Solar irradiance reference spectra (SIRS)

CEOS WGCV IVOS 31

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Carol Bruegge[1], Margit Haberreiter[2], David Crisp[1]

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

[2]PMOD/ WRC

Introduction

- Radiometric uncertainty requirements
  - OCO-2 & -3 are 5% relative to the sun (absolute)
  - MAIA is 5% absolute, 1.5% relative
- Accurate understanding of the solar irradiance spectra is required when converting surface reflectance measurements into top-of-atmosphere radiances, as needed for Vicarious Calibration of space-borne instruments.
  - Errors in retrieved science data products are cancelled if the retrieval code assumes the same model as used to calibrate the sensor

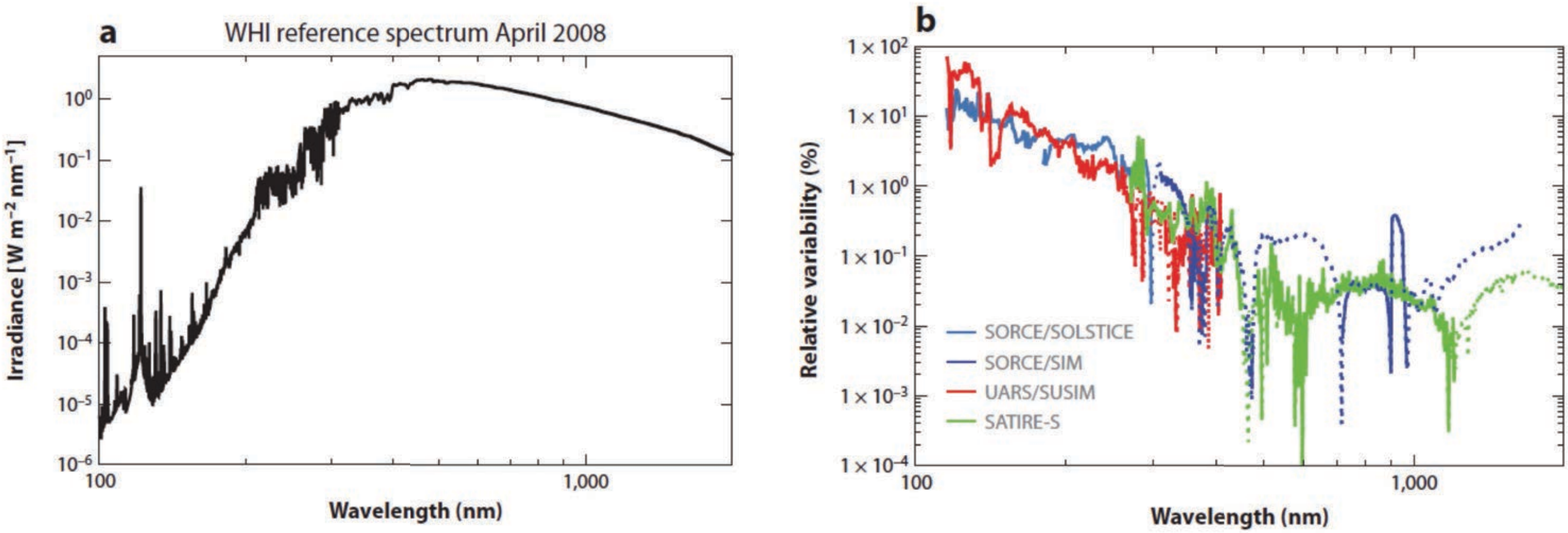
TSI

- TSI (Total Solar Irradiance) precision, as measured by space-based instruments, has a high degree of precision and is well correlated with sunspot number. Changes are ~0.1% through a solar cycle, with a 0.35% discrepancy among sensors.
  – Short (week-long) dips are co-incident with the passage of sunspots across the solar disk
  – TSI Radiometer Facility (TRF) allows TSI instruments to be compared against a NIST standard, prior to lauch
  – Post 2003 sensors (PREMOS & ACRIM3) agree to within 0.05%, TSI of 1,360.8±0.5 W m−2 is currently considered to best estimate of solar minimum

SIRS datasets

- SIRS (Solar Irradiance Reference Spectra)
  - The Labs & Neckel (1968) solar spectrum from 200 nm to 100 µm,
  - The Peyturaux (1968) solar spectral irradiance from 447.7 to 863.8 nm,
  - The Arvesen 1969 solar spectrum (Arvesen et al., 1969) from 205 to 2495 nm,
  - The Thekaekara 1973 solar spectrum (Thekaekara, 1974) from 115 nm to 400 µm,
  - The NASACV-990 reference solar spectrum (Colina et al., 1996) from 119.5 to 2500 nm,
  - The ATLAS 3 reference solar spectrum (Thuillier et al., 2003) from 0.5 to 2397.51 nm,
  - 2008 Whole Heliosphere Interval (WHI) from 0.1 to 2400 nm using a combination of satellite and sounding rocket observations (Woods et al., 2009),
  - The SCIAMACHY solar spectrum (Pagaran et al., 2011; Hilbig et al., 2017) from 235 to 2384 nm
  - SOLAR-ISS is low resolution SOLAR/ SOLSPEC measurements combined with high resolution ATLAS 3 (Meftah et al., 2017). Reanalysis corrects for sensor degradation
  - WCRP, as recommended by the EOS/ TERRA calibration working group (Wehrli, 1085)
    - Compilation uses Neckel & Labs (1984) in the visible. TIR is 1367 W/ m^2
  - SOLID (First European Comprehensive Solar Irradiance Data Exploitation, http://projects.pmodwrc.ch/solid/) merges 20 SSI observations into one SIRS (Haberreiter et al., 2017). This dataset is recommended by CEOS WGCV IVOS
    - Spectral Resolution: 0.005 nm; Spectral Range: 300 nm to 15 µm
    - The SOLID published composite can be found here: ftp://ftp.pmodwrc.ch/pub/projects/SOLID/database/composite_published/

