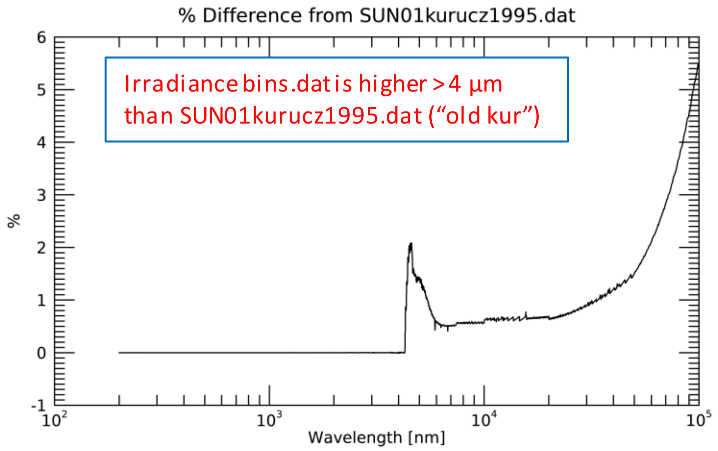
Traceability: from MODTRAN to Kurucz's Website of Data and Papers (http://kurucz.Harvard.edu/sun/)

http://kurucz.Harvard.edu/sun/irradiance/solarirr.tab
http://kurucz.harvard.edu/sun/irradiance/irradiancebins.dat

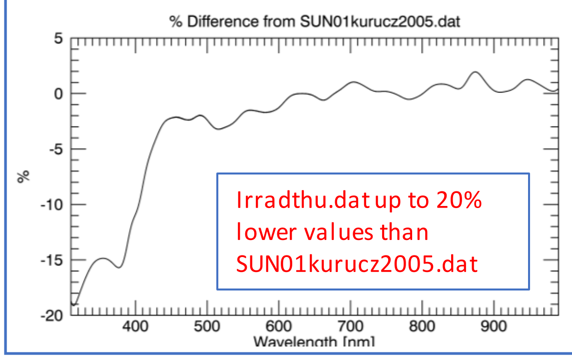
Irradiancebins.dat Computed solar spectrum. Validated, at reduced resolution, against irradiance observations in the visible.

