Impact of reference solar spectra differences on radiometric cross-calibration of satellite imagers

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Satellite Instrument Calibration

DN-to-Radiance		DN-to-Reflectance
Onboard calibrators: Tungsten Lamps (e.g., historical Landsats, CERES)	Reference Solar Spectrum	***Onboard calibrators:*** Solar Diffuser (e.g., MODIS, VIIRS, new Landsats)
Cross-calibration with a reference sensor: MODIS and VIIRS as reference (e.g., CERES project)		***Cross-calibration with a reference sensor:*** MODIS and VIIRS as reference (target DNs calibrated against TOA reflectance)

- Conversion of sensor-measured radiances to reflectance values, or vice-versa, is performed using a reference spectral solar irradiance

Objectives

- *Investigate radiometric inconsistency between different solar spectra*
- *Quantify the impacts of solar spectra differences in satellite inter-comparison*
- *Highlight the TSIS-1 HSRS and recommend using it as a common reference solar spectrum in Earth Remote Sensing community for improved and consistent retrievals between different sensors*

Solar spectra in use

- Earlier **Landsat MSS sensors** and **AVHRR** used *Neckel and Labs (1984)*
- **MODIS** instruments on board Terra and Aqua spacecrafts use a composite (known as MCST solar spectrum) of three different SSI datasets:
  - *Thuillier et al. (1998)* for wavelengths between 350-800 nm
  - *Neckel and Labs (1984)* between 800-1100 nm
  - *Smith and Gottlieb (1974)* between 1100-2500 nm
- **MERIS** on Envisat, **SeaWiFS**, **Sentinel-2**, **NOAA-20 VIIRS** use *Thuillier 2003* spectrum
- **VIIRS** on the SNPP satellite uses *Kurucz spectrum* from MODTRAN 4.0
- For AVHRRs onboard NOAA-15 through -17, the source of SSI data has not been documented well
- For NOAA-18 onwards, AVHRRs use a subset of SSI data compiled by Wehrli

List of solar spectra used in this study

Name	Description	Uncertainty (%)
TSIS-1 SIM	Measured by TSIS-1 SIM instrument on ISS	0.24-0.41%
HSRS	High-resolution solar line data normalized to the absolute irradiance scale of the TSIS-1 SIM and CSIM instruments	0.3-1.3%
Thuillier 2003	Measured by SOLSPEC and SOSP spectrometers from ATLAS and EURECA missions	1-3%
Kurucz (MODTRAN)	A theoretical spectrum of the solar continuum supplemented with observed and predicted solar lines	NA
MCST	Combination of Thuillier, Neckel and Labs, and Smith and Gottlieb used by MODIS L1B datasets	2-3%
SOLAR-ISS V2	Based on SOLAR/SOLSPEC spectroradiometer on ISS supplemented with observed and predicted solar lines	~1.26%
WHI 2008	Derived for the 2008 Whole Heliosphere Interval (WHI) using a combination of temporally coincident satellite and sounding rocket observations	3%

