The Full-Spectrum Extension of the TSIS-1 Hybrid Solar Reference and Impacts for Solar Irradiance Variability Modeling

O. Coddington, E. Richard, J. Lean, D. Harber, P. Pilewskie, T. Woods, M. Snow, K. Chance, X. Liu, K. Sun

Outline

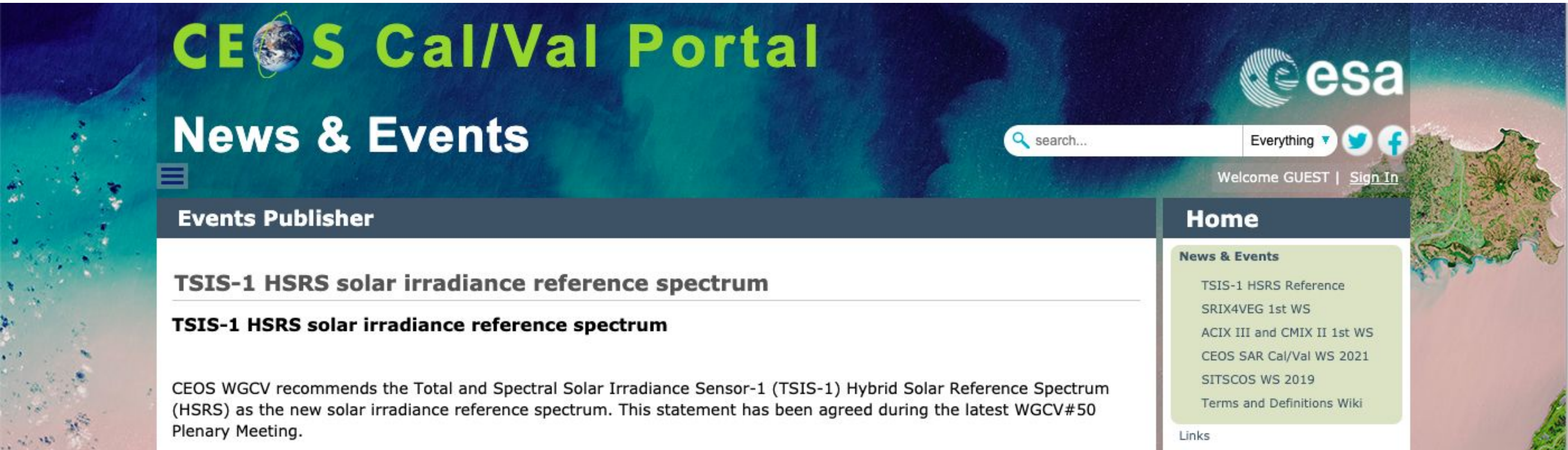
- Background & Motivation
- Methodology
- Results
- Application in solar irradiance variability modeling
- Summary

Background & Motivation

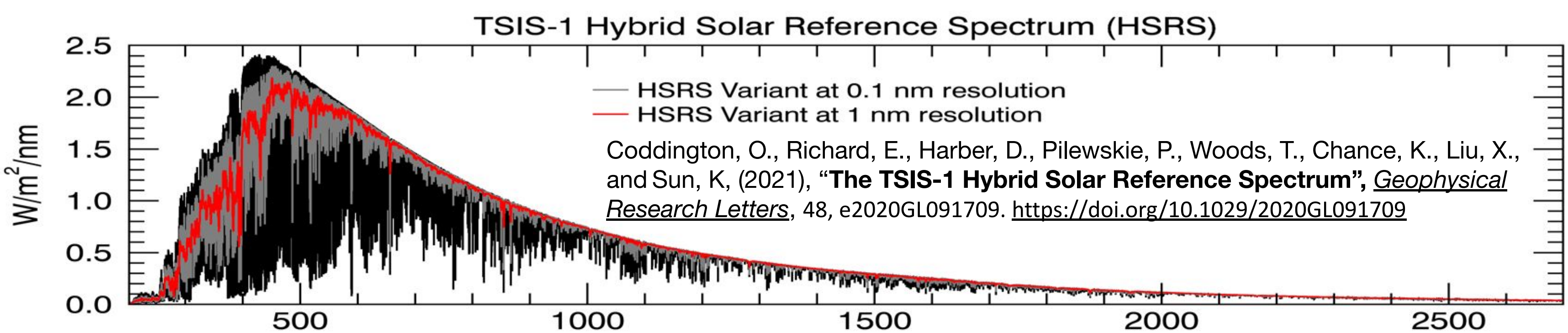
- Solar reference spectra have broad applicability to Earth science applications.
- The Total and Spectral Solar Irradiance Sensor (TSIS-1) Spectral Irradiance Monitor (SIM) and the CubeSat Compact SIM (CSIM) instruments have observed the solar spectrum to higher accuracy across the spectrum.
- The TSIS-1 Hybrid Solar Reference Spectrum (HSRS) is a composite spectrum.
- Extending the TSIS-1 HSRS to the full spectrum expands its utility for climate modeling, Earth energy budget science, and radiative transfer modeling.

TSIS-1 HSRS Formally Recognized

March 2022: The Committee on Earth Observation Satellites (CEOS) Working Group on Calibration and Validation (WGCV) recommended the TSIS-1 HSRS as the new solar irradiance reference spectrum standard [https://calvalportal.ceos.org/events/].



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

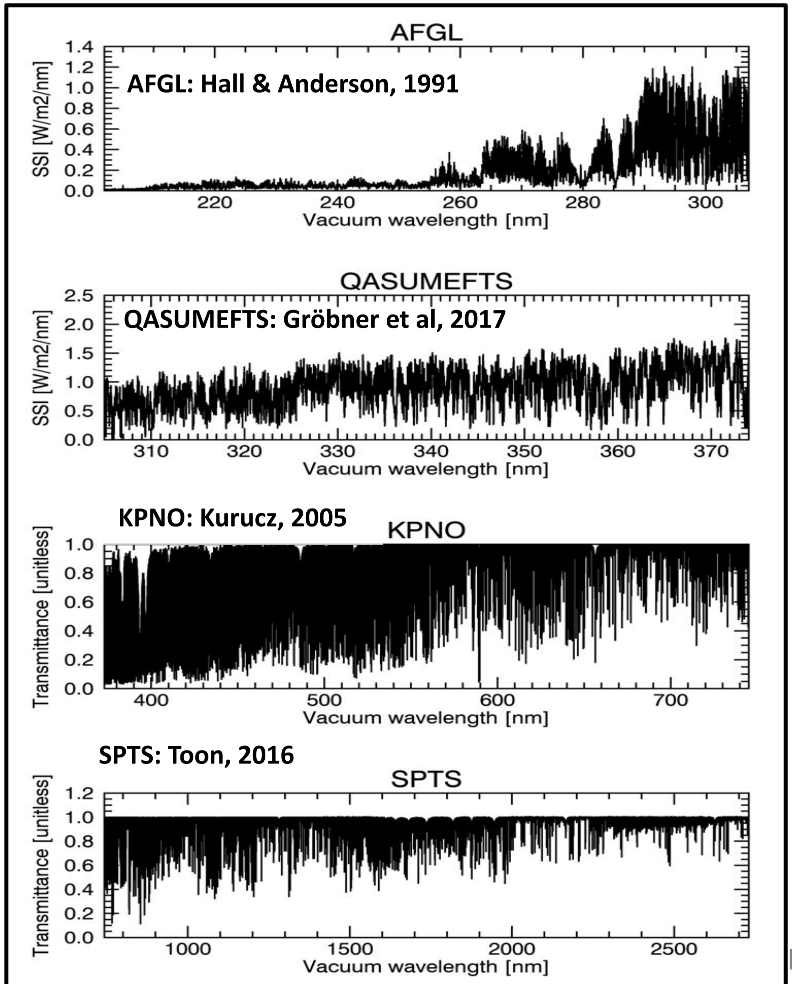


Coddington, O., Richard, E., Harber, D., Pilewskie, P., Woods, T., Chance, K., Liu, X., and Sun, K, (2021), "**The TSIS-1 Hybrid Solar Reference Spectrum**", *Geophysical Research Letters*, 48, e2020GL091709. https://doi.org/10.1029/2020GL091709