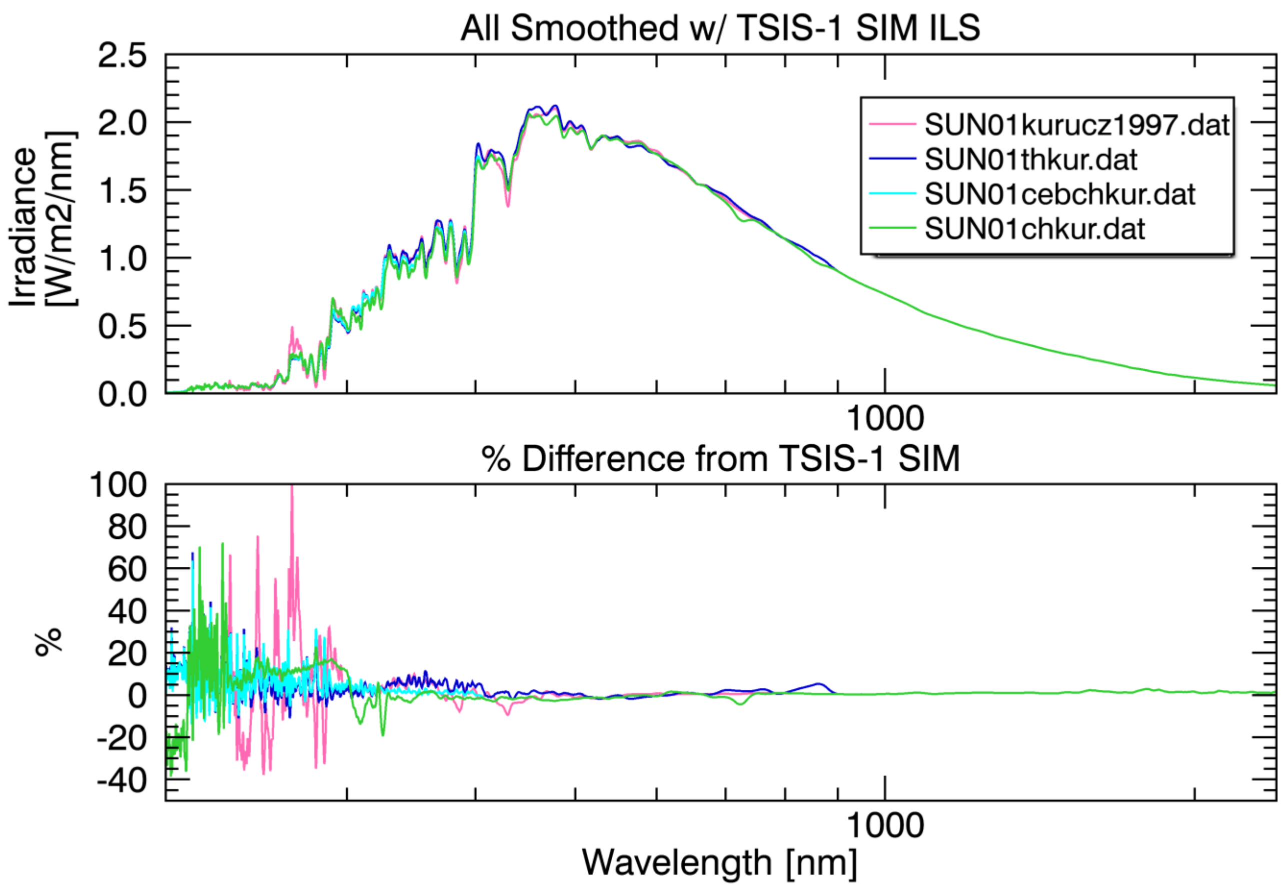
✗ ✓ ✗

SUN01kurucz1997.dat ("newkur"), with exception of MODTRAN corrections from 310-340 nm to match to ATLAS SSBUV



SUN01kurucz2005.dat is <u>inconsistent</u> with irradthu.dat. Kurucz website reports updating irradthu.dat in Jan 2010. Did MODTRAN implement that later update? I don't know.