TSI Comparison

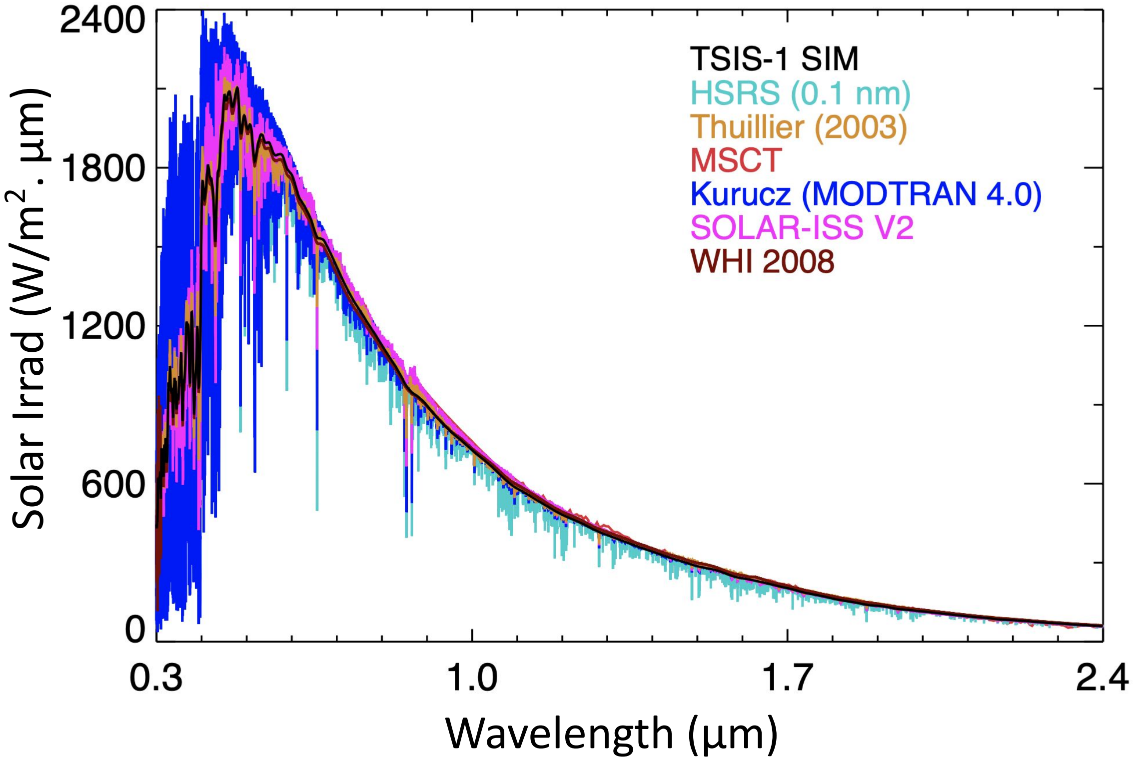


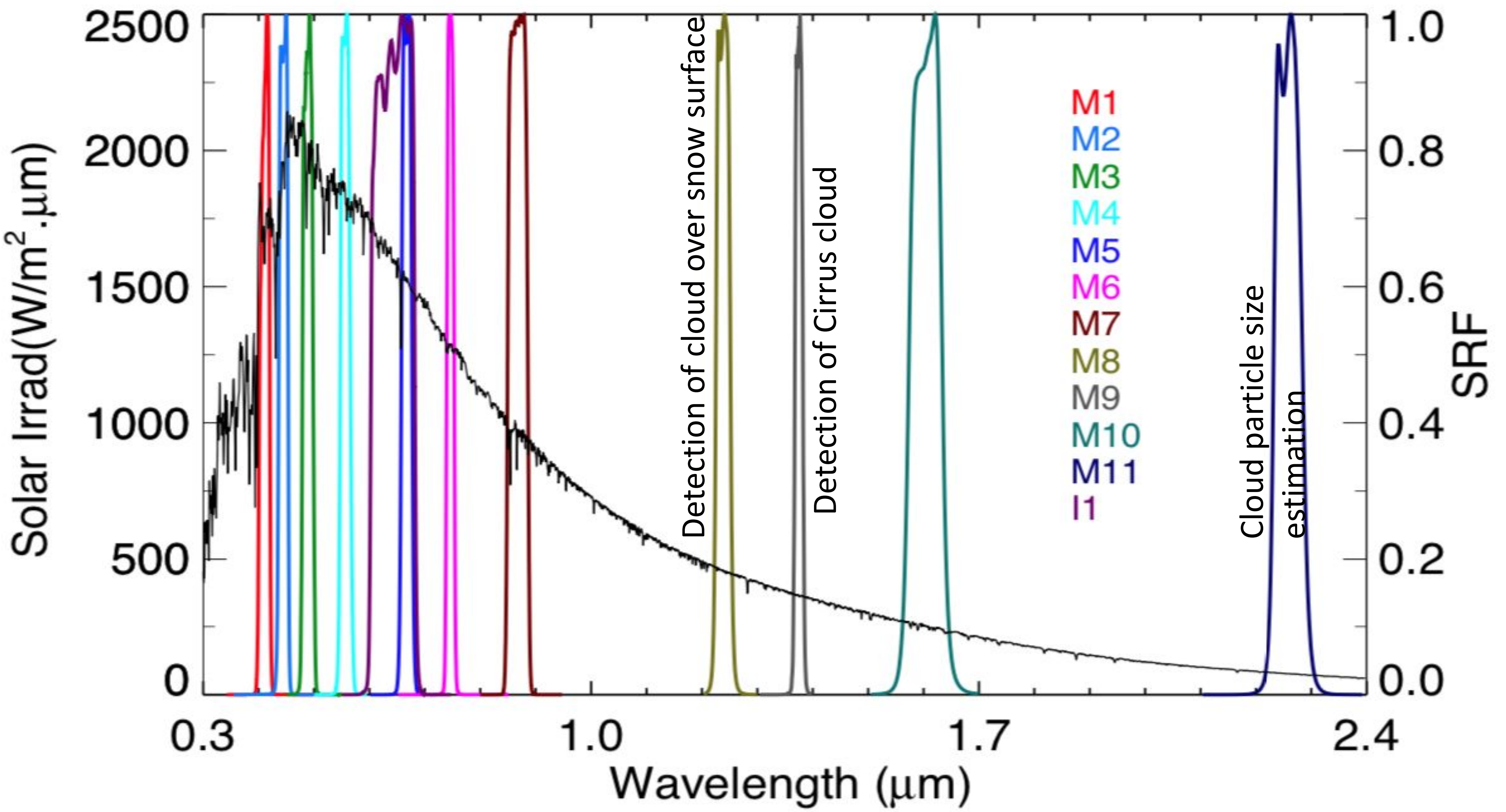
Table 2: Total integrated solar irradiance values derived for all eight SSI datasets and their differences with the TSI value adopted by IAU.