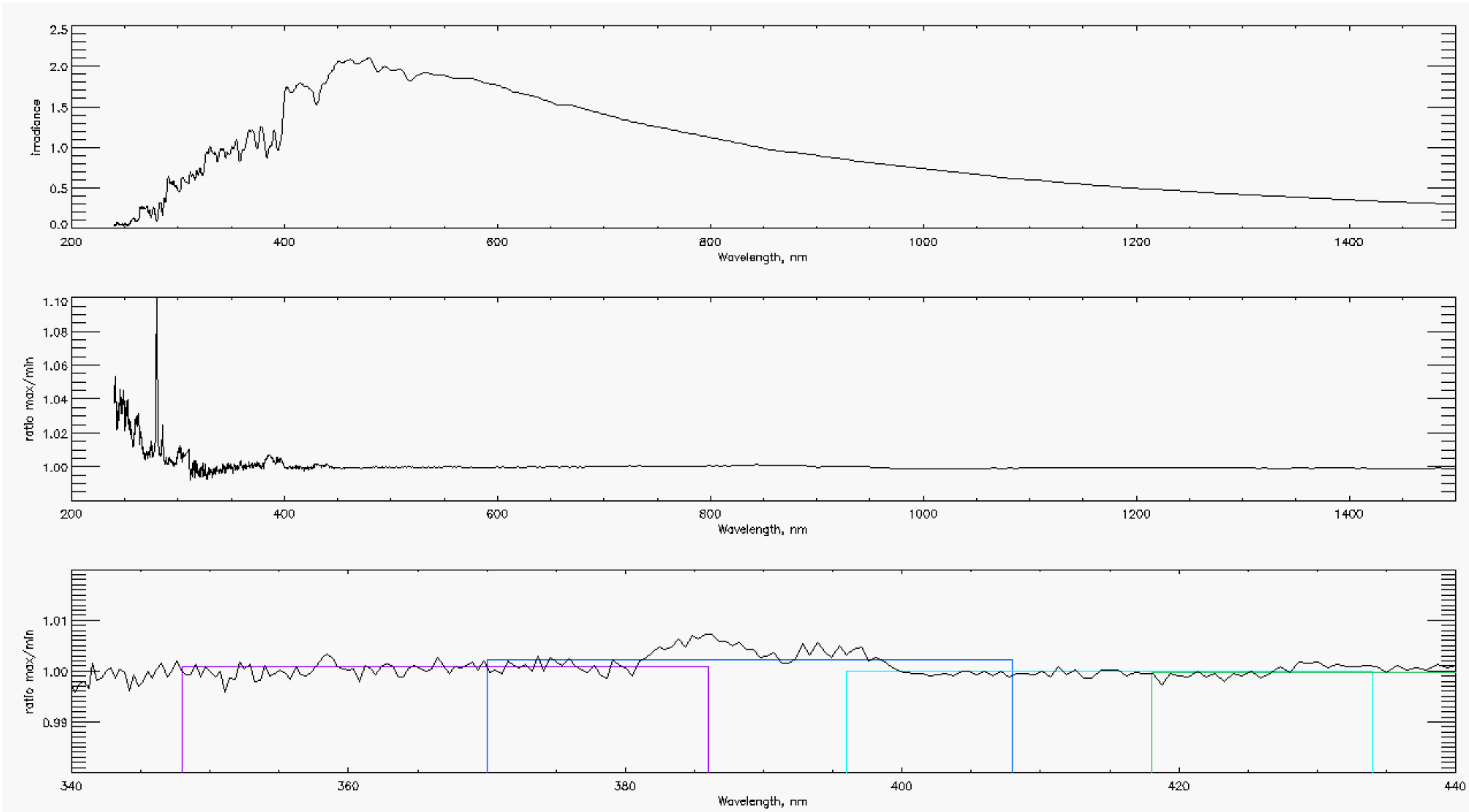
SSI



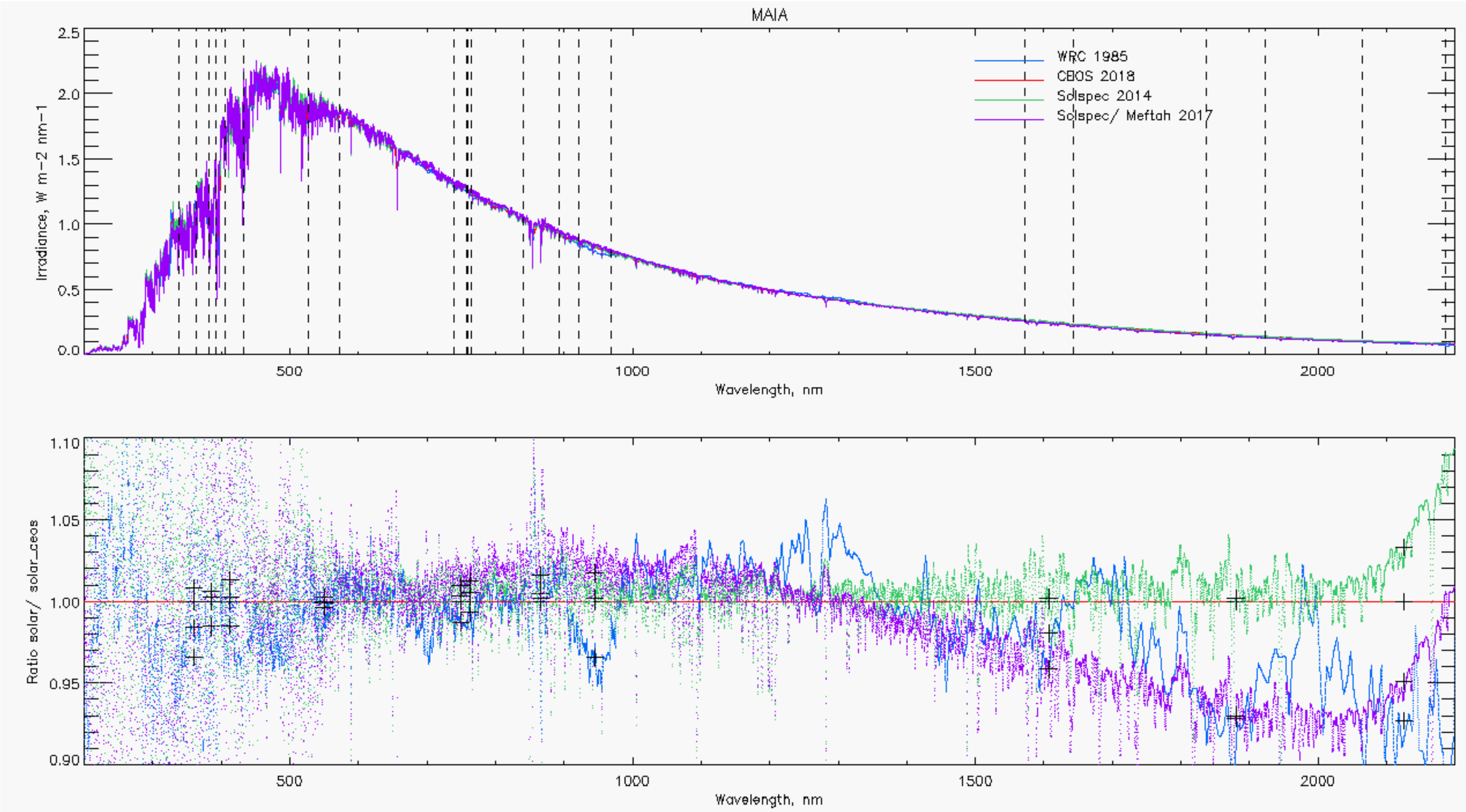
- SSI (Solar Spectral Irradiance) variability between solar maximum and minimum is wavelength dependent.
  - Variability is <1% at wavelengths above 350 nm
  - Strong emission line is Ly-α

Woods, T. N., P. C. Chamberlin, J. W. Harder, R. A. Hock, M. Snow, F. G. Eparvier, J. Fontenla, W. E. McClintock, and E. C. Richard (2009), Solar Irradiance Reference Spectra (SIRS) for the 2008 Whole Heliosphere Interval (WHI), Geophys. Res. Lett.,36, L01101, doi:10.1029/2008GL036373.

Max to min SSI ratio



Comparison of SIRS



OCO-2 SIRS

- Comprised of a pseudo-transmittance spectrum for solar Fraunhofer lines and a solar continuum spectrum. The pseudo-transmittance spectrum is generated from an empirical solar line list developed for the TCCON project (Toon, 2014). This solar line list has been derived by simultaneous fitting of multiple high-resolution ground-based, airborne, and space-borne Fourier transform spectrometer (FTS) solar spectra (Toon, 2014; Toon et al. 2015). The solar continuum model was derived by fitting the low-resolution extraterrestrial solar spectrum acquired by the ATLAS 3 Solar Spectrum (SOLSPEC) instrument (Thuillier et al., 2003).
- References:

  - Thuillier, G., Hersé, M., Labs, D., and Foujols, T., Peetermans, W., Gillotay, D., Simon, P. C., and Mandel, H.: The solar spectral irradiance from 200 to 2400 nm as measured by the SOLSPEC spectrometer from the ATLAS and EURECA missions, Sol. Phys., 214, 1–22, 2003.
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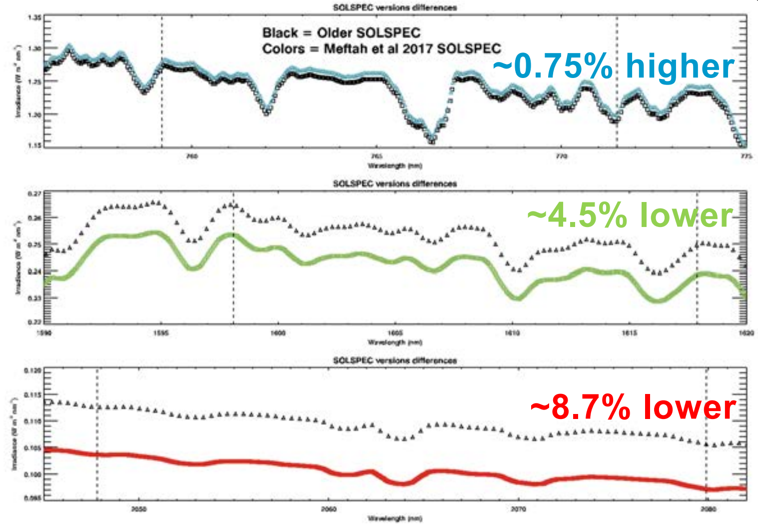
  - Toon, G. C., Blavier, J.-F., Sen, B., Kleinboehl, H., Boesch, H., Sung, K., Nair, H., Frankenberg, C., and Aaron, S.: Improved Solar Reference Spectrum, in: 11th International Workshop on Greenhouse Gas Measurements from Space (IWGGMS), 2015.

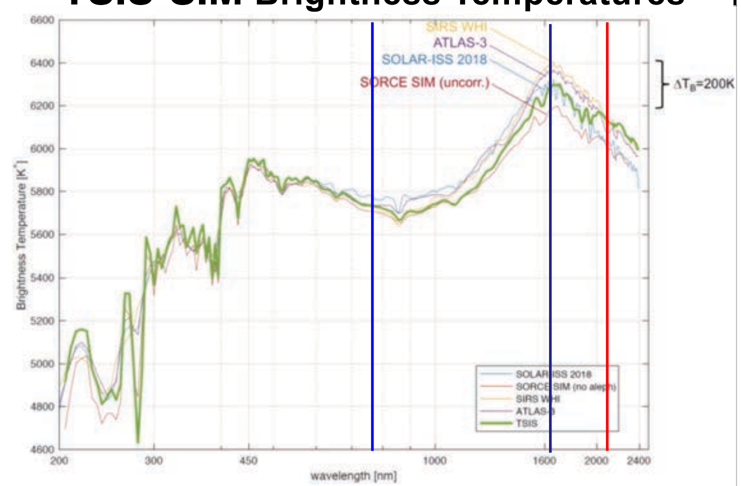
Updates to the Top of Atmosphere Solar Flux

- Accurate estimates of the top-of-atmosphere (TOA) solar flux are critical to X_{CO2} retrievals
- For OCO-2, we construct the solar spectrum by combining a high resolution solar "transmission spectrum" (provided by Geoff Toon) and a continuum derived from the ATLAS 3 SOLSPEC experiment
- Two recent studies have identified biases in the ATLAS 3 SOLSPEC fluxes
  - Reanalysis of the ISS SOLar SOLSPEC observations (Meftah et al. 2018)
  - New data from the ISS TSIS SSI instrument (Richard et al. 2018)
- Both studies show the largest differences in the CO_2 channels

Solar ISS values are:



TSIS-SIM Brightness Temperatures



Largest Differences seen in the SWIR

Open Question regarding SSI Spectra

Margit Haberreiter

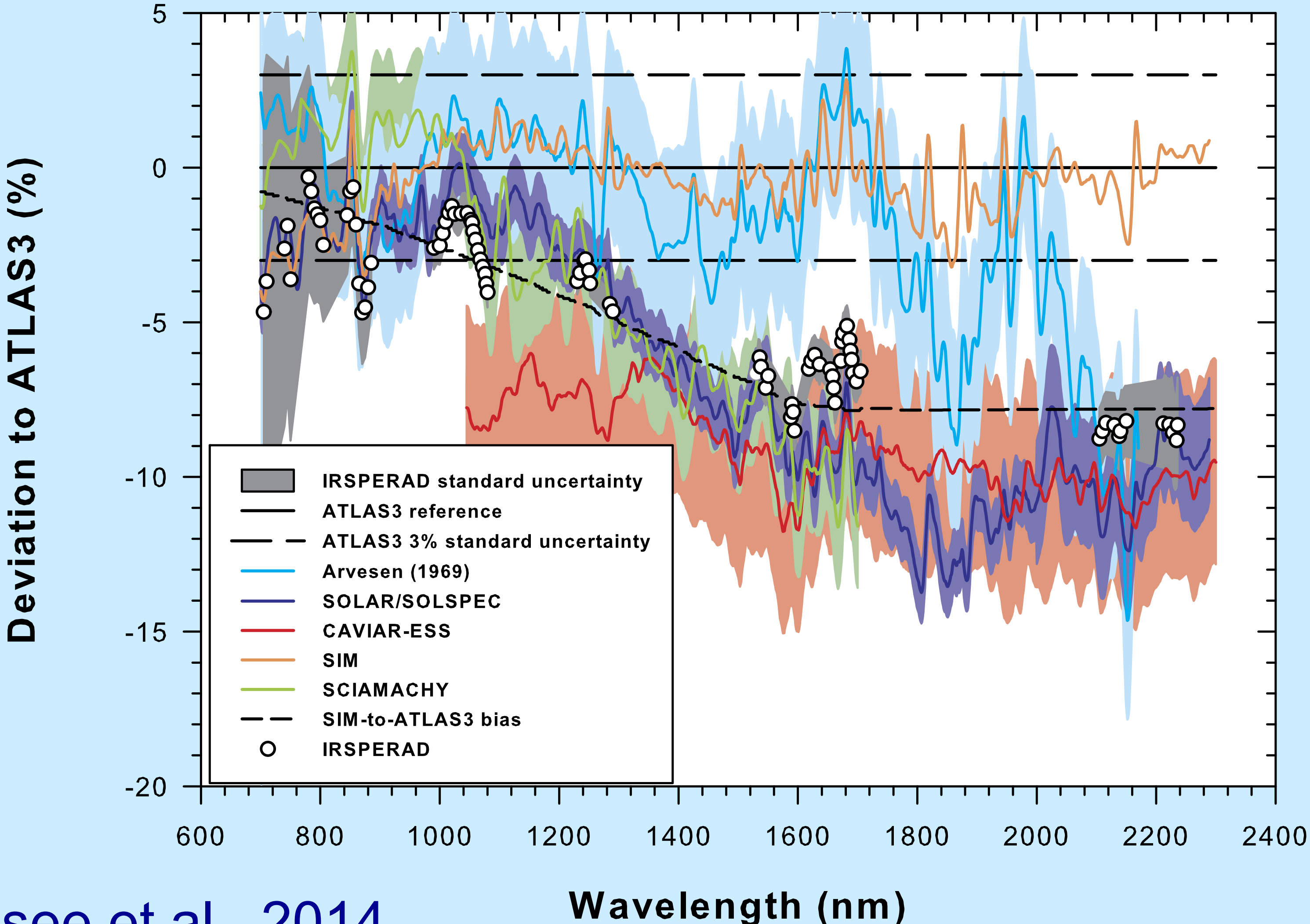
PMOD/WRC

March 27, 2019

Current Reference spectra

1. **ATLAS3 (Thuillier et al., 2004):**
   - **space based measurement**
2. **ISPERAD NIR (Bolsee et al., 2014)**
   - **Bouguer-Langley Technique (ground-based)**
3. **SOLID (Haberreiter et al., 2017)**
   - **composite of space-based measurements**
4. **ISS SOLSPEC1, 2, 2rev (Thuillier et al., 2015)**
   - **space-based measurement**
5. Meftah et al. (2017)
   - Space-based measurement (based on SOLSPEC)