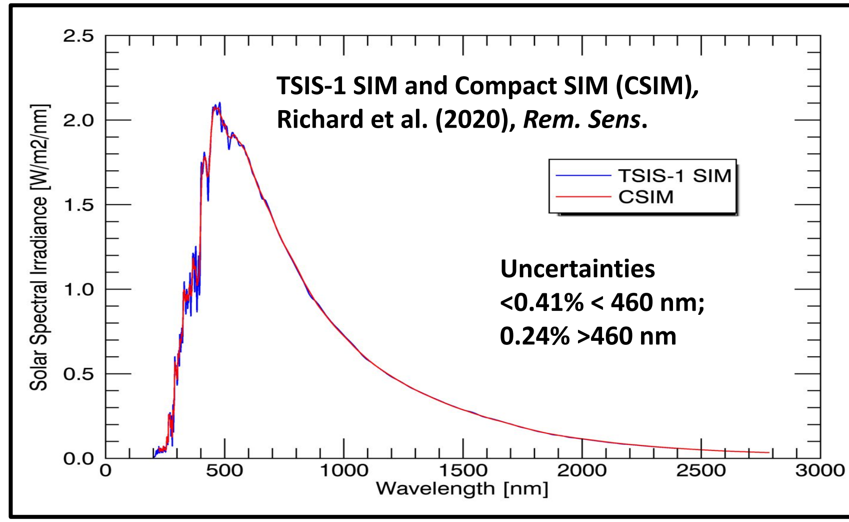
Methodology

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

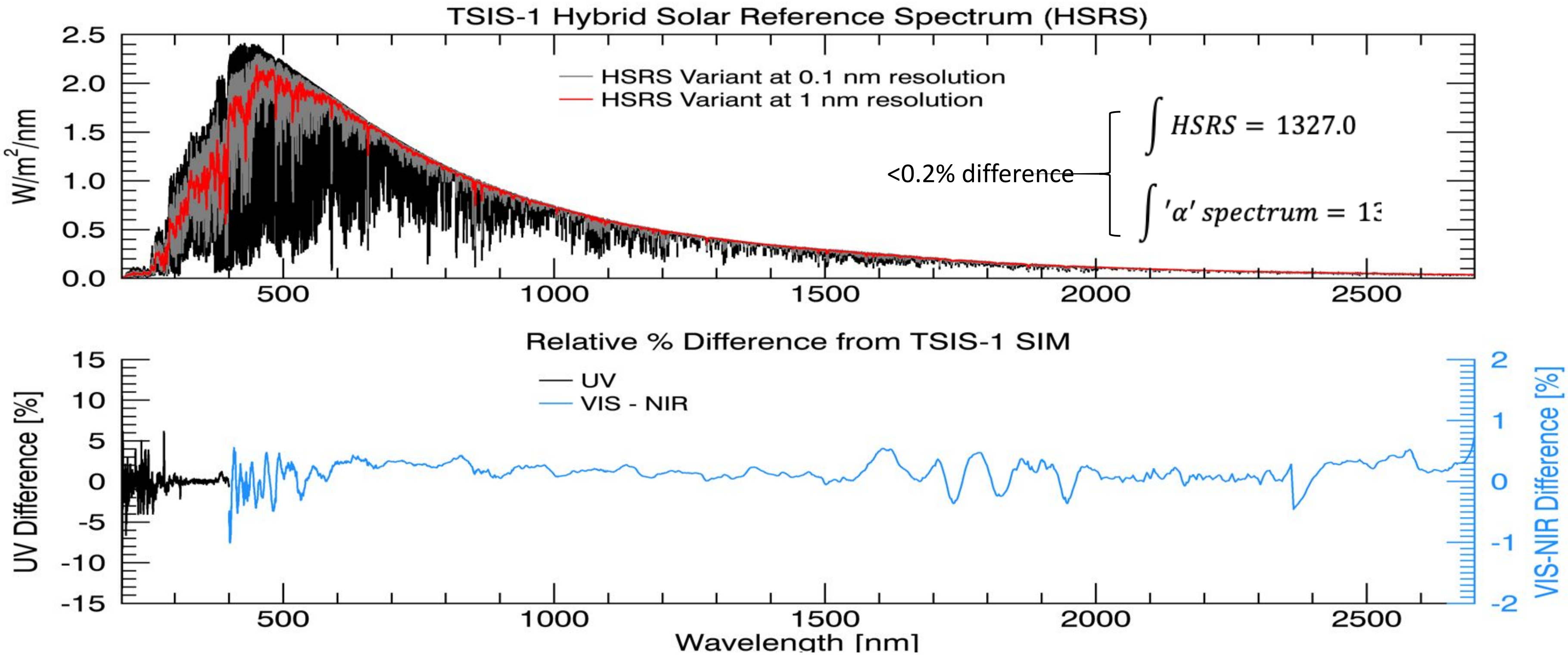


High-Accuracy Datasets, α



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

The TSIS-1 HSRS

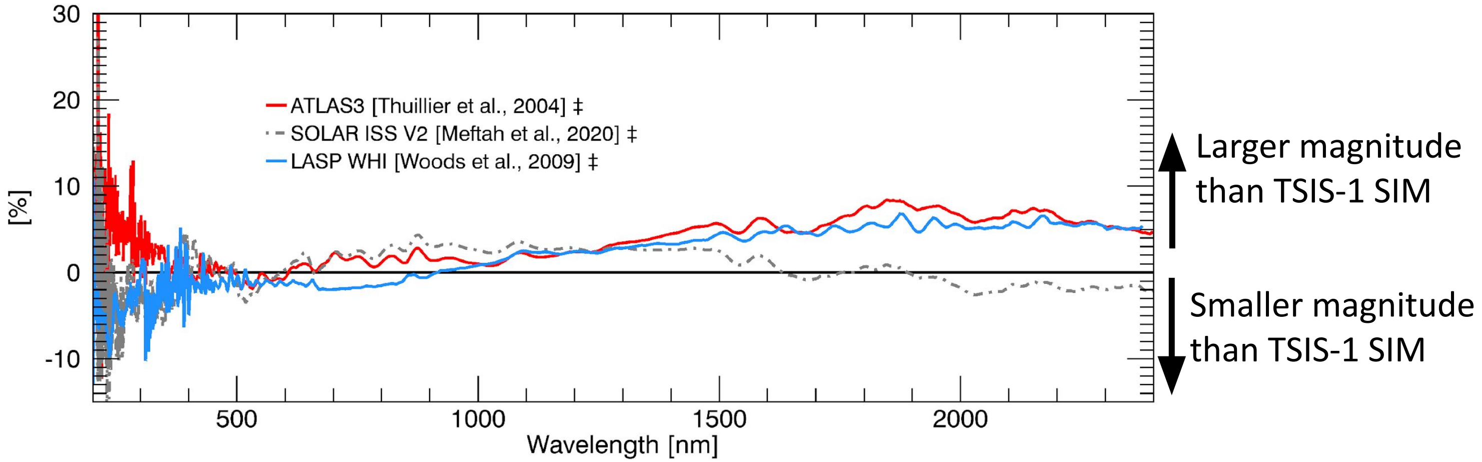


Coddington, O., Richard, E., Harber, D., Pilewskie, P., Woods, T., Chance, K., Liu, X., and Sun, K, (2021), "**The TSIS-1 Hybrid Solar Reference Spectrum",** *Geophysical Research Letters*, 48, e2020GL091709. https://doi.org/10.1029/2020GL091709

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

TSIS-1 SIM Comparison to other Solar Reference Spectra

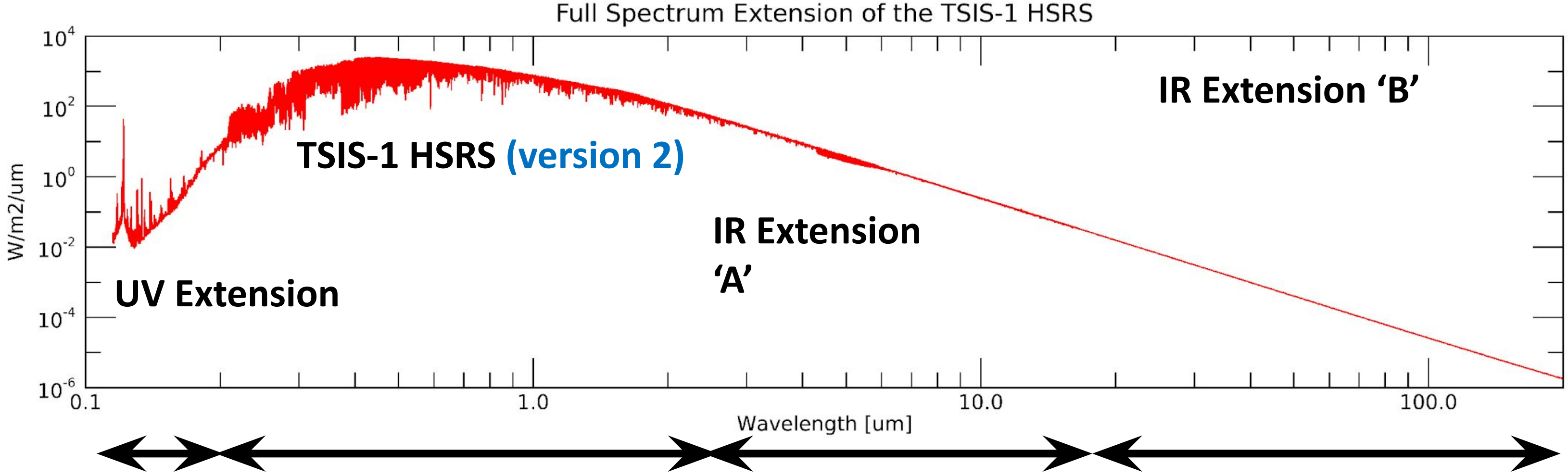
Relative percent difference between TSIS-1 SIM and several other commonly used reference spectra.