Spectrum	205-2390 nm (W/m²)	+52.0 W/m² (115-205 nm and 2390-100,000 nm)	Difference from IAU TSI (1361 W/m²) (W/m²)	% Difference
MCST	1335.1	1387.1	+15.1	+1.1
Thuillier 2003	1315.2 †	1367.2 †	+6.2 †	+0.5
SOLAR-ISS V2	1320.8	1372.8	+11.8	+0.9
WHI 2008	1309.1 ‡	1361.1 ‡	+0.1 ‡	0
Kurucz (MODTRAN 4.0)	1315.2	1367.2	+6.2	+0.5
TSIS-1 HSRS (0.1 nm)	1310.7	1362.7	+1.7	+0.1
TSIS-1 SIM	1309.0	1361.0	0	0

† Includes the 1.4% wavelength-independent normalization (reduction) to match TSI of 1368 W/m² (Thuillier et al., 2003). Without the normalization, the Thuillier spectra integral from 205-2390 nm is 1333.6 W/m², resulting in a greater TSI of 1386 W/m².

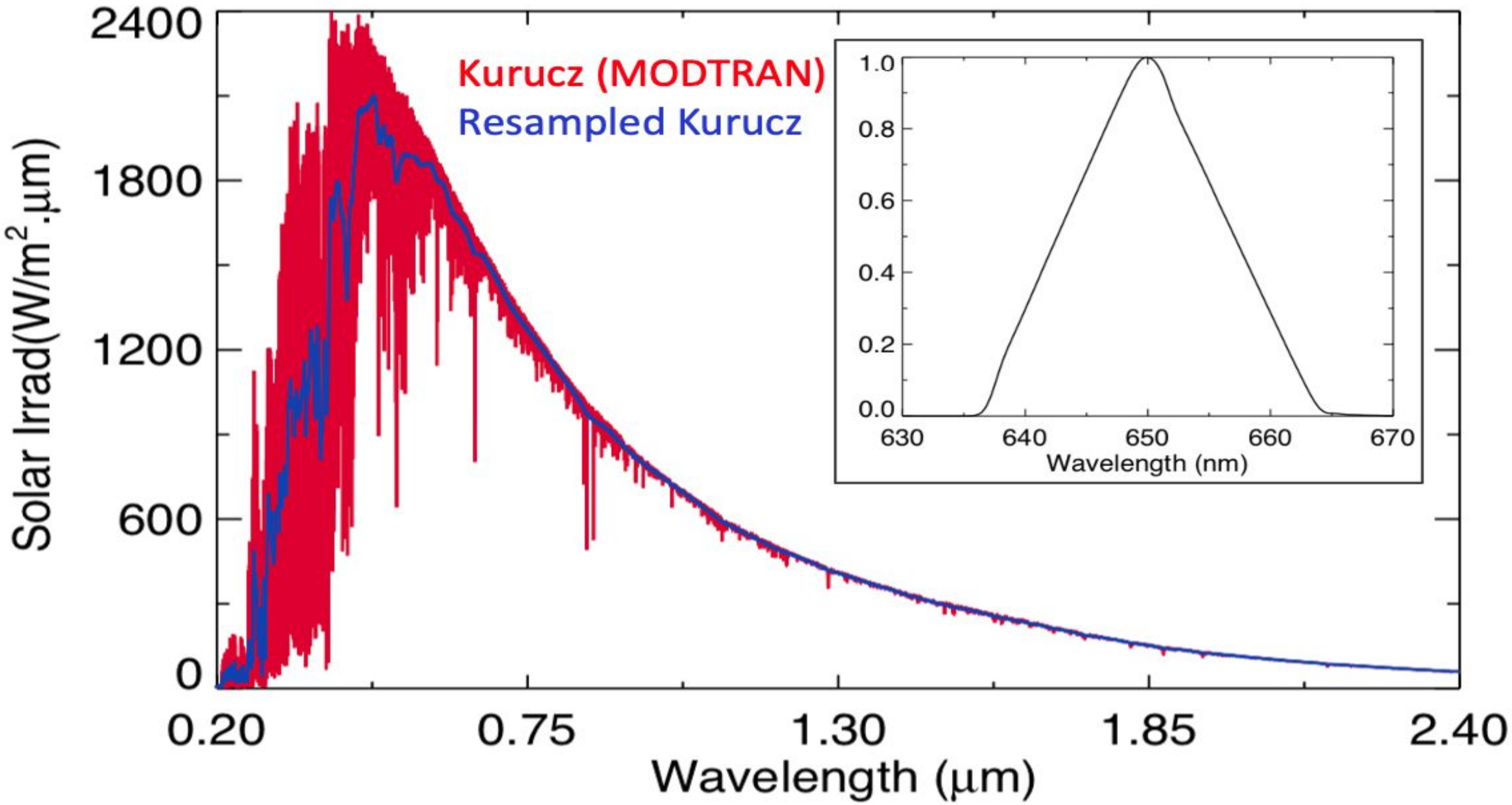
‡ Includes the 0.909% wavelength-independent normalization (reduction) to match TSI of 1361 W/m² (Woods et al., 2000). Without the normalization, the integral from 205-2390 nm is 1321.0 W/m².

