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Using the CEOS-WGCV recommended solar irradiance model: impacts and recommendations

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CEOS-WGCV-IVOS subgroup

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- Committee on Earth Observation Satellites (CEOS)
    - International coordination of civil, space-based, Earth observation programs

- Working Group on Calibration & Validation (WGCV)
    - Ensure long-term confidence in the accuracy and quality of EO data and products
    - Forum for exchange and information sharing - https://calvalportal.ceos.org/

- The Infrared and Visible Optical Sensors Subgroup (IVOS)
    - Ensure high quality calibration and validation of infrared and visible optical data from Earth observation satellites

CEOS Committee on Earth Observation Satellites

Solar irradiance models

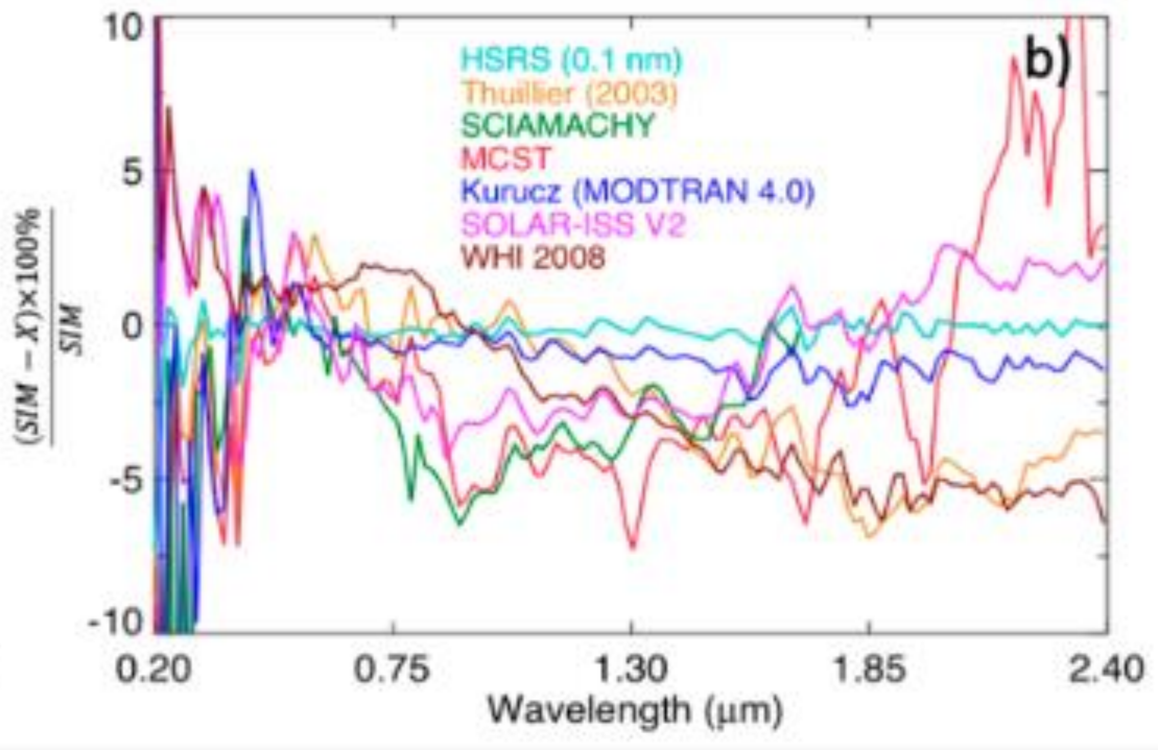
- Solar irradiance models are used in many applications, e.g.:
  - constraining the solar forcing in climate models
  - converting between satellite radiance and reflectance
  - absolute radiometric calibration using the Sun as reference
  - atmospheric correction algorithms to retrieve surface products

- A range of solar irradiance models are available (Thuillier et al. 2003; Kurucz 2005, Fontenla et al. 2011, …) which differ by more than their reported uncertainties

- TSIS-1 HSRS (Coddington et al. 2021) provides a new high-resolution solar reference spectrum at higher accuracy than any previously reported

- In March 2022, CEOS endorsed the use of TSIS-1 HSRS as common reference solar irradiance spectrum - https://calvalportal.ceos.org/web/guest/tsis-1-hsrs