Comparison of spectra versus ATLAS3

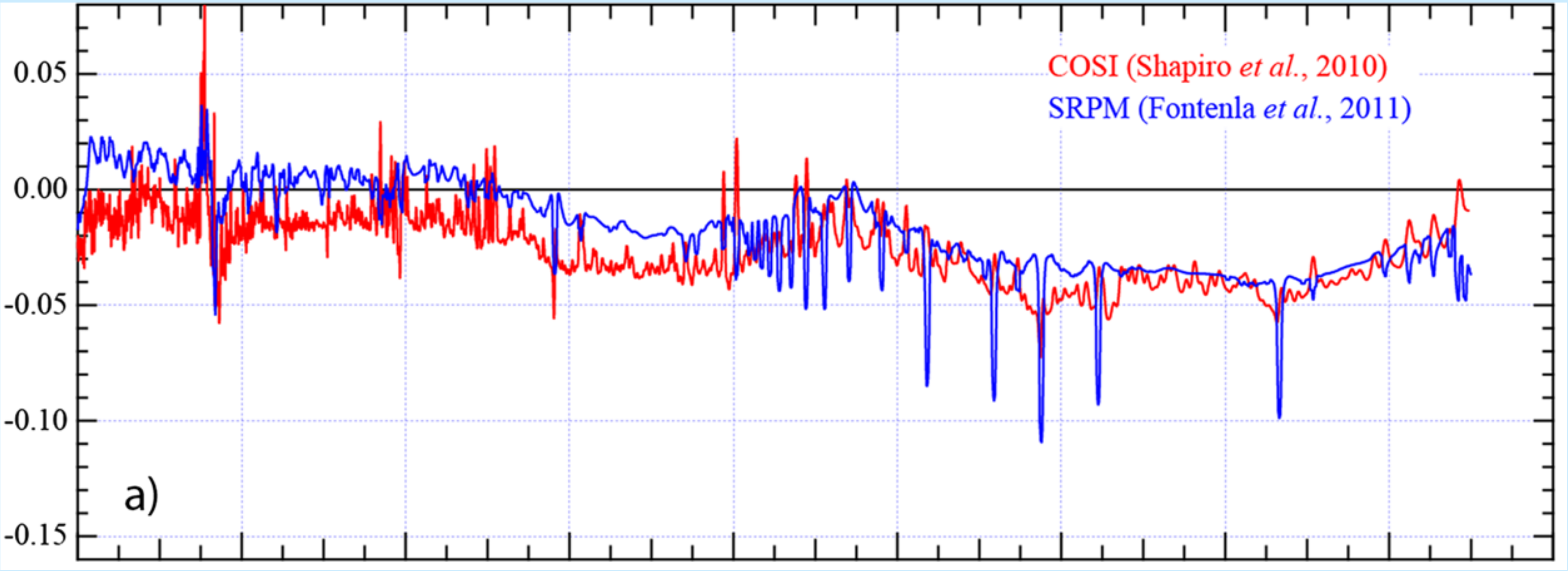


Bolsee et al., 2014

3 Key Points

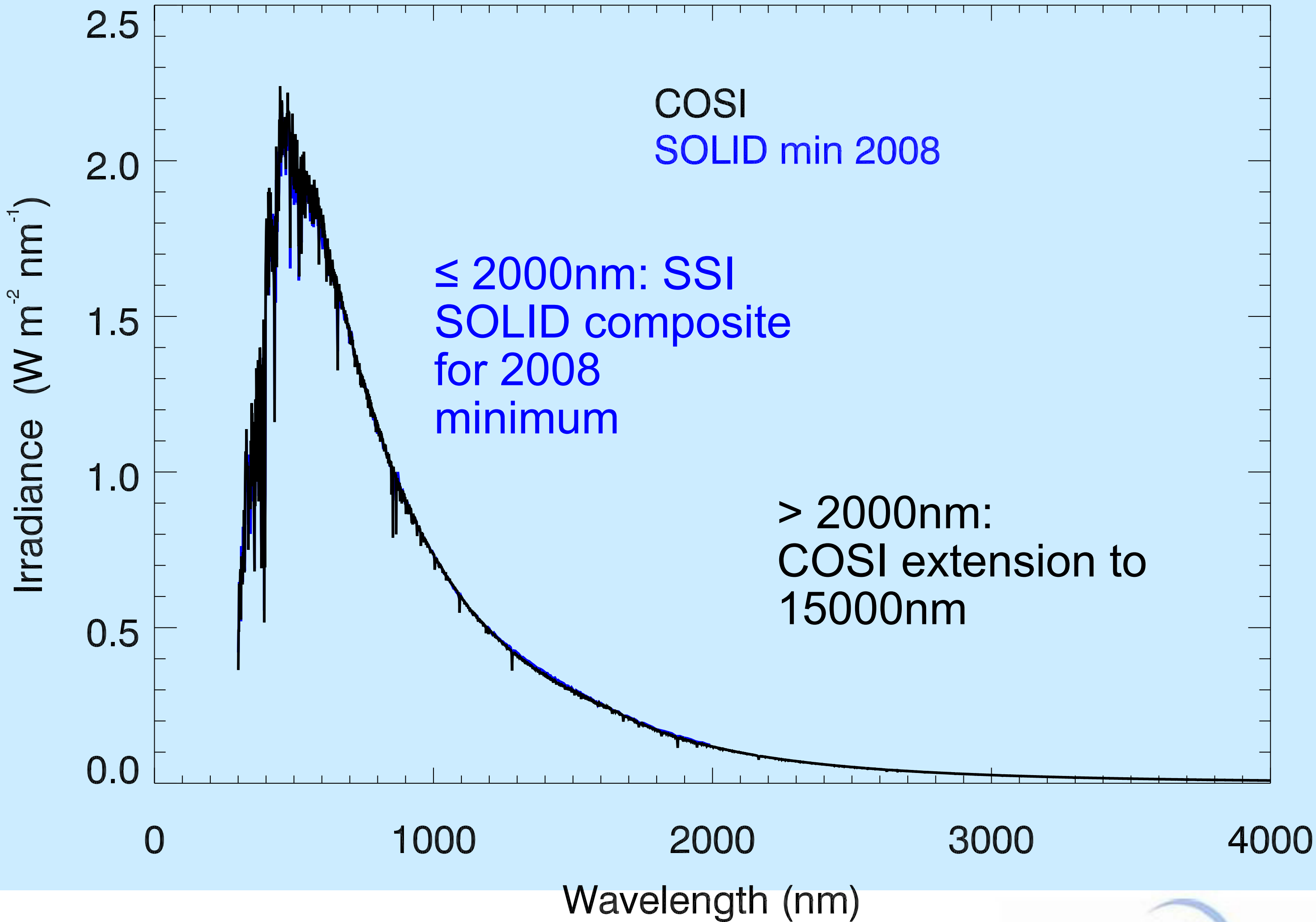
1. Synthetic calculations (COSI, SRPM) of the solar spectrum agree within 5% with ATLAS3 (and SOLID) see e.g. Thuillier et al., 2015
2. The uncertainty of the measurement increases towards longer wavelength (IR), therefore need to be taken with care see e.g. Meftah et al., 2018, Helbig et al., 2018
3. Large deviations of SSI measurements from synthetic spectra in the IR part cannot be explained by theory see e.g. Thuillier et al., 2015