- TSI values agree within ~1%
- *Impact on sensor retrievals could be much greater as they rely on specific wavelength differences*



SRFs of NOAA-20 VIIRS RSB along with the Thuillier 2003 solar spectrum (in black) in the background

Resampling of solar spectra



- Because of high accuracy of TSIS-1 SIM, absolute comparison is performed relative to the TSIS-1 SIM spectra
- All other solar spectra are resampled to spectral resolution of TSIS-1 SIM

Band-integrated solar constants

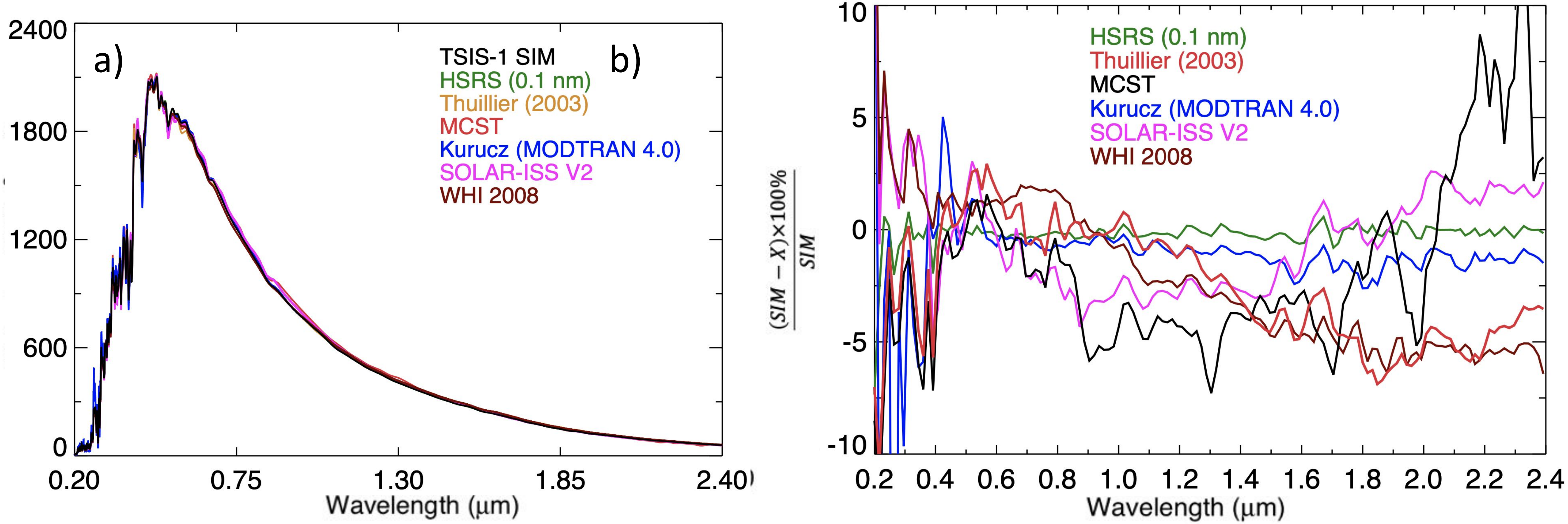
$$L_\lambda = \frac{\rho_\lambda \cdot \cos\theta \cdot E_{SUN}}{\pi \cdot d^2}$$

$$E_{SUN} = \frac{\int_{\lambda_1}^{\lambda_2} SRF(\lambda) \cdot S(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} SRF(\lambda) d\lambda}$$

$$\Delta E_{SUN} = \left(\frac{E_{SUN,Thuillier} - E_{SUN,X}}{E_{SUN,Thuillier}} \right) \times 100\%$$