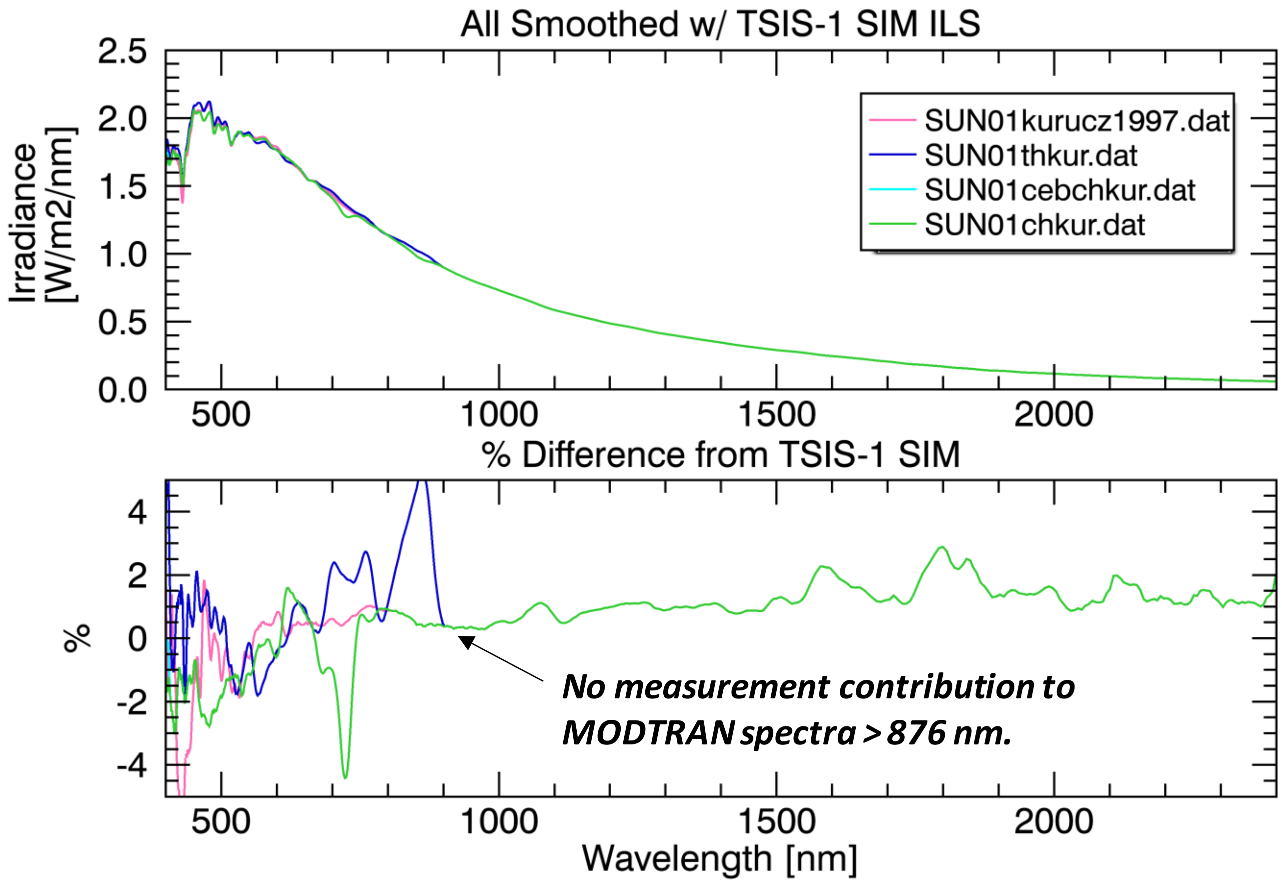




$$\% \ difference = \frac{(Spectrum_X - reference)}{reference} \ x \ 100$$

Comparing 4 MODTRAN "Kurucz" Spectra with TSIS-1 SIM

- 200-2400 nm; log scale



$$\% \, difference = \frac{(Spectrum_X - reference)}{reference} \, x \, 100$$

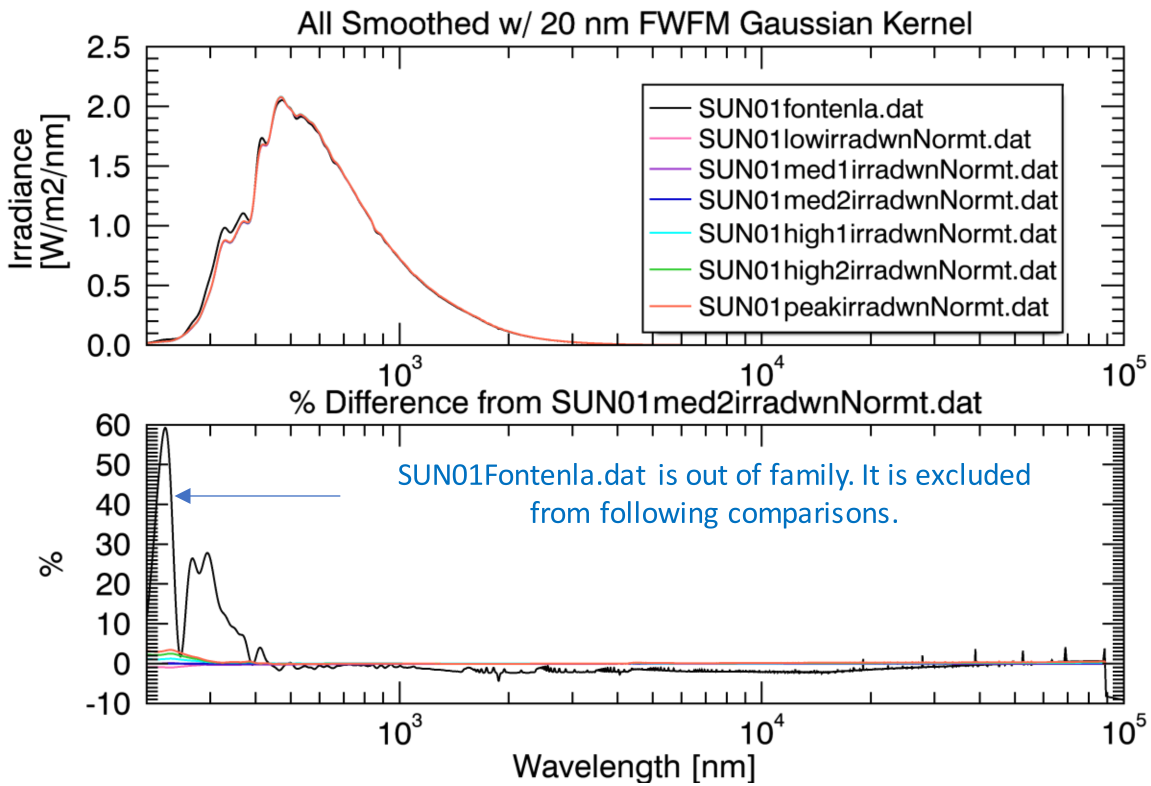
Comparing 4 MODTRAN "Kurucz" Spectra with TSIS-1 SIM

- 400-2400 nm; linear scale

Fontenla Spectra

All MODTRAN Fontenla Spectra

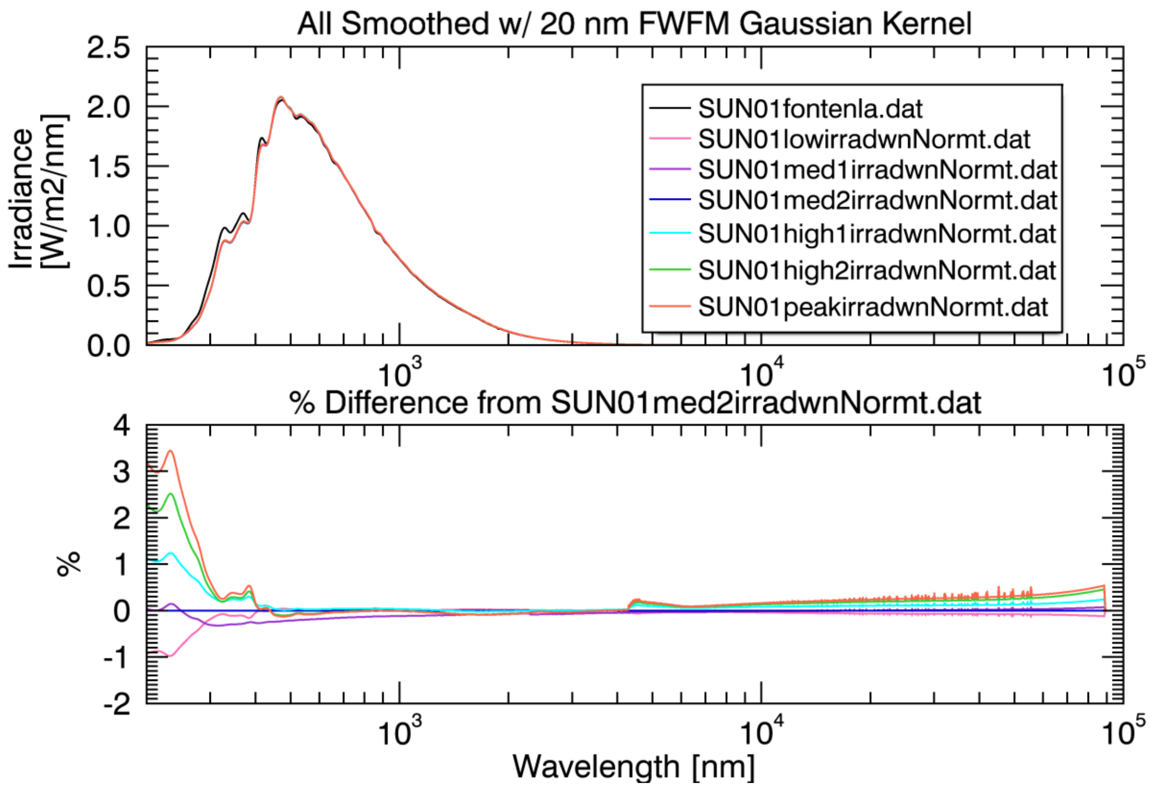
Semi-empirical approach that determines best fit of observed (at moderate spatial resolution) and simulated spectra from a 1-D radiative transfer model with varying temperature & density.