Spectrum	**205-2390 (W/m^2)**	**+ 52 (W/m^2)***	**TSI (W/m^2)**	**Diff (W/m^2)**	**% Diff.**
	1333.6	1385.6	1361	+ 24.6	+ 1.8
	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

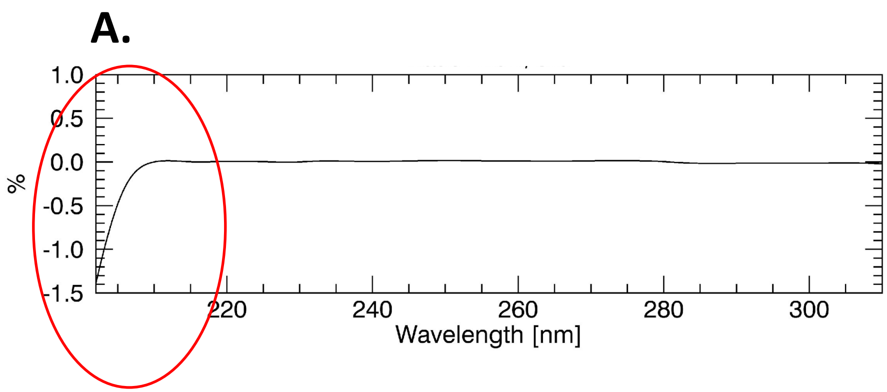


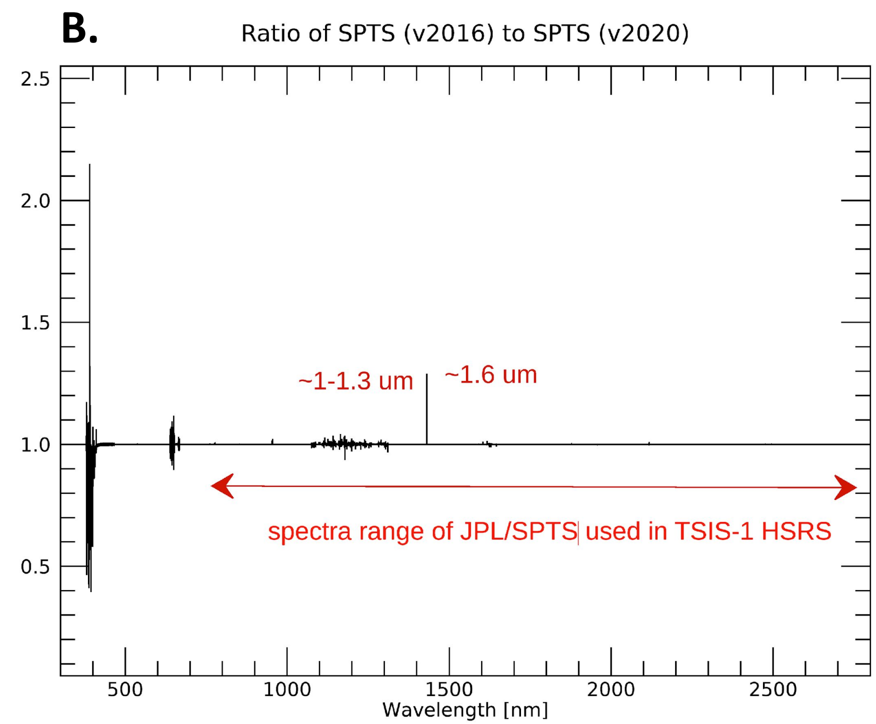
> 9 orders of magnitude in irradiance

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

Version 2 of the TSIS-1 HSRS

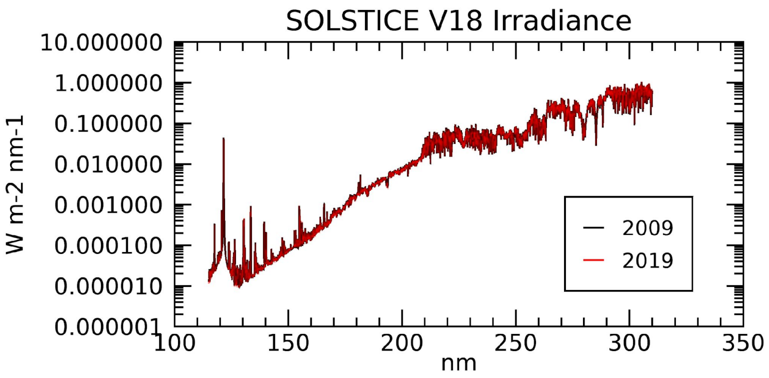
- …is an incremental update.
  - **Fig A**. Corrects a mistake I made that impacts the radiometric baseline between 202 and 210 nm.
  - **Fig B**. Updates the JPL SPTS high spectral resolution lines for ~760 nm onward to the latest version [G. Toon, https://mark4sun.jpl.nasa.gov/toon/solar/solar_spectrum.html]

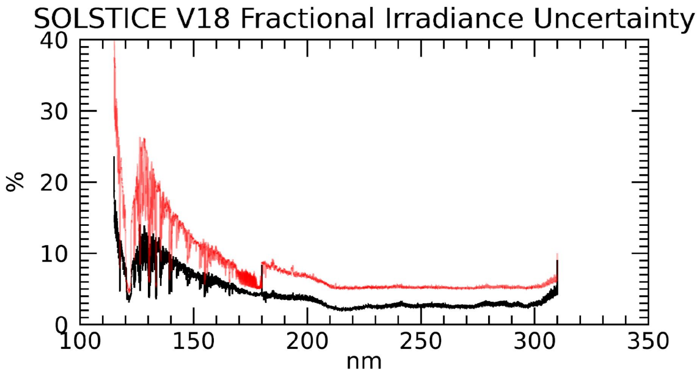




UV Extension

- Final (v18) SORCE SOLSTICE data for 115 – 202 nm. [Snow et al., Sol. Phys., 2022 (just published)]
- During 2009 solar minimum.
  - 2009 and 2019 solar minimum irradiance indistinguishable, within measurement uncertainty.
  - Smaller measurement uncertainties in 2009.





IR “Extension A”

- Spans 2.73 to 16.5 μm.
- The spectral ratio method is used to bring JPL/SPTS solar line data to the Kurucz, 1997 irradiance scale.
  - I’ve traced Kurucz, 1997 to MODTRAN’s “newkur.dat”, except for 310-340 nm.

THE SOLAR IRRADIANCE BY COMPUTATION

Robert L. Kurucz

Harvard-Smithsonian Center for Astrophysics
60 Garden St, Cambridge, MA 02138, USA

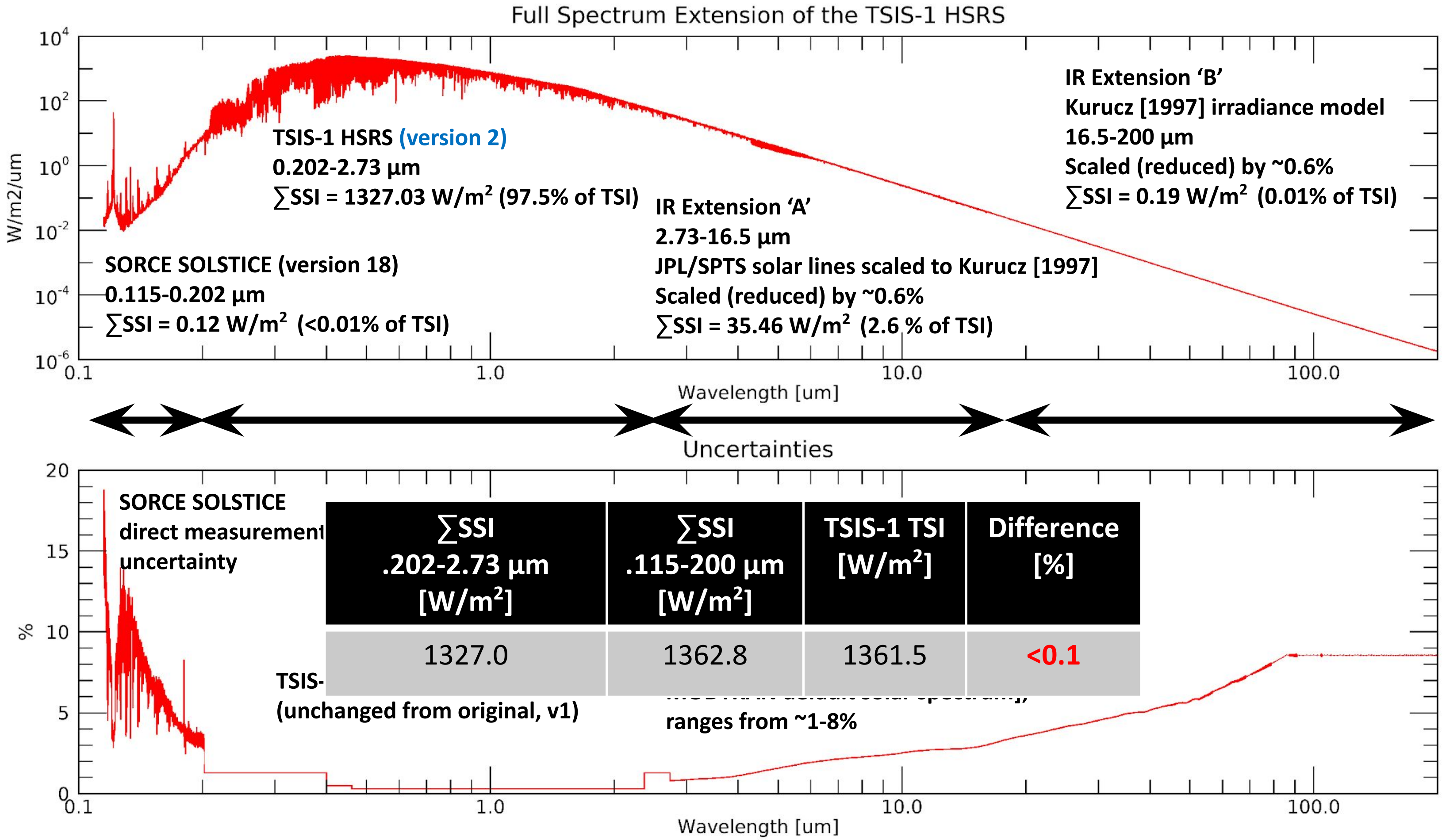
November 25, 1997

- Then, a ~0.6% reduction (wavelength-independent) merges the result seamlessly to the TSIS-1 HSRS at 2.73 μm and preserves the shape of the Kurucz continuum irradiance.