Solar irradiance differences



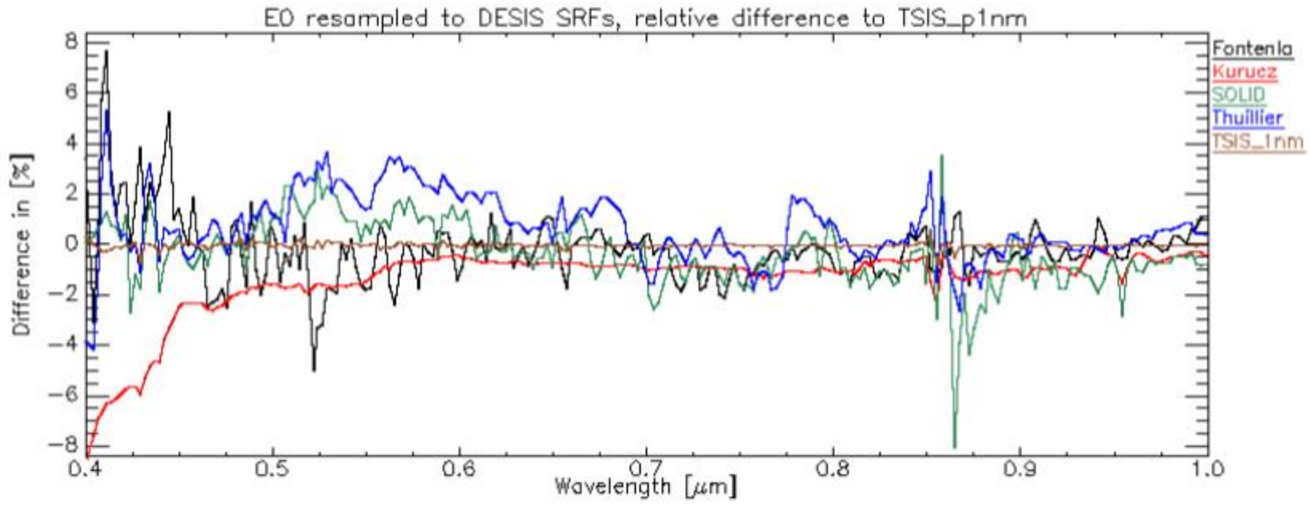


Figure 5. Relative difference of solar irradiance spectra resampled to DESIS in relation to TSIS_p1nm. "Fontenla" denotes Fontenla 2011, "Kurucz" to Kurucz 2005, "Thuillier" to Thuillier et al., 2003, "SOLID" to the SOLID composite, "TSIS_1nm" to the TSIS HSRS at 1 nm resolution.

Bhatt et al. 2021
https://doi.org/10.3390/rs13081438

Publication in preparation

Satellites calibrated using reflectance panel

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- Satellites such as Sentinel-2, Sentinel-3, MERIS, … are calibrated using reflectance panel, and use Thuillier spectrum to obtain calibrated radiance
- Some solar irradiance models don‘t cover full SWIR up to 2.5 µm (Thuillier extends to ~2.4 µm). As a consequence, some missions (e.g. ENMAP) use Fontenla or other models
- We investigate differences between the obtained radiances using Thuillier et al 2003; and using the CEOS-recommended TSIS-1 spectrum
- When using radiances from such sensors, a correction can be applied in order to be consistent with TSIS
- (Note e.g. Landsat-8/9 are calibrated separately in radiance and reflectance, and thus don’t use a model solar irradiance spectrum)

Solar spectra considered

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- Thuillier et al (2003)
  - Previous CEOS recommended spectrum
  - Based on the space-based measurements of the solar irradiance obtained from ATLAS & EURECA missions
  - Used in L1B processing of Sentinel-2, Sentinel-3, MERIS, NOAA-20 VIIRS, ...
  - Mean absolute uncertainty of 2 to 3%
  - Downloaded from https://oceancolor.gsfc.nasa.gov/docs/rsr/f0.txt