These models are described in a series of papers (The Astrophysical Journal, 2006, 2009, 2011) and references within.

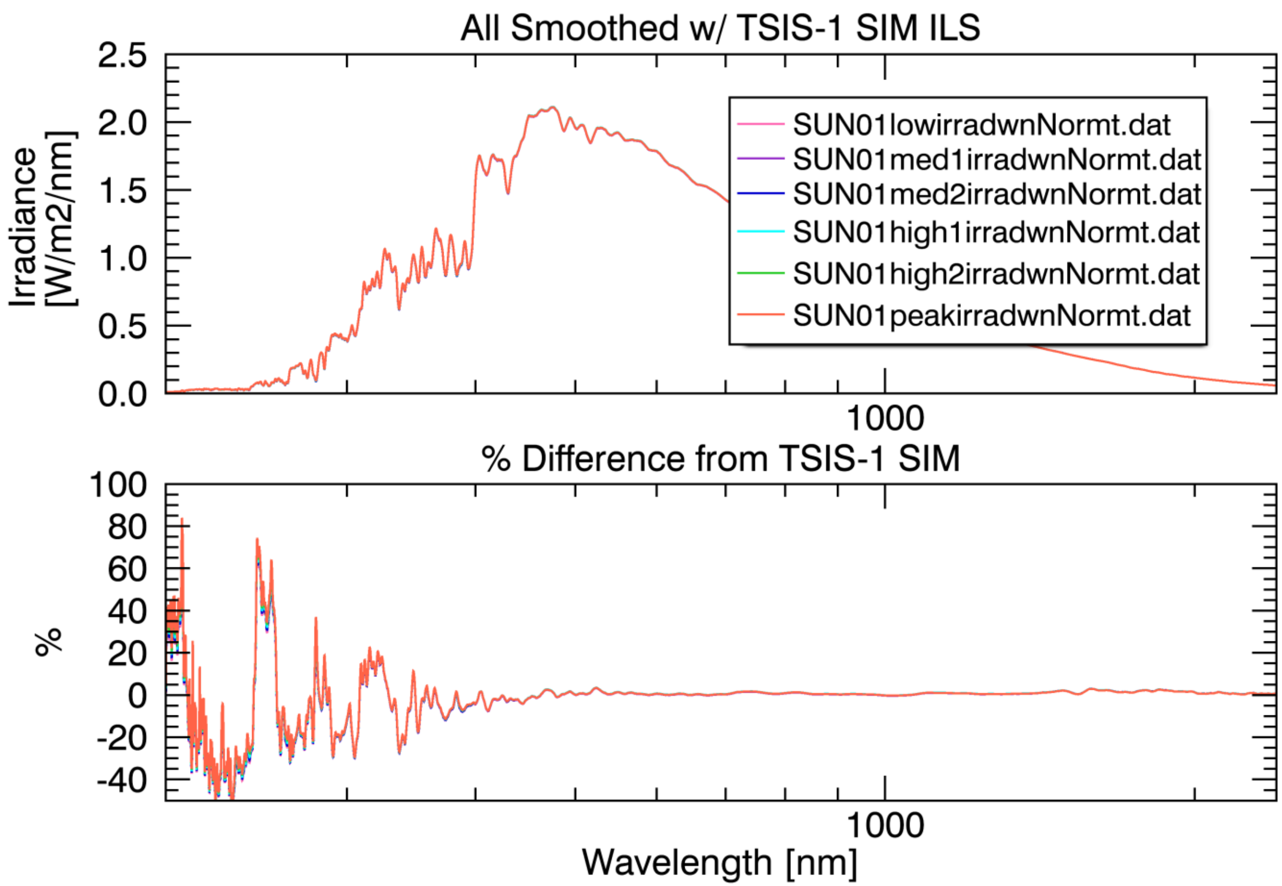
SUN01med2irradwnNormt.dat is the current MODTRAN default spectrum

Relative Differences of All MODTRAN Fontenla Spectra from the default.