1. Synthetic calculations (COSI, SRPM) agree with ATLAS3

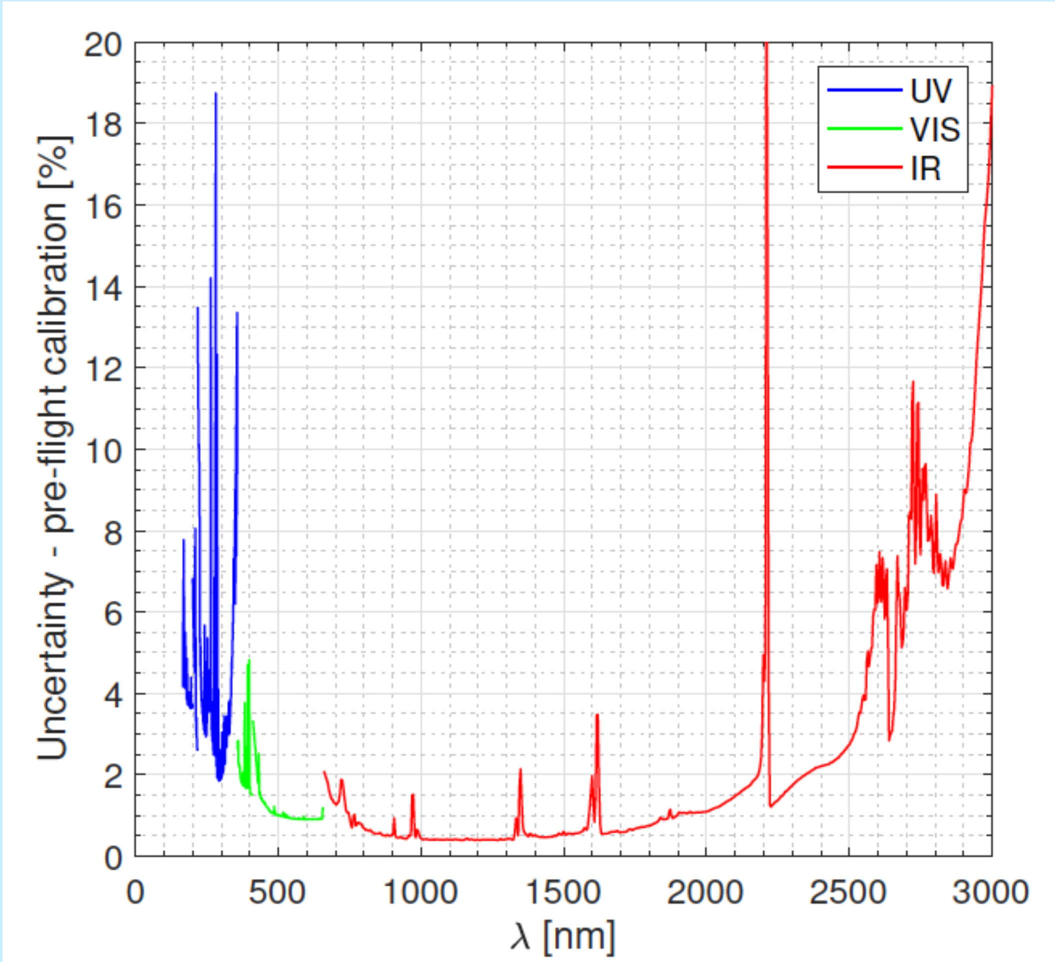


Uncertainty < 5 % (apart from spurious lines in SRPM)
See Thuillier et al. (2015) for details