- E_{SUN} values are computed for all RSB of NOAA-20 VIIRS using the eight SSI datasets
- A percent difference (ΔE_{SUN}) is computed relative to the Thuillier 2003 spectra (official SSI data used by the VIIRS ground processing)

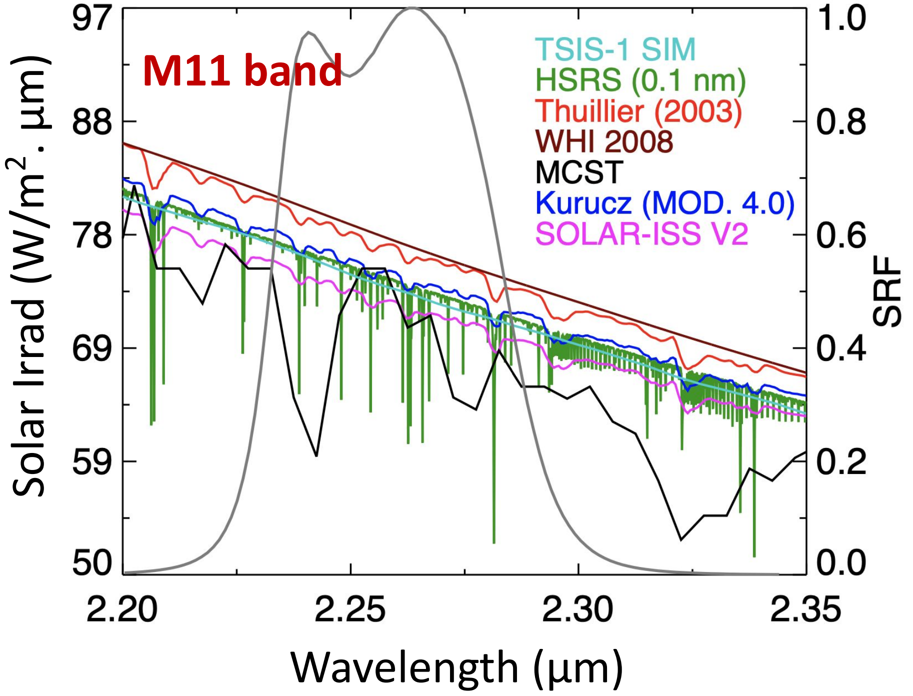
Absolute difference analysis



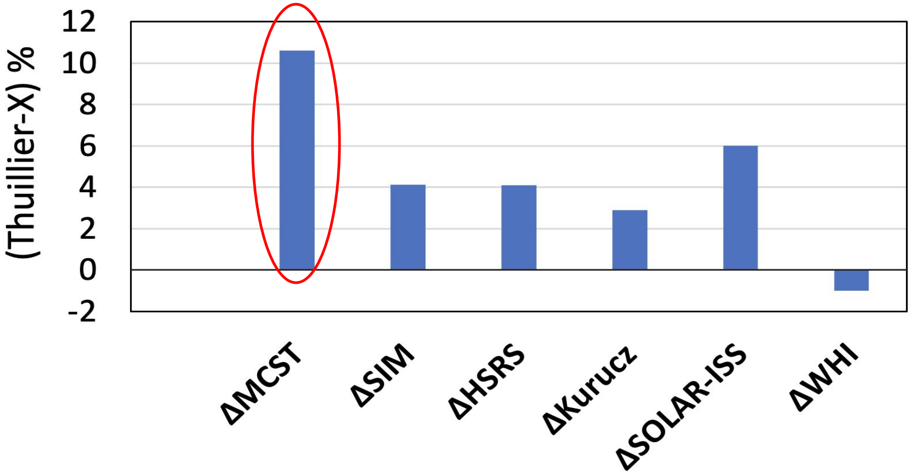
(a) Resampled solar spectra after convolving with TSIS-1 SIM LSF. (b) Relative difference with respect to the TSIS-1 SIM spectrum computed as a function of wavelength

- Noticeable differences can be seen between TSIS-1 SIM and other spectra
- Thuillier spectrum is consistent with the TSIS-1 SIM measurements within ~2.5% in VIS/NIR and wavelengths. At SWIR wavelengths, the difference reaches to ~7%
- Difference between the MCST and TSIS-1 SIM spectra is greater than 10% near 2.3 μm