Integrated SSI of MODTRAN Fontenla Spectra

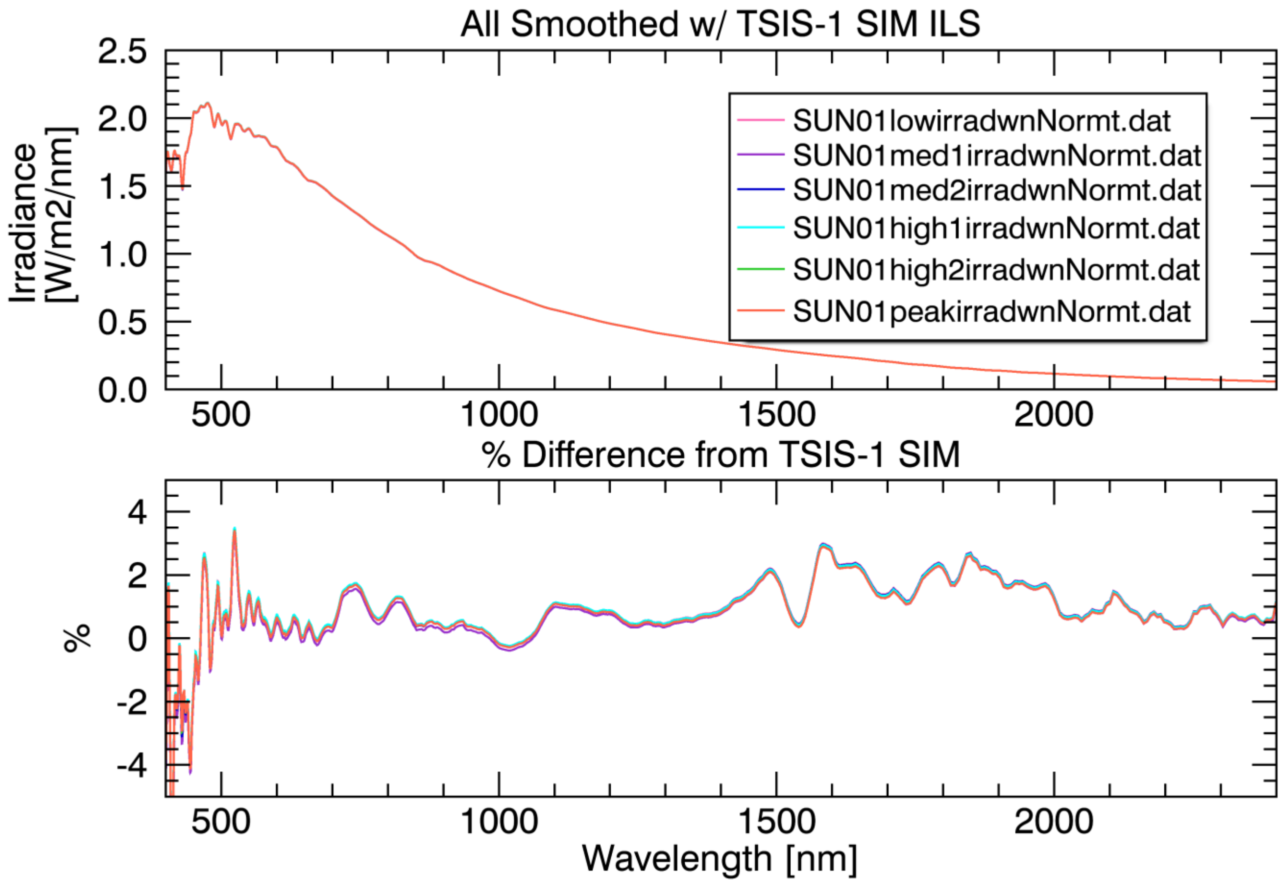
Name	Integrated SSI 200-100,000 nm [W/m^2]	Comments
SUN01fontenla.dat	1361.25	
SUN01lowirradwnNormt.dat	1361.15	
SUN01med1irradwnNormt.dat	1358.96	
SUN01med2irradwnNormt.dat	1361.15	The MODTRAN "default"
SUN01high1irradwnNormt.dat	1361.80	
SUN01high2irradwnNormt.dat	1361.07	
SUN01peakirradwnNormt.dat	1361.11	