IR “Extension B”

- Spans 16.5 to 200 µm.
- Solely the Kurucz, 1997 irradiance data.
- Overall, wavelength-independent reduction (by ~0.6%) to seamlessly merge to IR ”extension A” at 16.5 microns

The ‘Full-Spectrum’ TSIS-1 HSRS



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

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 - t**o be submitted to *Geophysical Research Letters*

Next talk: Dan Marsh (NCAR) initial results of a WACCM climate model study comparing this spectrum and NRLSSI2 in 2019 solar minimum.

Solar Spectral Irradiance Reference Spectrum for the 2008-2009 Solar Cycle Minimum

Motivation: Why 2008-2009? *SIST2, Wang & Lean, ApJ, 2021*

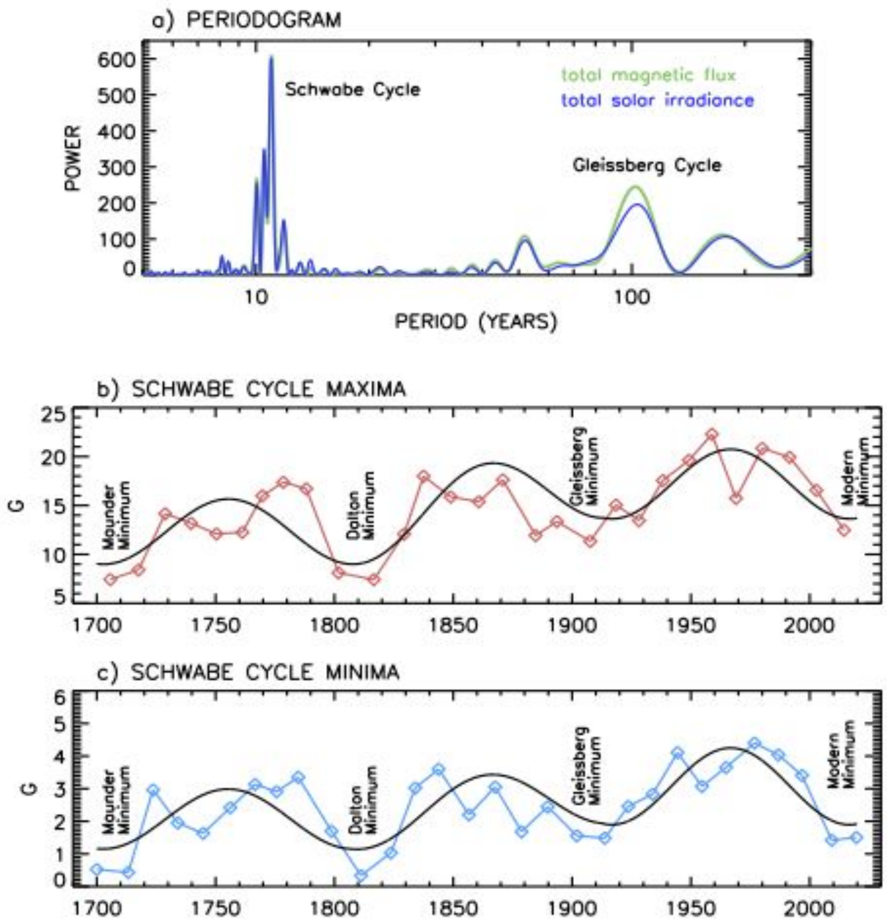
- the 11-year "Schwabe" cycle minimum in 2008-2009 was also the most recent minimum of the ~100-year "Gleissberg" cycle
- Gleissberg cycle modulates Schwabe cycle maxima and minima

Current Version v02r01: *pre-SIST, Coddington et al., BAMS 2015*

- Wavelength Interval: 115.5 to 999,999.5 nm
- SSI "quiet Sun" reference spectrum based on SORCE TIM & SIM
  absolute scale and measurements in WHI (March - April 2008)

Future Version v03r00: *incorporating multiple SIST1,2 &3 results*

- Extended Wavelength Interval: 0.5 to 1,999,999.5 nm
- SSI "quiet Sun" reference spectrum based on TSIS-1 TIM & SIM
  absolute scale and measurements in 2019 Schwabe cycle minimum

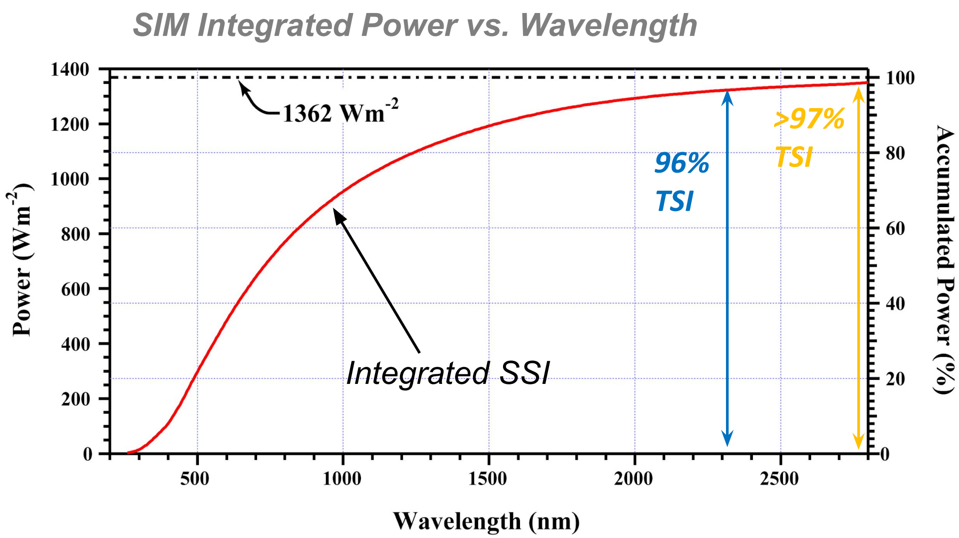


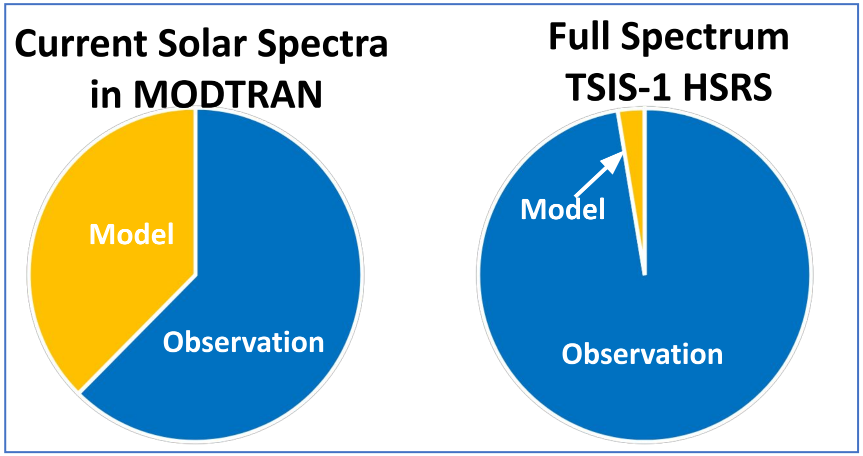
Application: A New NOAA Solar Spectral Irradiance Climate Data Record

Summary

- The TSIS-1 HSRS provides a new important 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.

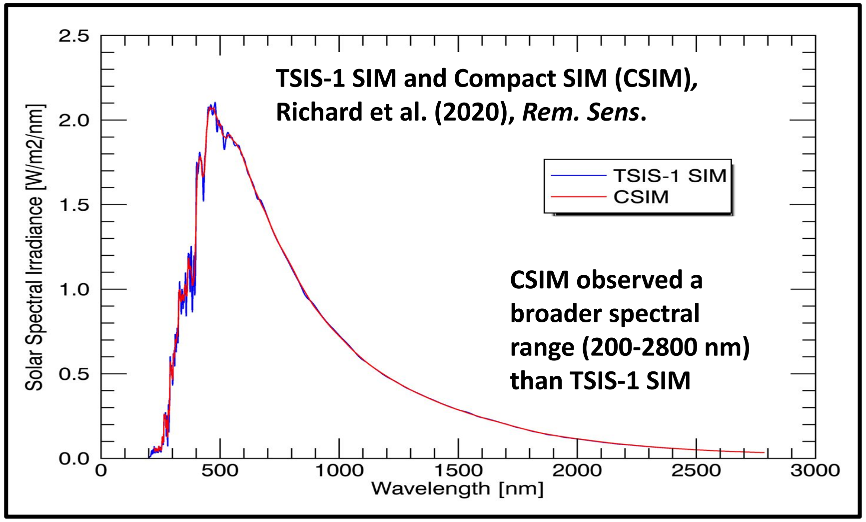
Implications for Inclusion in Radiative Transfer Modeling: Increases the proportion of integrated total incoming energy contributed by solar irradiance observations than from models.