1. Synthetic calculations (COSI) agree with SOLID

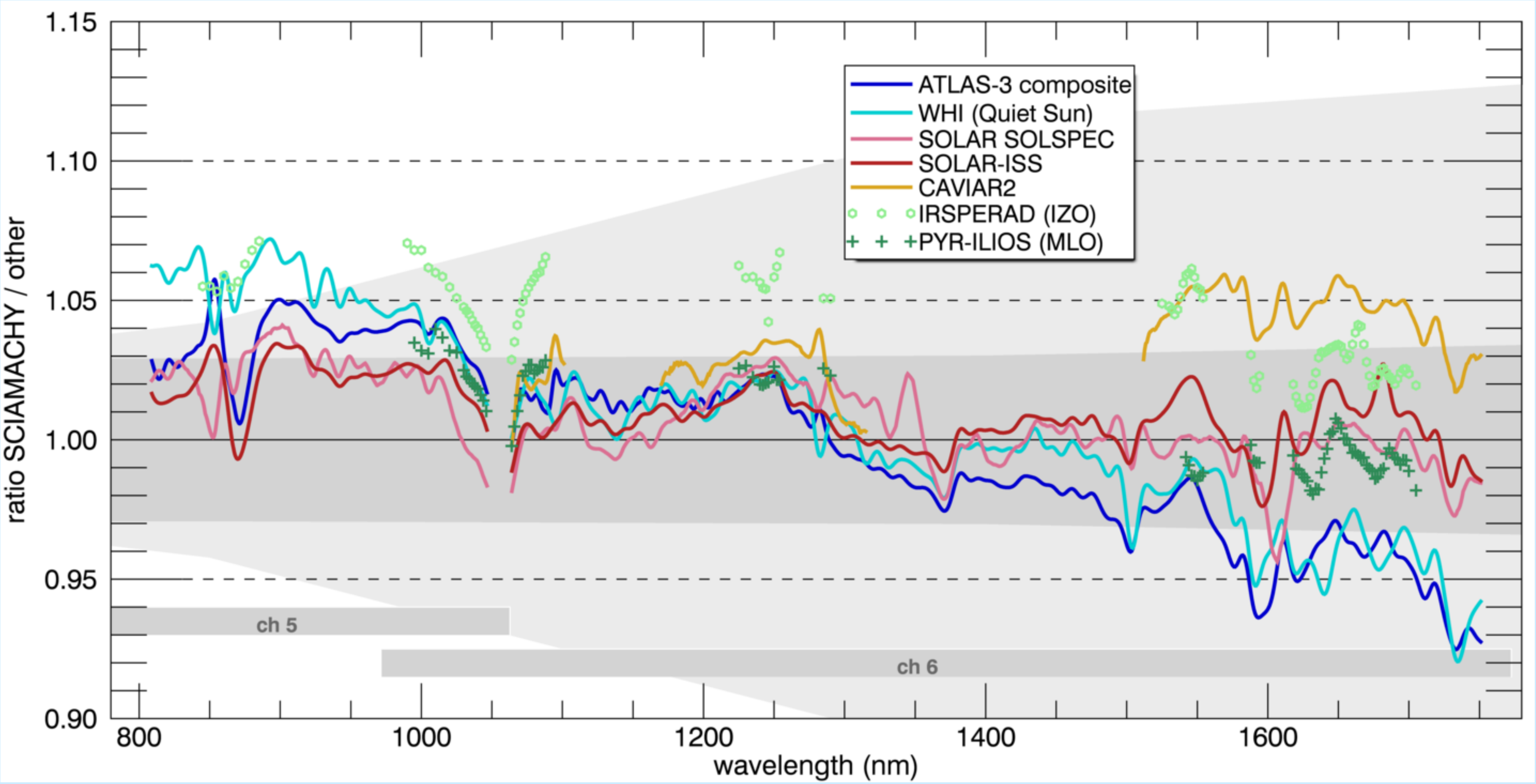


2. Increase of uncertainty towards the IR (e.g. SOLSPEC Data)



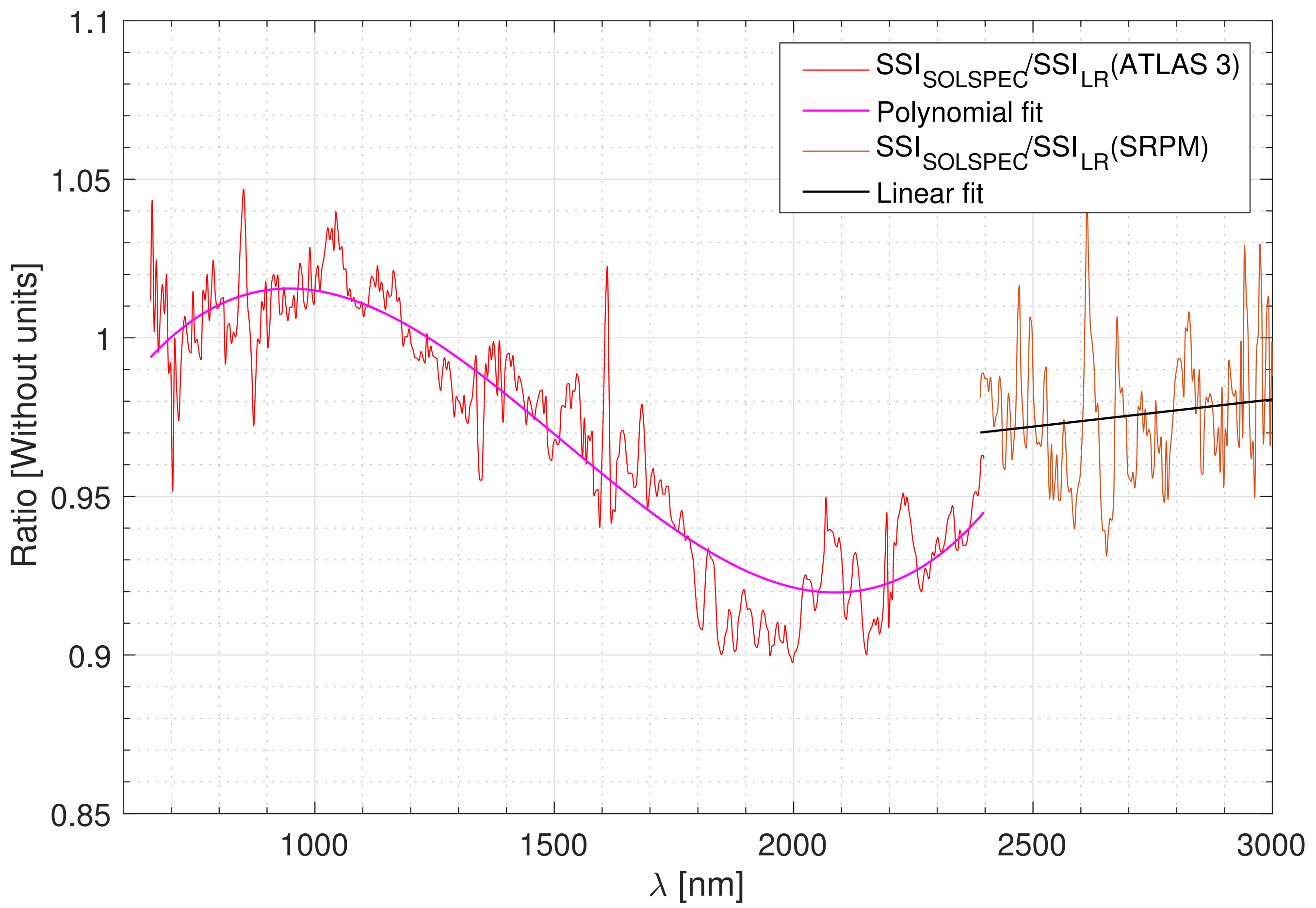
Meftah et al., 2018

2. Increase of uncertainty towards the IR (e.g. SCIAMACHY Data)



Hilbig et al., 2018, Solar Physics

SOLSPEC by Meftah+2018



- large difference in the IR (up to 9%)
- Difficult to explain with theoretical calculations

3. Observed spectrum should be in agreement with theory

- Theoretical calculations take into account:
  – Solar atmosphere structure, Temperature profile
  – Solar abundance, opacities
- In particular the IR part of the spectrum is largely determined by the continuum, i.e. the continuum opacity and the temperature
- If the shape of the IR part of the spectrum is considerably different it cannot be easily reconciled with theory.
- The theoretical calculations agree well with SOLID (also in shape). Therefore they should be considered as the spectrum to be recommended (unlessthey can be proven wrong from a theoretical point of view).

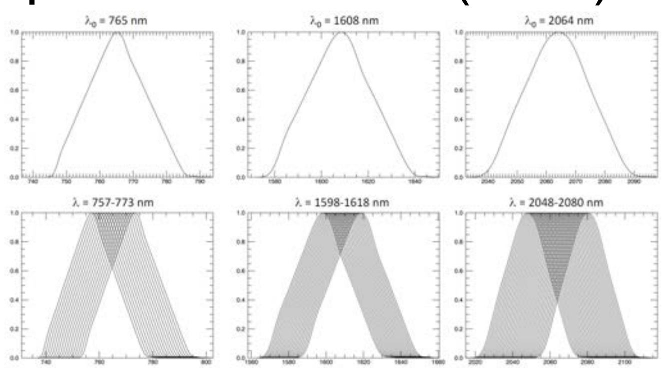
Conclusion

- SSI observations show a large uncertainty in the IR (Thuillier et al., 2015, Helbig et al. 2018, Meftah et al., 2018), therefore need to be taken with care
- A decrease by 9-10% from the ATLAS or SOLID spectrum cannot be reconciled with modelled spectra (COSI, SRPM) as it would contradict the current knowledge of the temperature profile and opacities in the solar atmosphere;
- TSI is an important boundary condition and needs to be fulfilled. If the IR is considerably lower (by a few W/m^2) in the IR, this needs to be compensated at other wavelegths. SOLID is constrained to the latest TSI values by Schmutz+ and Kopp+
- Based on these considerations, SOLID is considered to be more correct in the IR

Adjusting the OCO-2 Solar Continuum

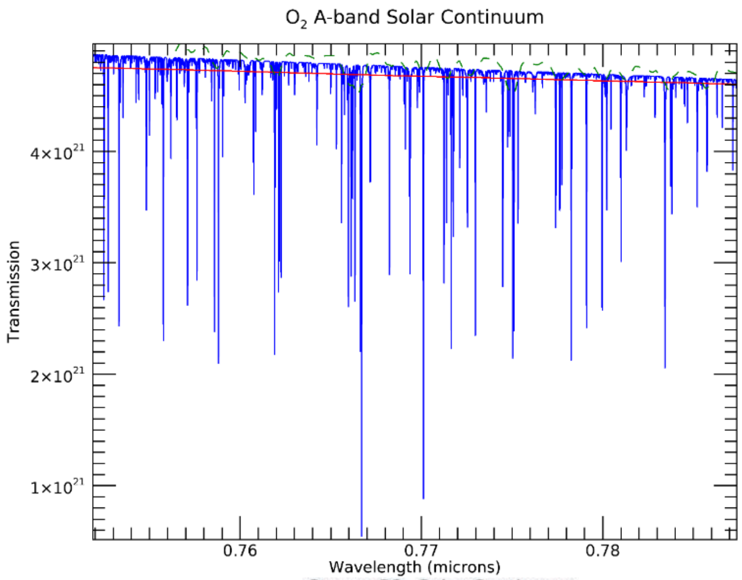
Approach:

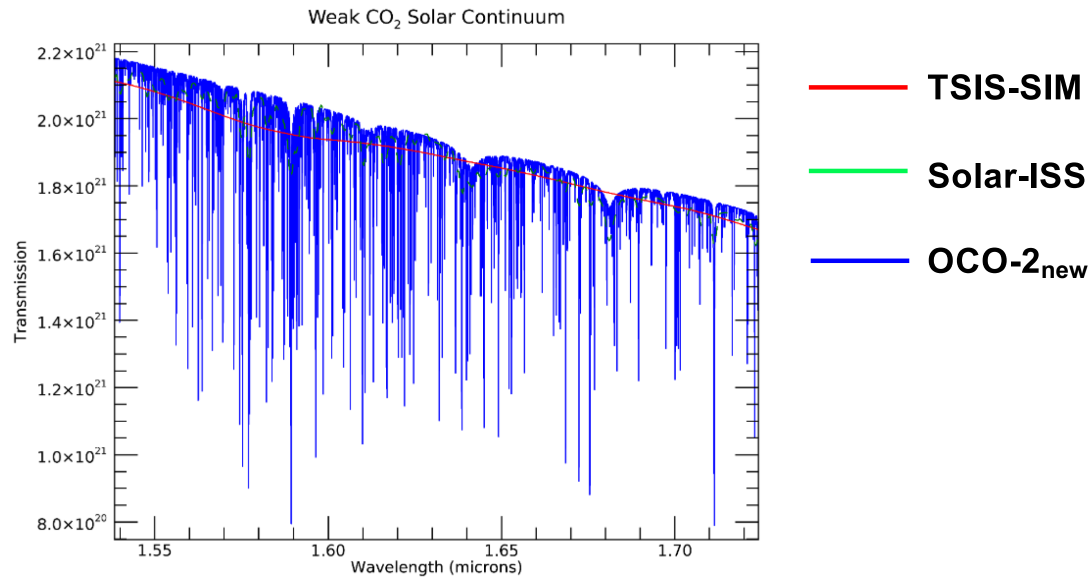
- Current OCO-2 solar spectral continuum in each channel (v6/v7/v8) was compared to the Solar-ISS solar spectra recently received from Meftah et al. and the TSIS-SIM solar spectra from Richard et al.
  - The TSIS-SIM values were adopted as the standard here
- The OCO-2 continuum values were:
  - Scaled by a multiplicative offset and slope (offset + slope*(λ-λ_{min})),
  - Multiplied by the high resolution transmission spectrum
  - Convolved with the TSIS-SIM Spectral Response Function (SRF)
- Plotting convention in plots that follow:
  - Original OCO-2 L2 continuum plotted in g
  - Scaled continuum plotted in black
  - TSIS-SIM plotted in red
  - Solar-ISS plotted in green
  - High-res OCO-2 solar spectra (blue)