$$\% \; difference = \frac{(Spectrum_X - reference)}{reference} \; x \; 100$$

Comparing all MODTRAN Fontenla Spectra with TSIS-1 SIM

- 200-2400 nm; log scale

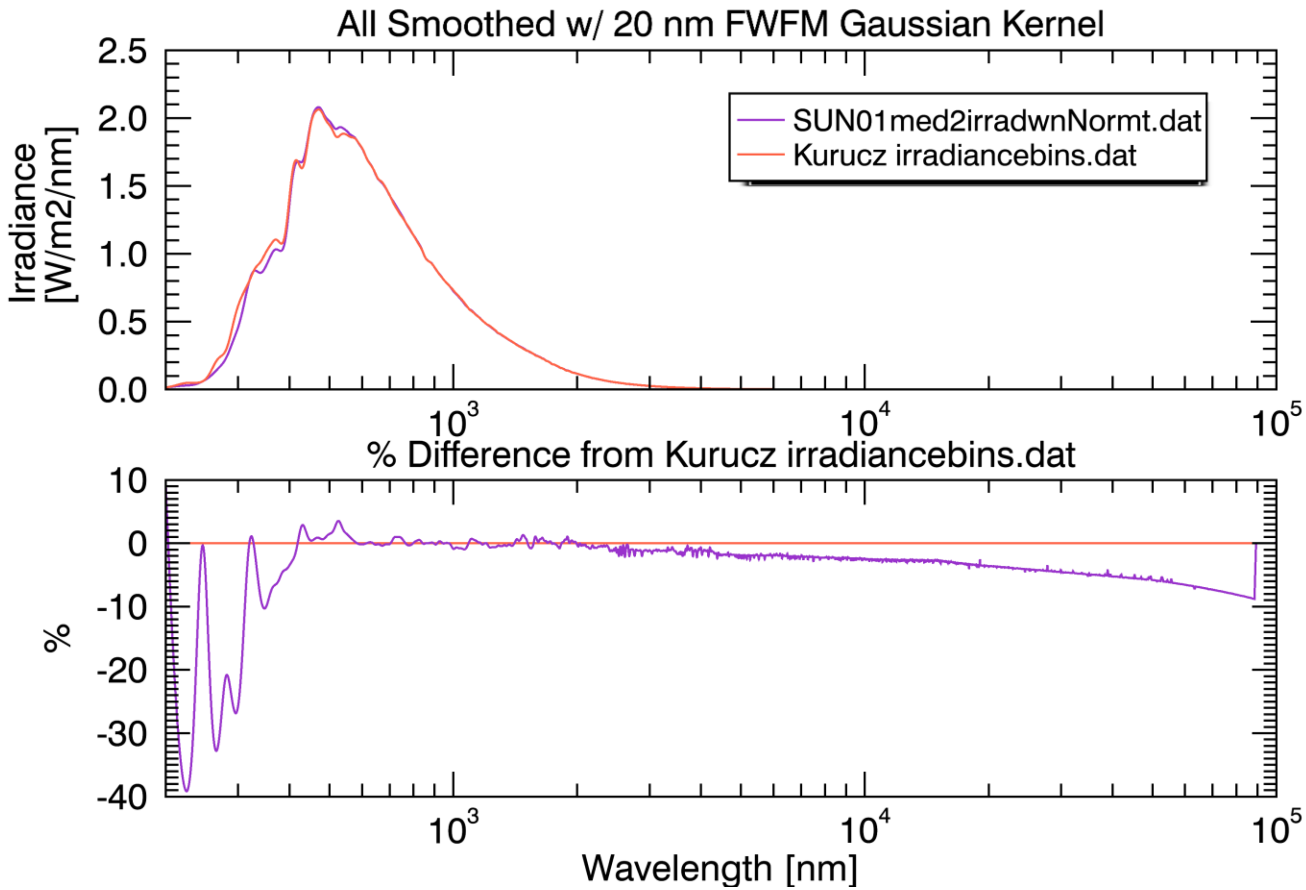


$$\% \ difference = \frac{(Spectrum_X - reference)}{reference} \ x\ 100$$

Comparing all MODTRAN Fontenla Spectra with TSIS-1 SIM

- 400-2400 nm; linear scale