E_{SUN} values for NOAA-20 VIIRS channels

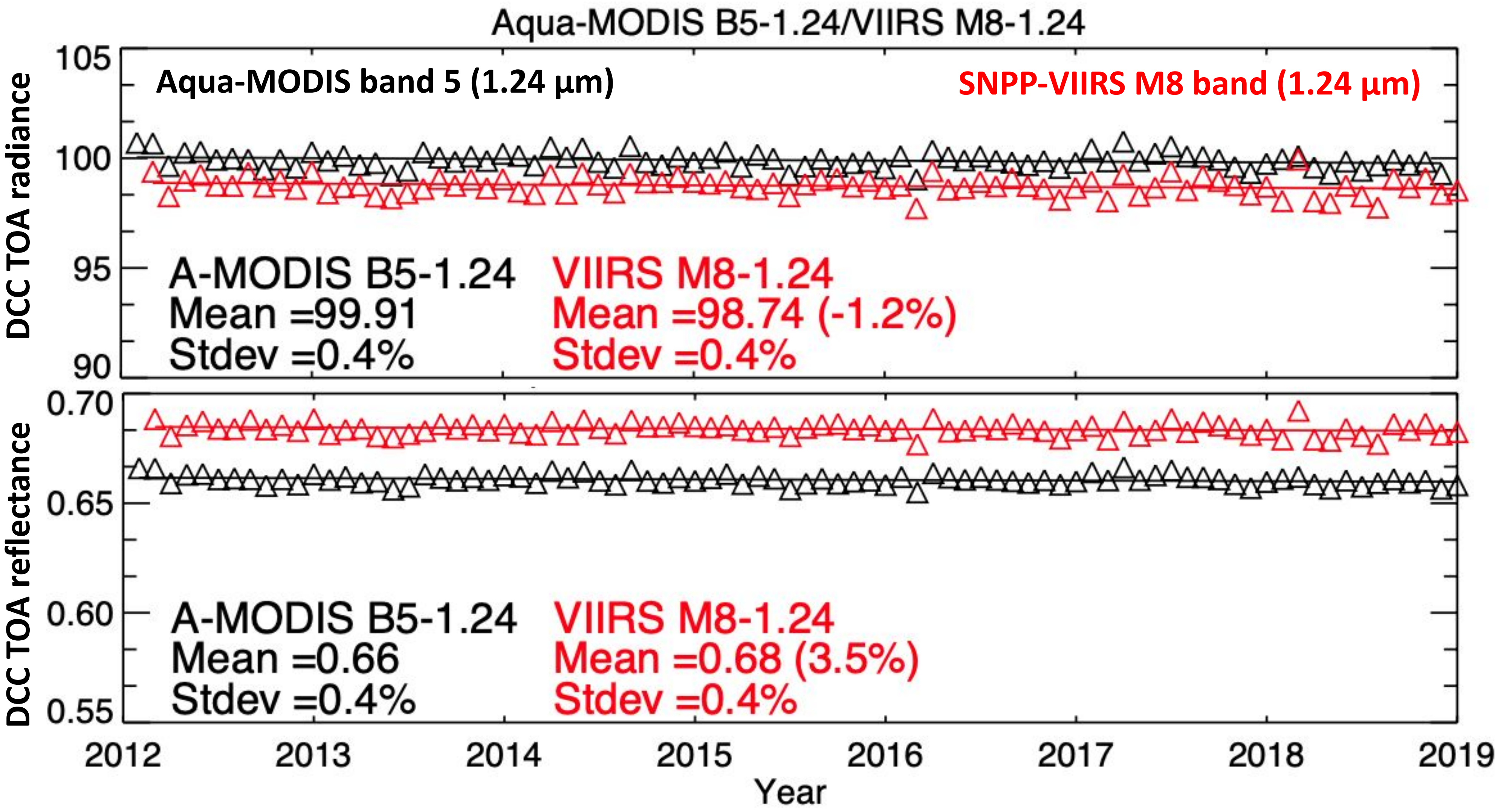


NOAA20 VIIRS band	Difference in E_{sun} relative to Thuillier (%)					
	MCST	TSIS-1 SIM	HSRS (0.1 nm)	Kurucz (MODTRAN)	SOLAR ISS v2	WHI 2009
M1 (0.41 µm)	-1.40	-0.54	-0.51	-0.08	-2.28	0.81
M2 (0.45 µm)	-1.41	-0.61	-0.56	2.09	-1.71	0.78
M3 (0.49 µm)	-1.40	-0.78	-0.78	-0.48	-1.54	0.15
M4 (0.56 µm)	-1.40	-2.26	-2.06	-2.06	-1.33	-1.02
M5 (0.67 µm)	-1.44	-0.98	-1.40	-1.64	-1.15	0.54
I1 (0.64 µm)	-1.43	-0.95	-1.30	-1.42	-2.0	0.42
M6 (0.75 µm)	-1.40	0.41	0.25	-0.24	-1.95	2.12
M7 (0.87 µm)	-2.71	0.12	0.18	0.11	-3.23	0.65
M8 (1.24 µm)	-4.33	0.88	0.77	-0.19	-1.39	-1.45
M9 (1.38 µm)	-0.56	2.48	2.35	1.62	0.12	-0.75
M10 (1.61 µm)	1.11	3.96	3.60	2.18	2.99	-0.45