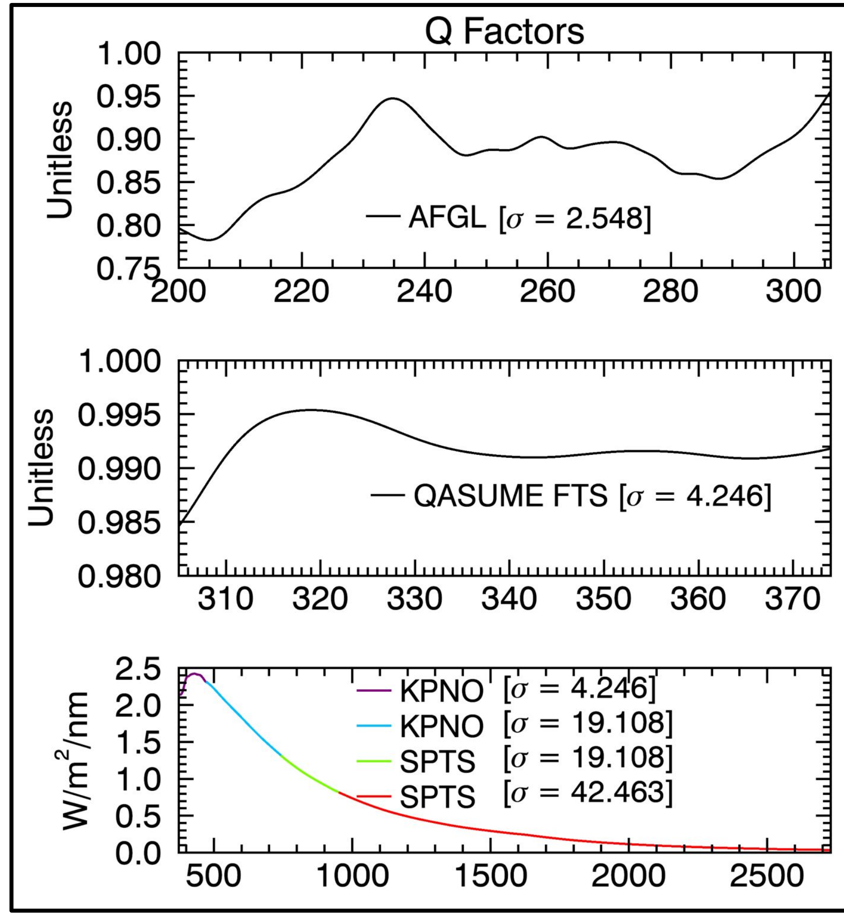
Backups

High-Accuracy Datasets, α

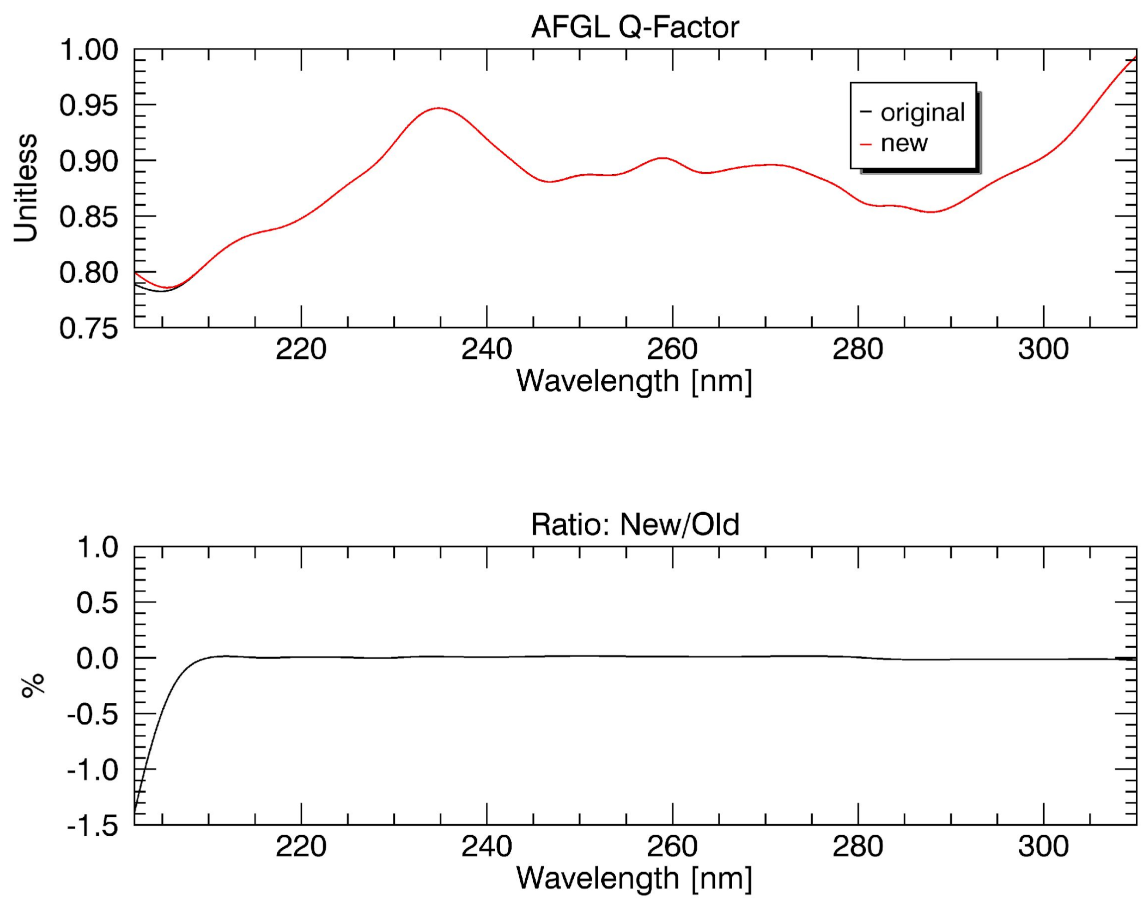


*The TSIS-1 HSRS represents solar minimum irradiance levels between solar cycles 24 and 25.

Q Factors

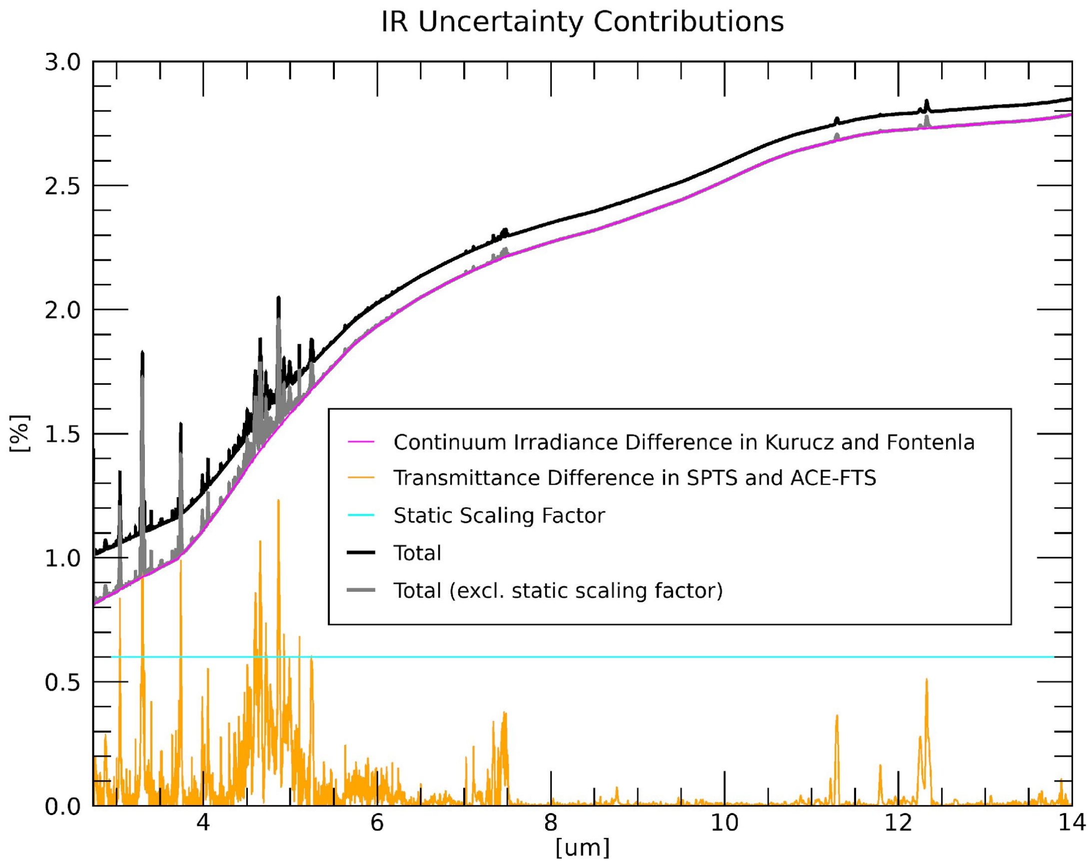


*The *Q* factor adjusts broad, continuum features while leaving fine spectral features undisturbed.



AFGL Q-Factor
1.00
0.95
0.90
0.85
0.80
0.75
Unitless
original
new
220
240
260
280
300
Wavelength [nm]
Ratio: New/Old
1.0
0.5
0.0
-0.5
-1.0
-1.5
%
220
240
260
280
300
Wavelength [nm]

IR Extension "A" Uncertainties



I can use the ACE vs JPL solar line comparison to add an additional uncertainty contribution between 2.7 and 14 microns. But, dominant source of uncertainty comes from the irradiance difference in the Kurucz and Fontenla models. Conclusion: JPL/SPTS solar lines are sufficient for the full spectrum extension of the TSIS-1 HSRS. This can be revisited later.