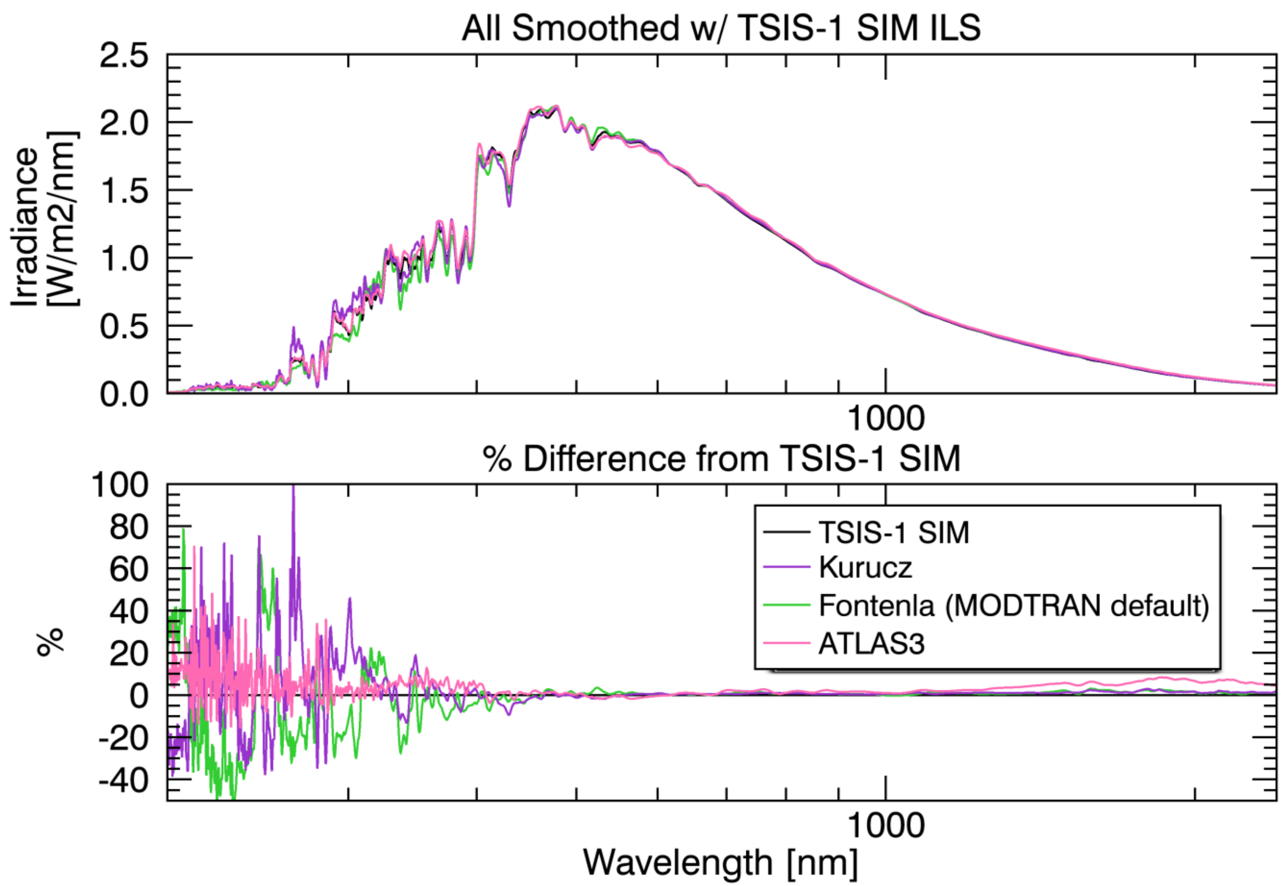
Comparisons of the Theoretical Kurucz and Fontenla Spectra



$$\% \ difference = \frac{(Spectrum_X - reference)}{reference} \ x \ 100$$

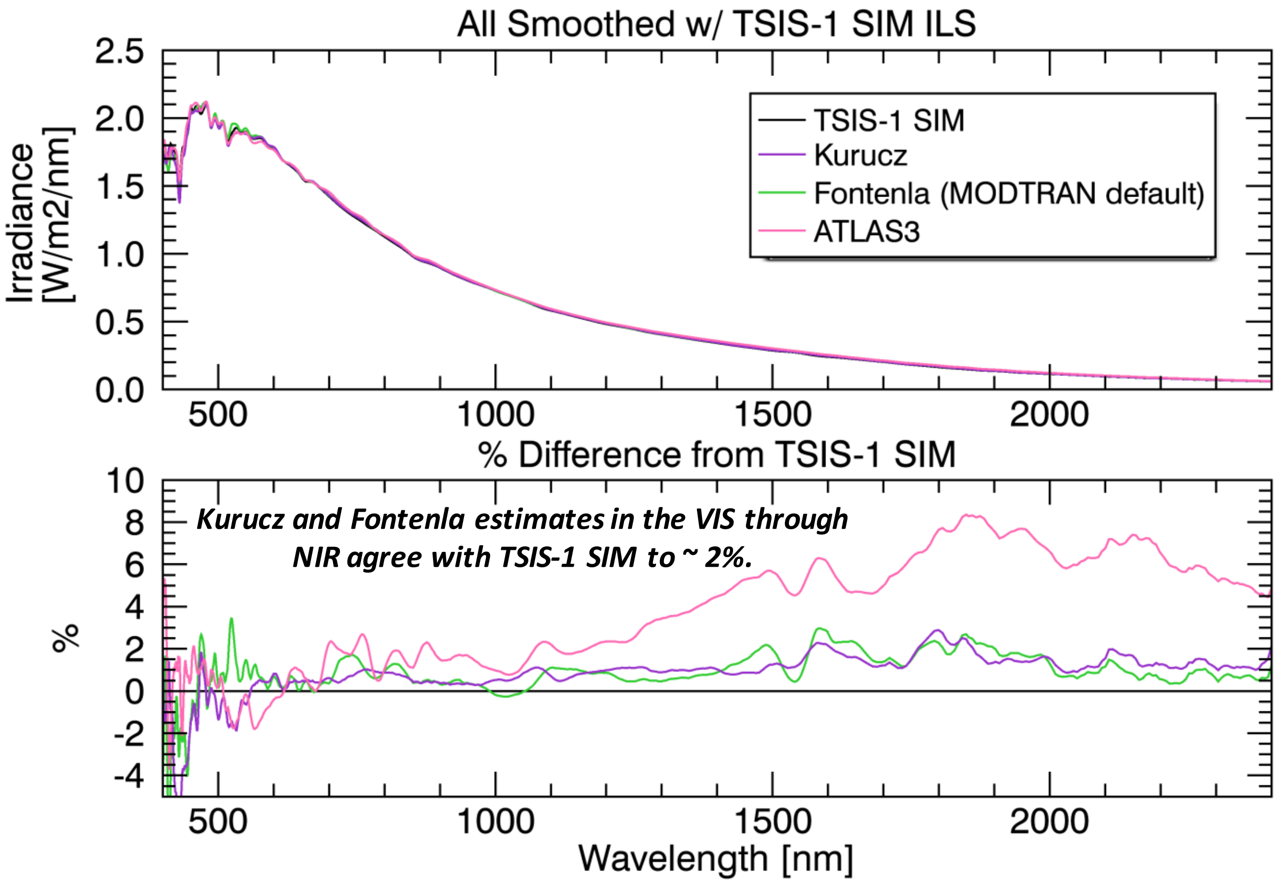
- Largest differences (30-40%) below 400 nm. Differences are 2-8% in the infrared with Fontenla spectrum systematically smaller magnitude than Kurucz computed spectrum above 2000 nm.