- Coddington et al (2021) – TSIS-1 HSRS (v2)
  - Current CEOS recommended spectrum (since March 2022)
  - Also recommended in 2022 GSICS meeting
  - Developed by applying a modified spectral ratio method to normalize very high spectral resolution solar line data to the absolute irradiance scale of the TSIS-1 Spectral Irradiance Monitor (SIM) and the CubeSat Compact SIM
  - Uncertainty is 0.5% from 0.4 to 0.46 μm, 0.3% from 0.46 to 2.365 μm, and 1.3% below 400 nm and above 2365 nm
  - Downloaded from https://lasp.colorado.edu/lisird/data/tsis1_hsrs_p1nm

TOA Radiance Modelling methodology

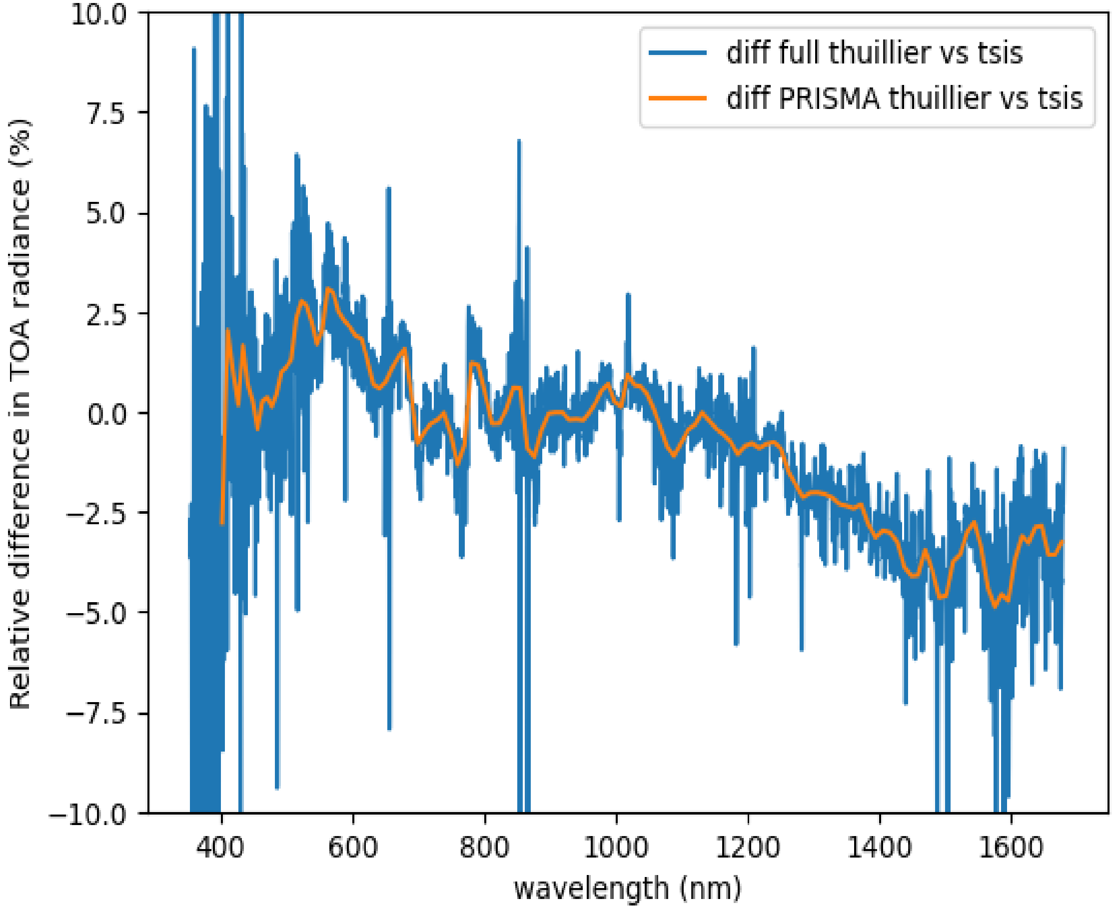
- Using in-house (NPL) python tool that wraps various RT codes such as Libradtran & 6S (RTTOV and Eradiate under development), with consistent inputs and outputs