Construction of a Solar Spectral Irradiance Reference Spectrum for the 2008-2009 Solar Cycle Minimum

1) 2019 TSIS-1 extended Hybrid Solar Reference Spectrum, 202 to 200,000 nm, 1nm bins

Coddington et al., GRL, 2021

2) Extend to FUV (115.5-199.5 nm)
   - SORCE SSI observations in 2009 minimum, scaled to match HSRS at 292.5 nm

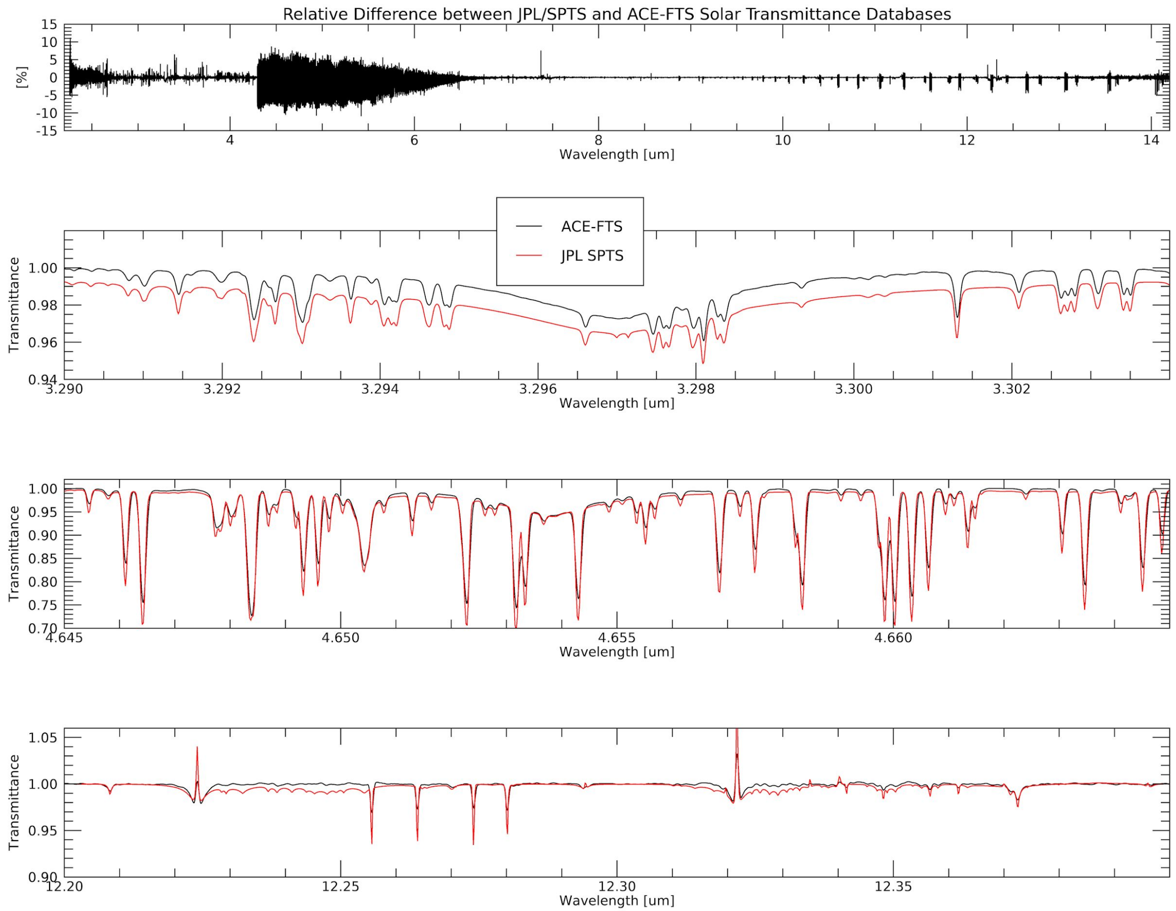
3) Extend to X-ray (0-36 nm) & EUV (37-114 nm)
   - TIMED SEE observations in 2009 solar minimum, scaled to match at 115 nm
   - SORCE X-ray observations in 2009 solar minimum

4) Adjust for different solar activity

Lean et al., E&SS, 2021

   - from 2019 (1-7 Dec 2019) to 2008-2009 (19 Nov 2008- 1 May 2009)
   - preliminary adjustments use NRLSSI3 SIST2 model
   - revised adjustments will use new NRLSSI4 model developed from SIST3

Solar Transmittance Database Comparisons



Potential Residual in JPL/SPTS?

Differences in spectral resolution

Potential Residual in JPL/SPTS?

Provenance of MODTRAN “Kurucz” Spectra

Robert Kurucz’s Website of Data and papers

http://kurucz.harvard.edu/sun/irradiance/solarirr.tab

http://kurucz.harvard.edu/sun/irradiance/irradiancebins.dat

THE SOLAR IRRADIANCE BY COMPUTATION

Robert L. Kurucz

Harvard-Smithsonian Center for Astrophysics
60 Garden St, Cambridge, MA 02138, USA

November 25, 1997

- Irradiancebins.dat
  - **SUN01kurucz1997.dat**
    - Became known as “newkur.dat”
    - Corrections from 310 to 340 nm to match ATLAS SSBUV
    - Corrections made by MODTRAN team
  - SUN01thkur.dat
    - SOLSPEC from 200 to 876 nm augmented with Kurucz.
    - Courtesy G. Thuillier
  - SUN01cebchkur.dat
    - ATLAS SSBUV from 200 to 406 nm augmented by Kitt Peak data and Kurucz
    - Courtesy R. Cebula
  - SUN01chkur.dat
    - Kitt Peak from 230 to 800 nm augmented with Kurucz
    - O2 absorption lines replaced with those of Kurucz.
    - Courtesy K. Chance

Solar Reference Spectra in MODTRAN

Above 876 nm, all these spectra are identical

Provenance of MODTRAN "Kurucz" Spectra

Robert Kurucz's Website of Data and papers

*I have not found a dataset on the website that can be traced to the MODTRAN spectra in the IR

Robert Kurucz's Website of Data and papers

http://kurucz.harvard.edu/sun/irradiance2005/irrad.ps

http://kurucz.harvard.edu/sun/irradiance2005/irradthu.dat

*In 2005, Kurucz applied a Thuillier calibration.

***This calibration was updated 2 Jan 2010.**

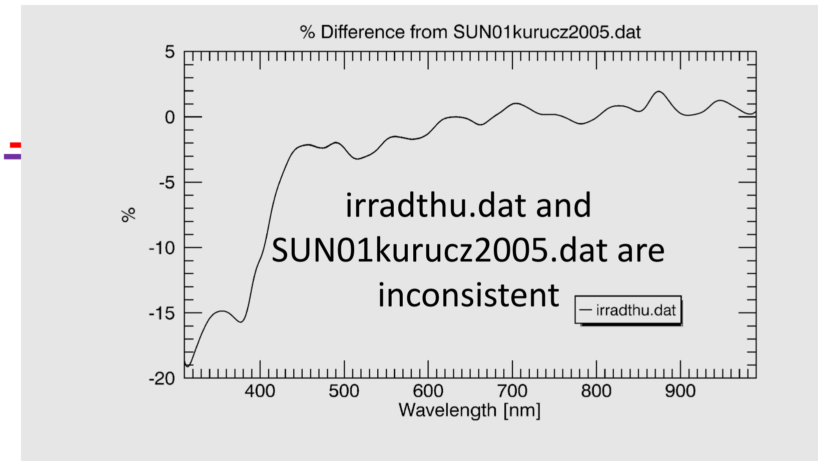
??

SUN01kurucz1995.dat

SUN01kurucz2005.dat

Became known as "oldkur.dat"