M11 (2.25 µm)	10.23	4.14	4.11	2.89	6.00	-1.01



- Difference in E_{SUN} value is wavelength dependent (computed here wrt Thuillier 2003)
- E_{SUN} discrepancies for the M11 (2.25 µm) band exceeds 10%
- *Two VIIRS instruments, if scaled to the same radiometric scale of absolute reflectance, their radiances can still differ by up to 3% because they use different reference spectra for ground processing.*

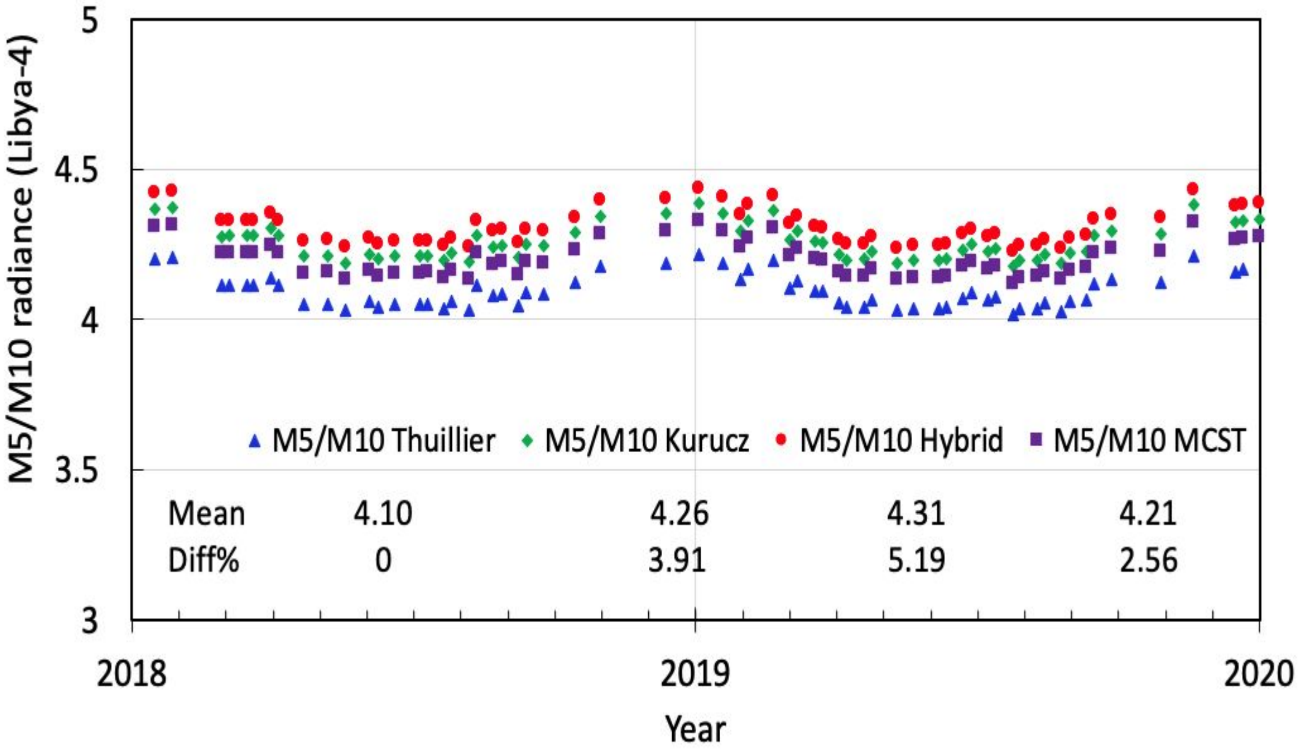
MODIS and VIIRS Cross-calibration



- Radiometric scaling is different between radiance and reflectance products
  - Aqua-MODIS 1.24 µm band radiances are ~1% brighter than those from a similar band in SNPP VIIRS
  - However, reflectance values are 3.5% darker than those from SNPP VIIRS