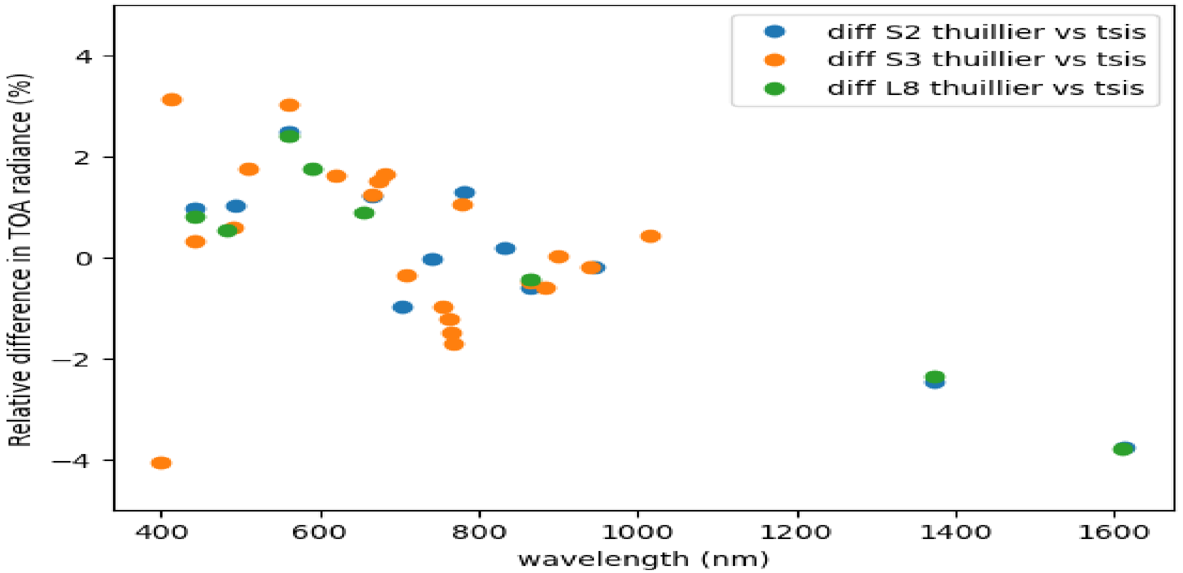
- Allows to specify extra-terrestrial solar irradiance models

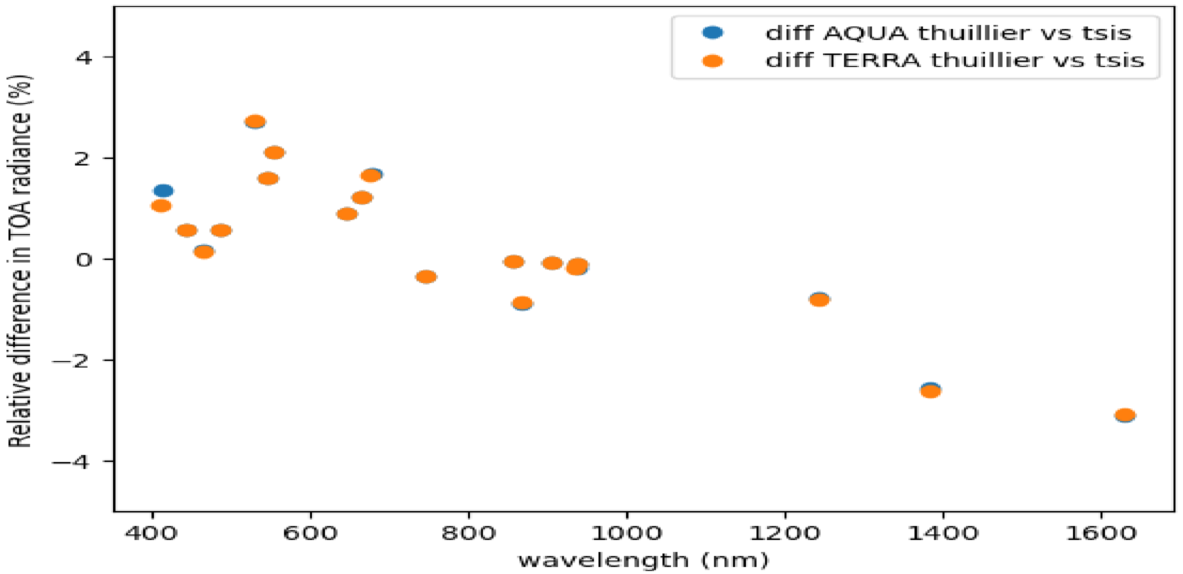
- Atmospheric properties from AERONET and/or ERA5+CAMS reanalysis datasets, surface reflectances from HYPERNETS