"The 2005 data was generated from an update of Kurucz data" per Lex Berk/MODTRAN

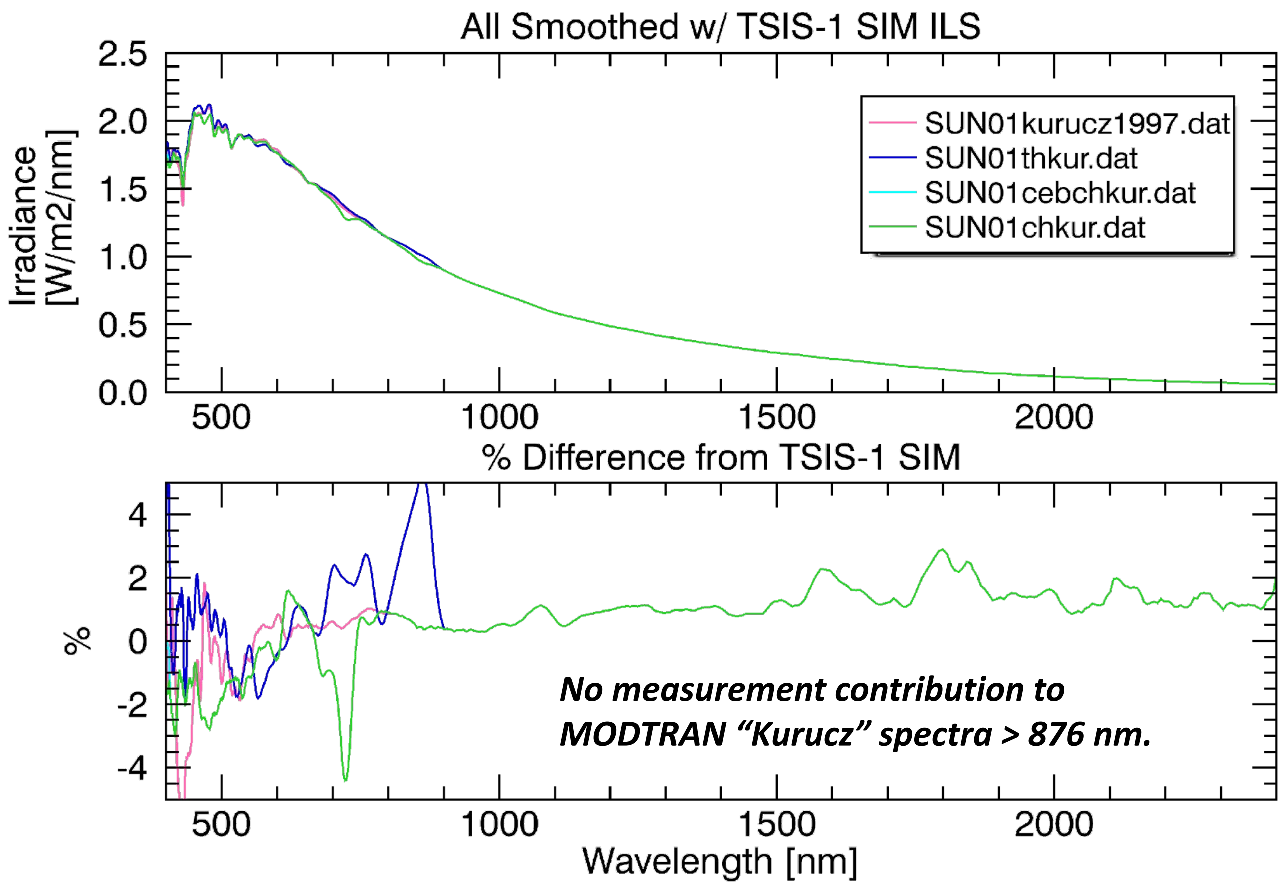


Solar Reference Spectra in MODTRAN

Above ~1000 nm, these MODTRAN data are identical.

Integrated SSI of MODTRAN "Kurucz" Spectra

Name	Integrated SSI 200-200,000 nm [W/m^2]	Integrated SSI 200-2400 nm [W/m^2]	Comments
SUN01kurucz1995.dat	1368.87	1317.64	Became known as "oldkur.dat". Also differs from "newkur.dat" in the IR. Might not be traceable to data on Kurucz website.
SUN01kurucz2005.dat	1400.51	1349.59	Inconsistent with a calibrated dataset (to SOLSPEC/Thuillier) on R. Kurucz's website. Identical to SUN01kurucz1995.dat > 1um.
SUN01kurucz1997.dat	1368.04	1316.94	Became known as "newkur.dat". Traceable to 'irradiancebins.dat' on Kurucz website.
SUN01thkur.dat	1376.23	1325.18	SOLSPEC data < 876 nm, augmented with Kurucz theoretical spectrum.
SUN01cebchkur.dat	1362.17	1311.06	SSBUV data from 200-406 nm, augmented with Kitt Peak ground observations and Kurucz theoretical spectrum.
SUN01chkur.dat	1359.75	1308.69	Kitt Peak ground observations from 230-800 nm augmented with Kurucz theoretical spectrum. Potential atmospheric residuals reported at 320-330 and 720 nm.



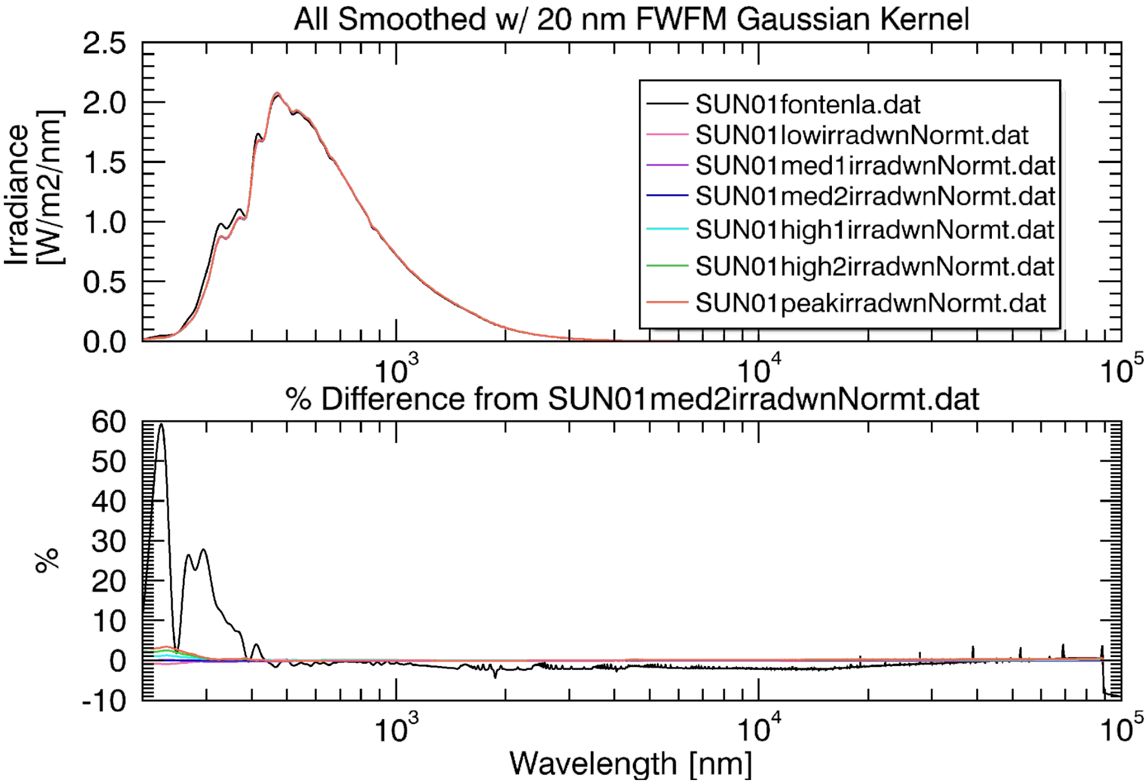
$$\% \; difference = \frac{(Spectrum_x - reference)}{reference} \; x \; 100$$

MODTRAN "Kurucz" Spectra vs TSIS-1 SIM

- 400-2400 nm; linear scale

All MODTRAN "Fontenla" Spectra

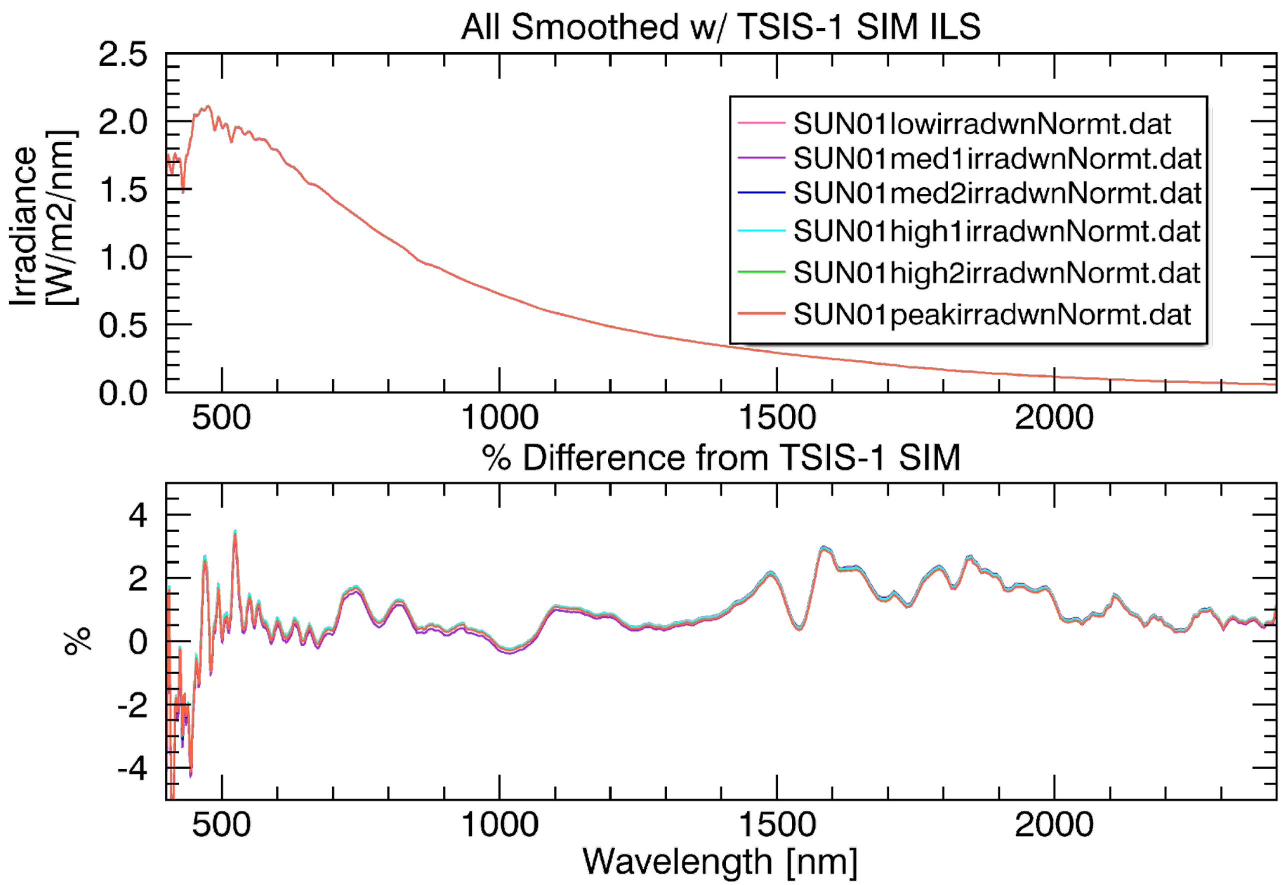
Semi-empirical approach that determines best fit of observed (at moderate spatial resolution) and simulated spectra from a 1-D radiative transfer model with varying temperature & density.