Inter-band calibration consistency

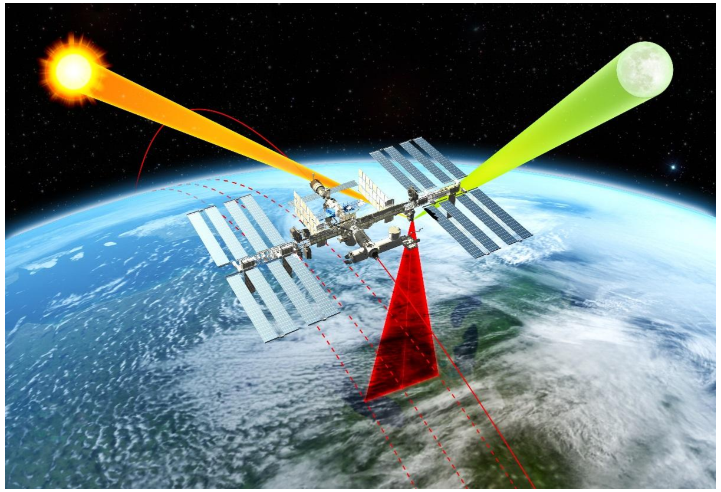
- Certain environmental retrievals may rely on combined use of multiple channels of satellite observations
- Examples
  - $NDVI = (\rho_{M7} - \rho_{M5})/(\rho_{M7} + \rho_{M5})$
  - Normalized Difference Snow Index (NDSI), a spectral index commonly used to monitor the extent of snow cover, as well as to distinguish between cloud and snow surface, relies on the satellite observations at 0.65 µm and 1.6 µm



M5=0.65 µm, M7=0.86 µm, M10=1.6 µm

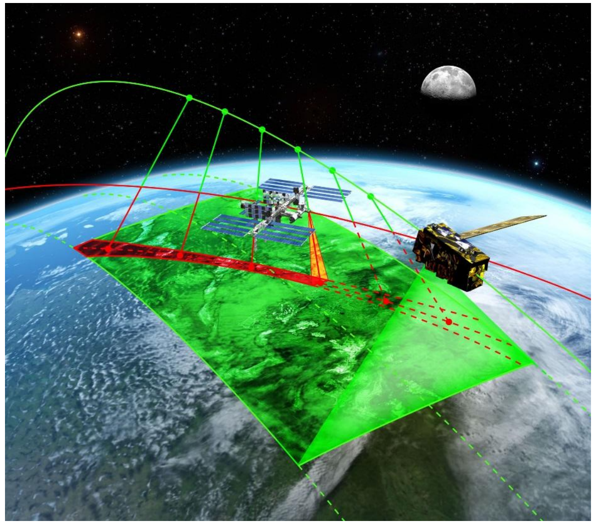
CLARREO Pathfinder as a SI-traceable radiometer

Objective #1: High Accuracy SI-Traceable Measurements



*Provide hyperspectral Earth reflectance measurements with accuracy improved by factor of **5-10 times** compared to the best operational sensors on orbit.*

Objective #2: Inter-Calibration Capabilities



*Demonstrate ability to transfer calibration to other key RS satellite sensors by inter-calibrating with **CERES & VIIRS**.*

CLARREO Pathfinder will provide both TOA reflectance (direct measurements) and radiance (using TSIS-1 HSRS) measurements for SI-traceable sensor intercalibration

- CERES-CPF intercalibration in radiance
- CERES-VIIRS intercalibration in reflectance

https://clarreo-pathfinder.larc.nasa.gov/

Conclusions

- *Radiometric calibration of satellite observations is tied to a reference solar irradiance model for radiance to reflectance conversion, or vice-versa*
- *Existing non-uniformity in the usage of reference solar spectra among the multiple satellites adds challenges to achieve radiometric harmonization and consistent retrievals across the sensors*
- *Owing to excellent radiometric accuracy and high spectral resolution, TSIS-1 HSRS is suitable to fulfill the need for a broad range of low and high spectral resolution applications*
- *CEOS and GSICS recommends TSIS-1 HSRS to be used as a common reference solar spectrum for use in the calibration of current and future RSB satellite instruments*
- *CLARREO Pathfinder using TSIS-1 HSRS will provide high-accuracy TOA Earth reflectance and radiance measurements to serve as reference for sensor inter-calibration in radiance and reflectance domains*

Bhatt, R.; Doelling, D.R.; Coddington, O.; Scarino, B.; Gopalan, A.; Haney, C. Quantifying the Impact of Solar Spectra on the Inter-Calibration of Satellite Instruments. *Remote Sens.* **2021**, *13*, 1438. https://doi.org/10.3390/rs13081438