- Matheo (https://matheo.readthedocs.io/en/latest/) python package used for convolution with spectral response function of sensors (building on pyspectral)

Observed TOA radiance differences for different sensors

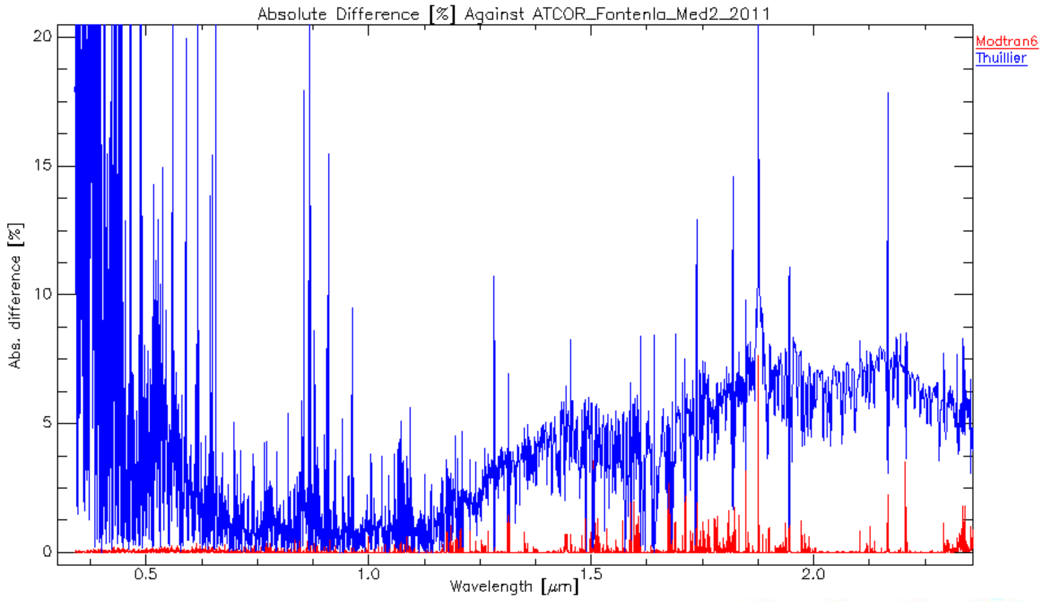


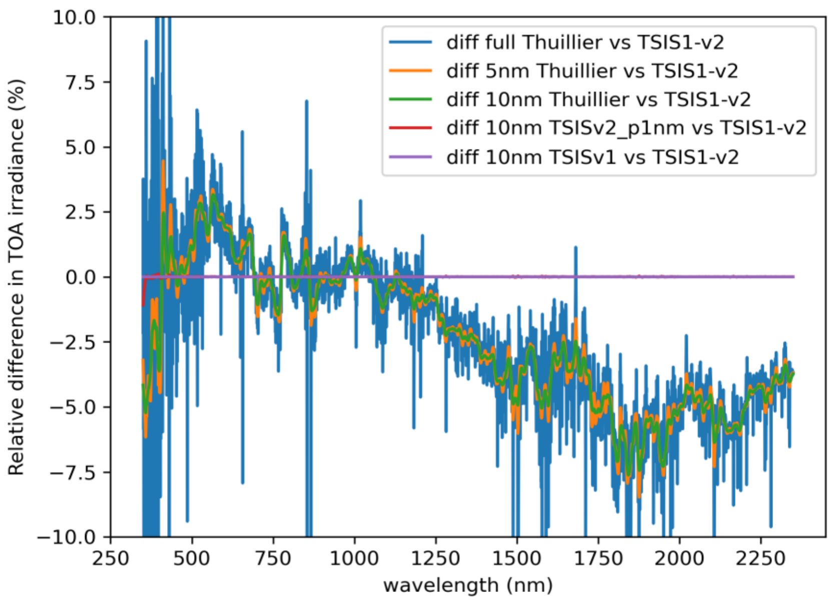




Need for traceability to which model was used

- For some solar irradiance models, there are different versions available from different sources
- In some cases, solar irradiance models (e.g. Fontenla included in MODTRAN) can be IP protected and thus not easily shared
- Key for users to have clarity exactly what model was used, and have access to data





Need for consistency when processing

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- Significant errors can be introduced in L2 products if a different solar irradiance model is used in the L2 processing than in the derivation of the L1C radiance estimation.