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

Integrated SSI of MODTRAN Fontenla Spectra

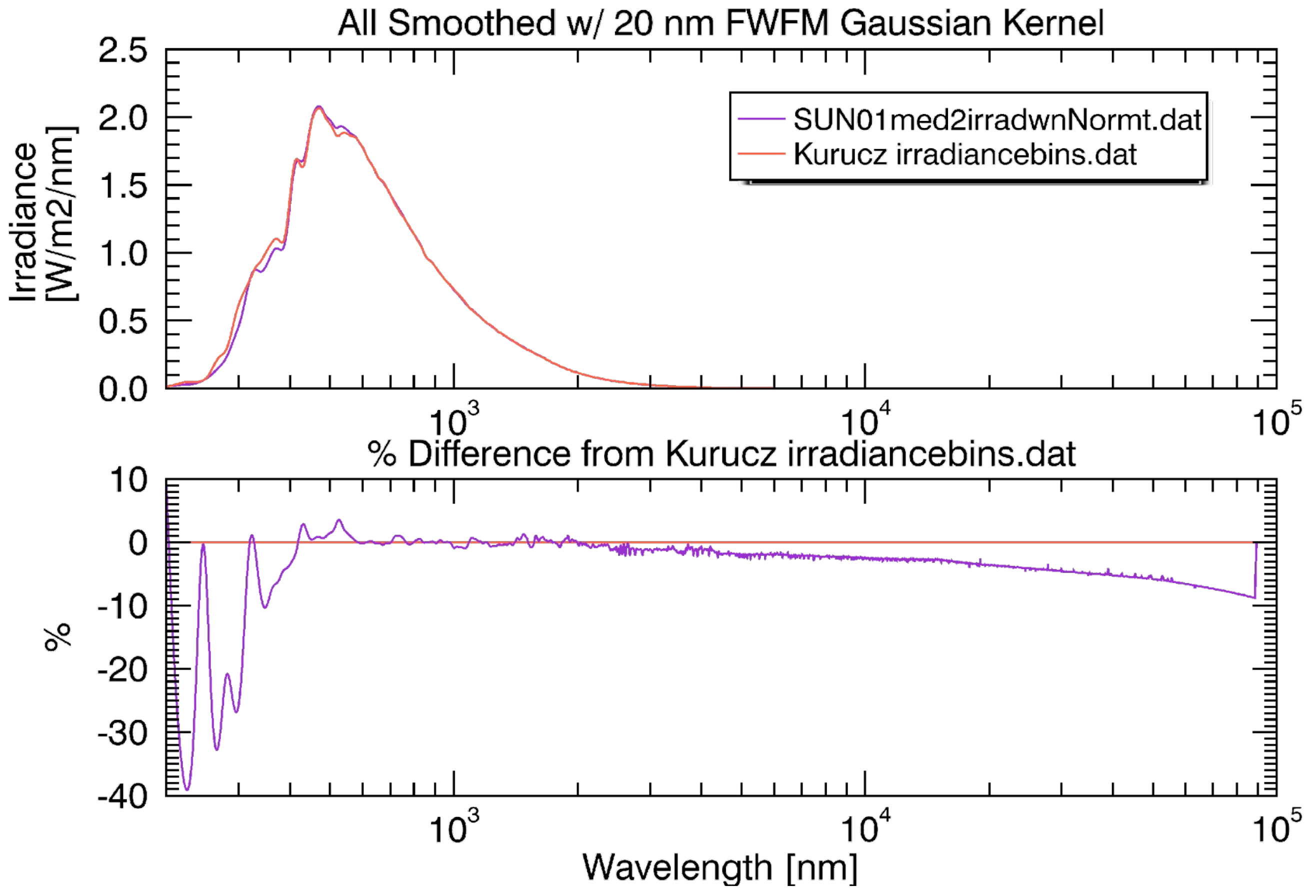
Name	Integrated SSI 200-100,000 nm [W/m^2]	Integrated SSI 200-2400 nm [W/m^2]	Comments
SUN01fontenla.dat	1361.25	1311.52	
SUN01lowirradwnNormt.dat	1361.15	1310.64	
SUN01med1irradwnNormt.dat	1358.96	1308.48	
SUN01med2irradwnNormt.dat	1361.15	1310.64	The MODTRAN “default”
SUN01high1irradwnNormt.dat	1361.80	1311.27	
SUN01high2irradwnNormt.dat	1361.07	1310.55	
SUN01peakirradwnNormt.dat	1361.11	1310.59	



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

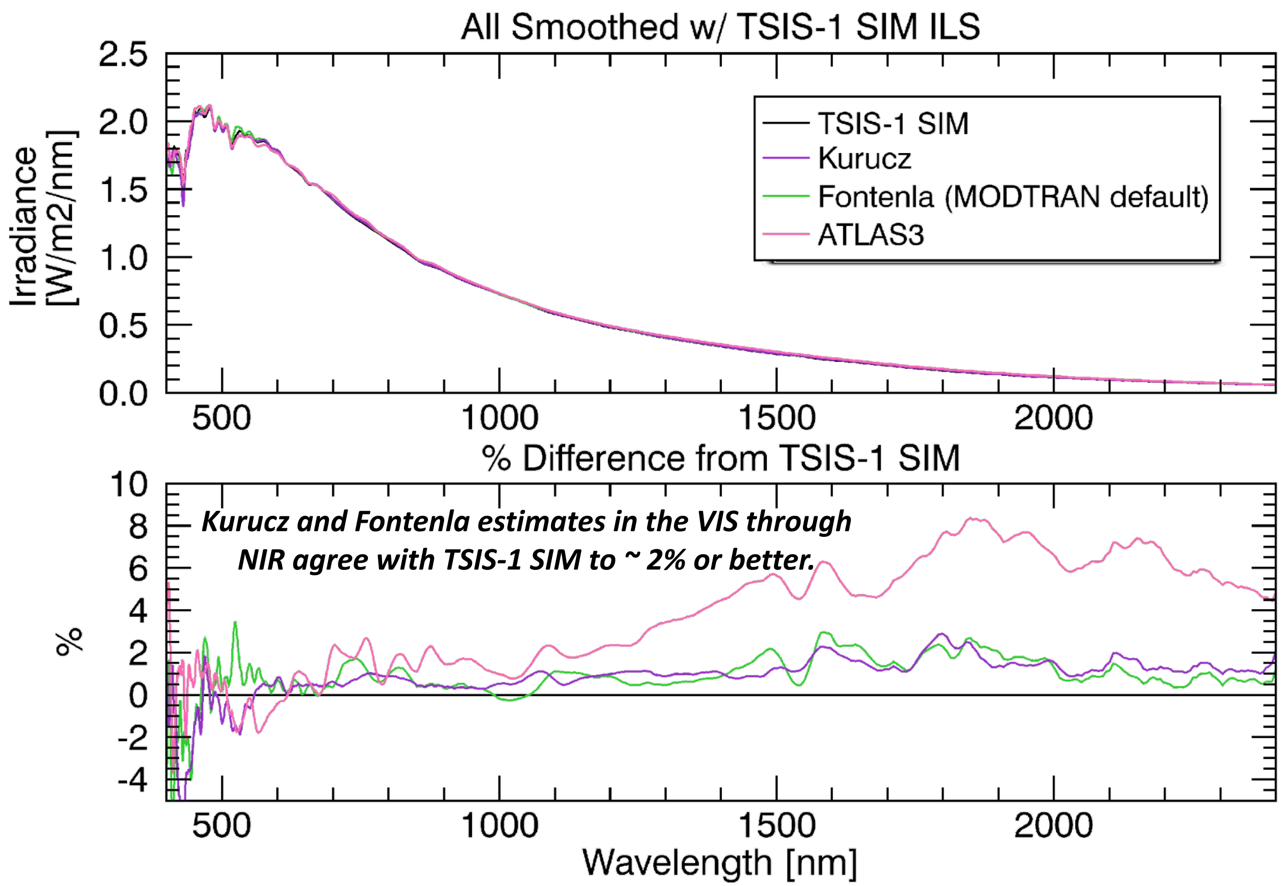
MODTRAN "Fontenla" Spectra vs TSIS-1 SIM

- 400-2400 nm; linear scale



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

- Largest differences (30-40%) below 400 nm. Differences are better than 10% in the visible through infrared



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

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