Kurucz, Fontenla, & ATLAS-3 Compared to TSIS-1 SIM



$$\% \, difference = \frac{(Spectrum_X - reference)}{reference} \, x \, 100$$

- 200-2400 nm; log scale
- ATLAS 3 data shown don't include the ~1.4% normalization to TSI



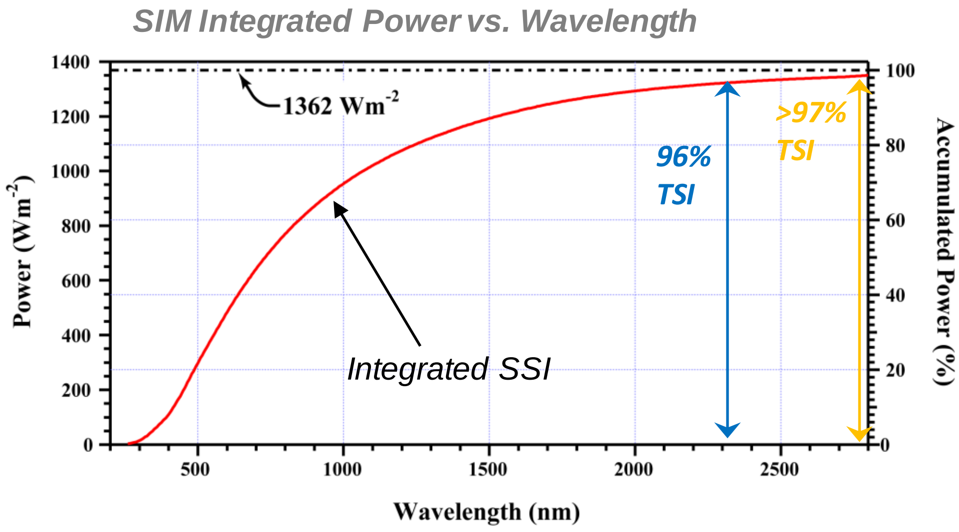
$$\%\ difference = \frac{(Spectrum_X - reference)}{reference}\ x\ 100$$

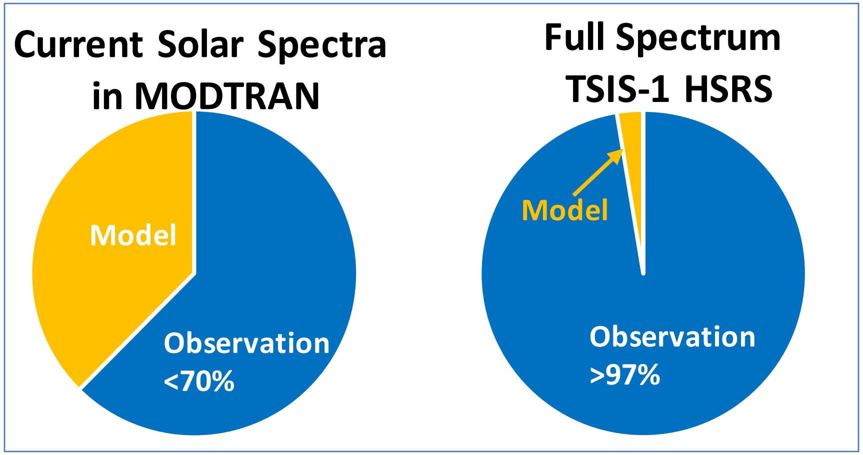
- 400-2400 nm; linear scale
- ATLAS 3 data shown don't include the ~1.4% normalization to TSI

Summary

- The TSIS-1 HSRS provides an important new constraint on the solar spectrum for Earth science applications.
- The 'Full Spectrum' TSIS-1 HSRS extends the utility of this reference spectrum to Earth energy budget studies, radiative transfer modeling, (MODTRAN, DART), solar variability modeling, etc.
  - A future version of the NOAA Solar Irradiance CDR will incorporate the TSIS-1 HSRS (plus additional changes)

Implications for Inclusion in Radiative Transfer Modeling: Increases the proportion of integrated total incoming energy contributed by solar irradiance observations than from models. Only a very small (<0.1%) adjustment is needed to be consistent with TSI.





The proportion of total incoming energy informed by models vs. observations.

(*The FS TSIS-1 HSRS to 16.6 microns is ~99.9% of TSI and a combination of model and observed lines.)