De Los Reyes et al. 2022 - https://doi.org/10.3390/rs14174237

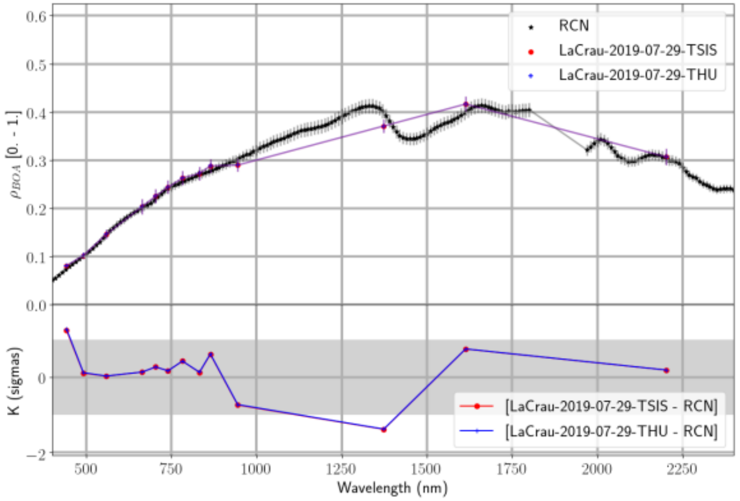

Figure 9. Consistent scenario. **Top**: L2A surface reflectance of RadCalNet (RCN) (black), PACO L2A with Thuillier 2003 (blue, "+") and TSIS (red, ".") solar models. **Bottom**: Uncertainty ratio (K) between each of L2A surface reflectance with the previous solar models with respect to RadCalNet in situ reference values. Grey band limits ± 1 sigma region.

Consistent Vs. Inconsistent usage of solar irradiance models

(example for RadCalNet "La Crau" and Sentinel-2)

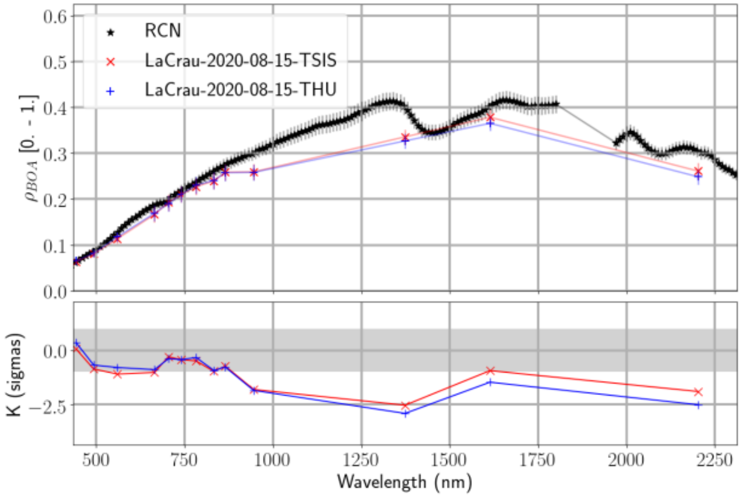

Figure 11. Inconsistent scenario for Sentinel-2. Top: L2A surface reflectance of RCN (black crosses), PACO L2A with Thuillier 2003 (blue, "+") and TSIS (red "×") solar models. Bottom: Uncertainty ratio (K) between each of L2A surface reflectance with the previous solar models with respect to RadCalNet (RCN) in situ reference values. Grey band limits ± 1 sigma region.

Using reflectance instead of radiance

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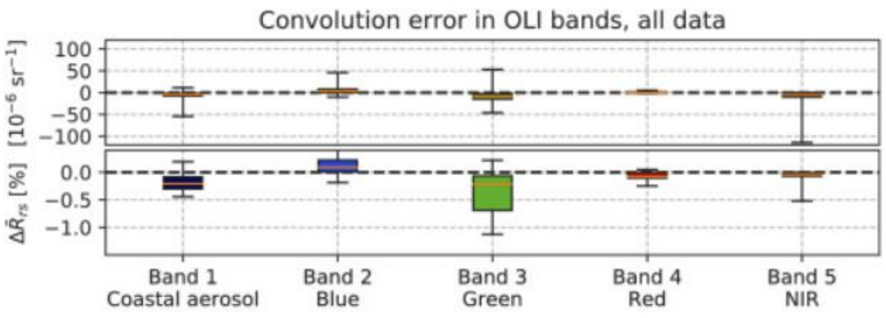
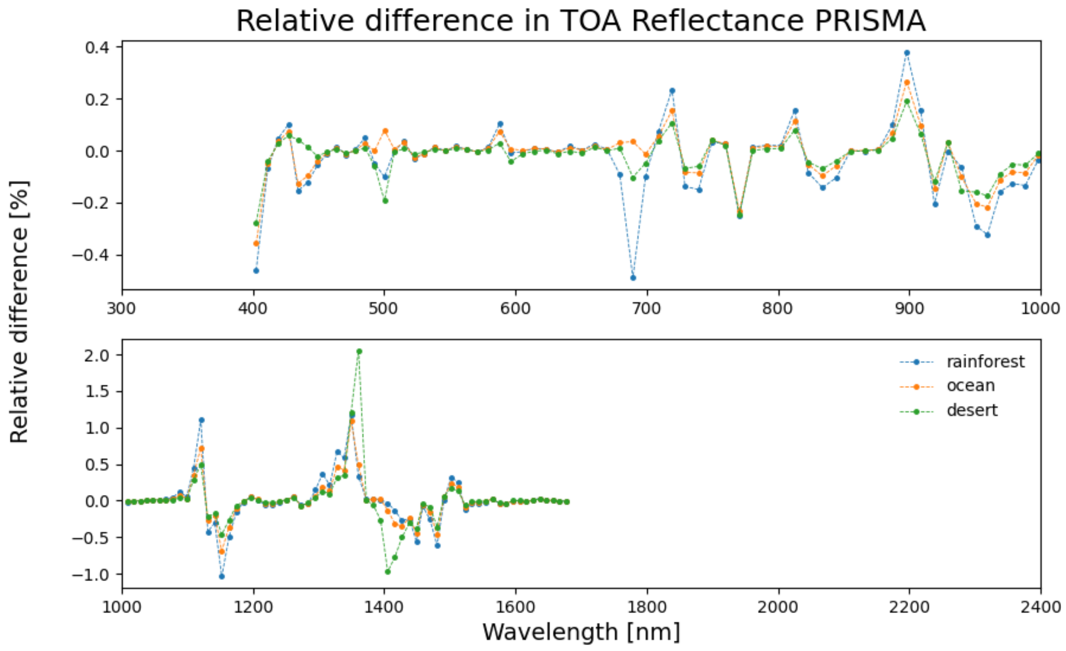
- Reflectance is more agnostic to what solar irradiance model was used
  - Sensors calibrated using solar diffusers
  - Radiative transfer models

- But spectral band integration should be applied to radiance and irradiance separately or can cause an error

$$\pi \int \frac{L(\lambda)}{E(\lambda)}\, RSR(\lambda) d\lambda \neq \pi \frac{\int L(\lambda)\, RSR(\lambda) d\lambda}{\int E(\lambda)\, RSR(\lambda) d\lambda}$$



Burggraaff 2020



Conclusions

- The CEOS-WGCV-IVOS subgroup recommends:
  - The use of the TSIS-1 HSRS solar irradiance model, which has significantly lower uncertainties
  - Satellite data providers must be clear in what solar irradiance model is used
  - Consistent solar irradiance models have to be used in the production of L1 radiance products and the retrieval of L2 surface products
  - Top-of-atmosphere reflectance products are more agnostic to the solar irradiance model used