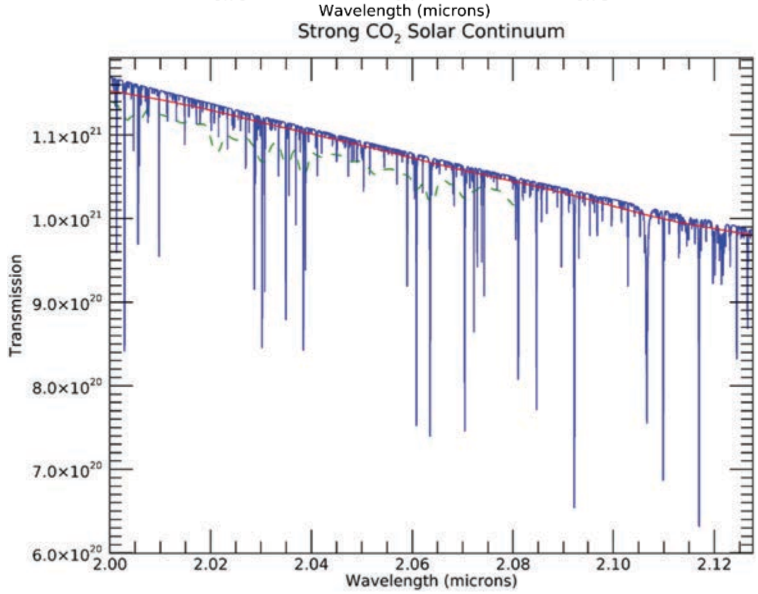


TSIS-SIM SRF

Solar Spectral Databases

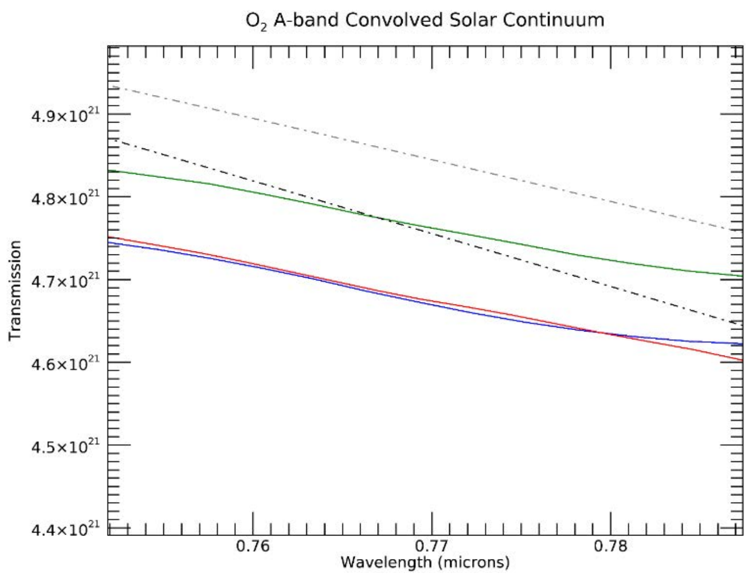


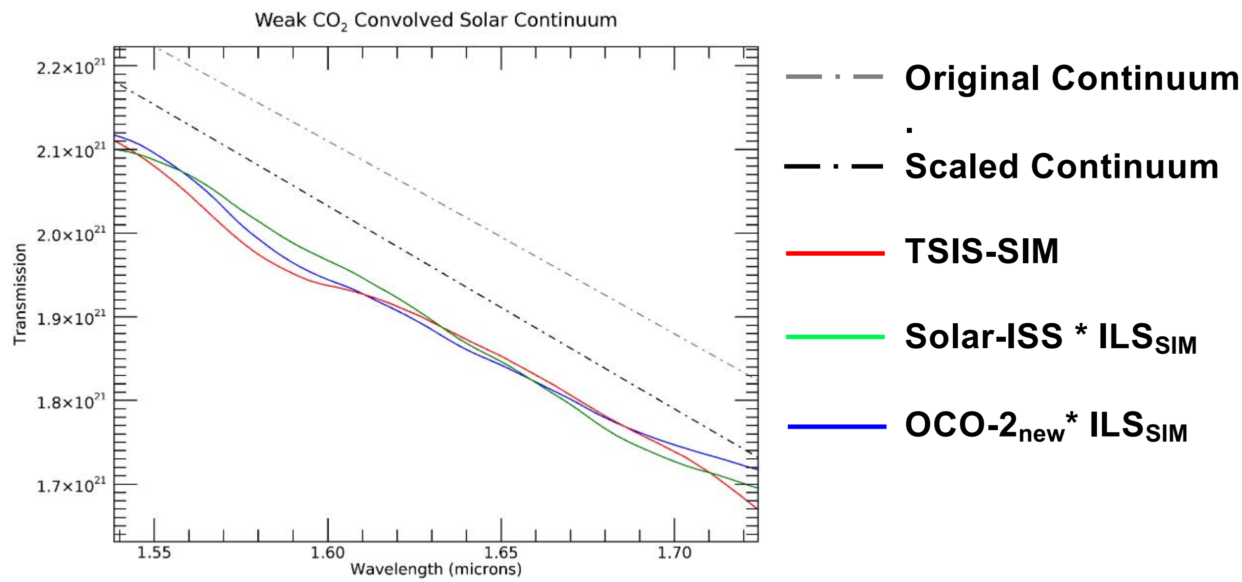


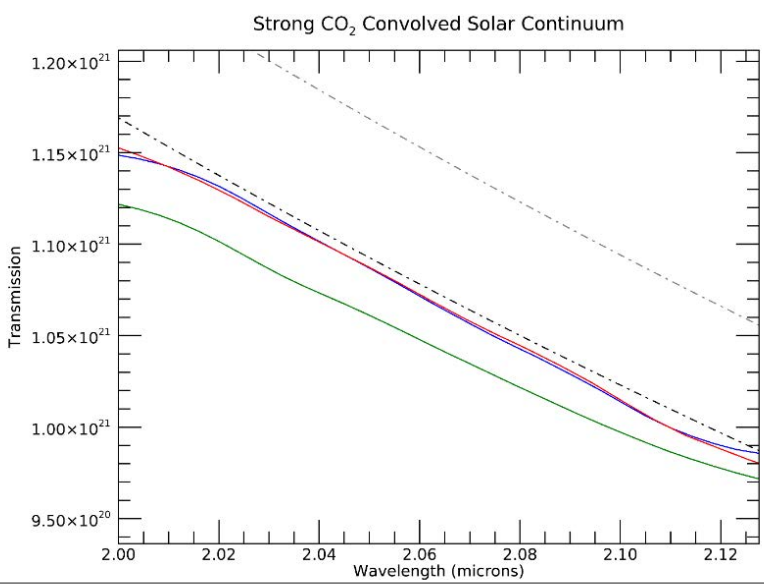


The OCO-2 continuum was scaled and then multiplied by the high-resolution solar line spectrum to produce a high resolution solar spectrum (blue). This spectrum is compared to the TSIS-SIM (red) and Solar-ISS spectrum (green) in each channel. The ABO2 and WCO2 channels have far more strong solar lines than the SCO2 channel.

Spectrally-Convolved Results







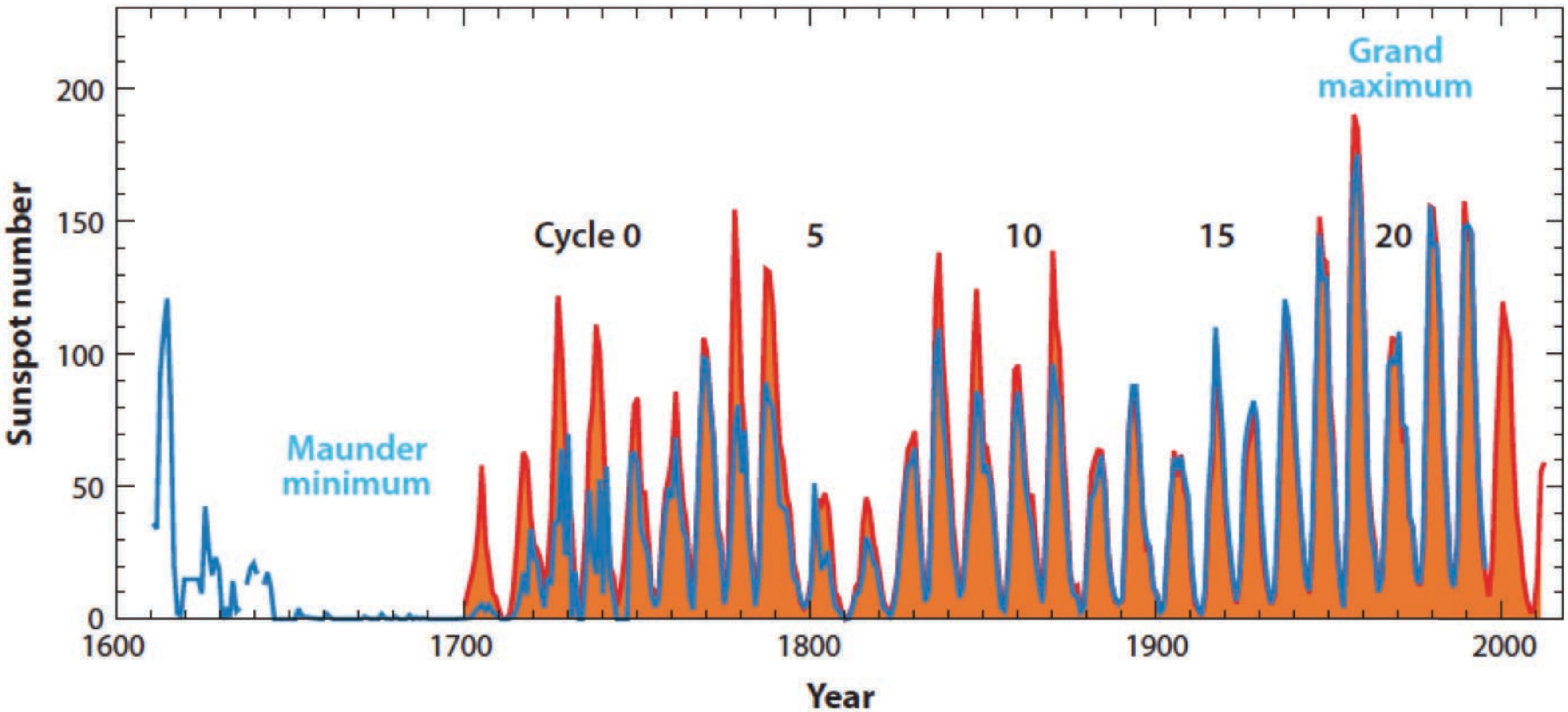
The OCO-2 high resolution solar spectrum with the scaled continuum was convolved with the TSIS-SIM spectral response function (SRF, blue) and compared to the TSIS-SIM (red) and the Solar-ISS spectrum (also convolved with the TSIS-SIM SRF (green)) to validate the scaled values.

Summary of Solar Flux Results

OCO-2 Continuum Scaling Factors:

- ABO2 Scaling:
  - $(0.987 - 0.3\ \Delta\lambda) \times F_{c(old)}$, $\Delta\lambda = (\lambda - \lambda_{min})$, $\lambda_{min} = 0.751880\ \mu m$
- WCO2 Scaling:
  - $(0.97 - 0.11\ \Delta\lambda) \times F_{c(old)}$, $\Delta\lambda = (\lambda - \lambda_{min})$, $\lambda_{min} = 0.\ 1.53846\ \mu m$
- SCO2 Scaling:
  - $0.935 \times F_{c(old)}$, No slope correction needed
- With these scaling factors, the OCO-2 solar spectrum produces better fits the TSIS-SIM spectrum
- These tests also revealed systematic differences between the TSIS-SIM and Solar-ISS standards:
  - Solar-ISS results are ~1.6% higher than TSIS-SIM at 0.765 μm
  - Solar-ISS and TSIS-SIM results are comparable at 1.61 μm
  - Solar-ISS results are 2.5% lower than the TSIS-SIM near 2.06 μm

Sunspot records



Sunspot activity has been recorded since 1610, one year after the invention of the telescope. Solar cycle lasts between 8 and 14 years, with an average length of approximately 11.2 years. Cycle amplitudes vary even more strongly, with the weakest known cycle (starting around 1700) being less than 10% in strength of the strongest cycle, cycle 19. The between the cycles the sunspot number reaches nearly zero. The "Grand minima" periods, such as the Maunder minimum between 1640 and 1700, occur in the "Little Ice Age" period 1450 to 1820.

Sunspots are the result of magnetic activity, which result in charged particles being emitted, and increased UV and VIS. Thus, altough sunspots are dark, they are correlated with an increase in SSI.

Solar models

- Solar models based on magnetic features have been successful in explaining irradiance changes.
- "Proxy models" combined proxies of solar surface magnetic features using regressions to match observed TSI changes. Proxies include the photometric sunspot index (PSI) derived from it (a measure of sunspot darkening), as well as MgII, CaII, and F10.7 used as an indicator of facular brightening.
  - The widely used MgII index is the ratio of the brightness in the cores of the MgII lines to their wings, making it relatively insensitive to instrumental degradation with time
  - More accurate proxy models employ spatially resolved observations of the full solar disc, which account for the center-to-limb variation of spot and facular contrasts
- Physical models still use proxies, but the brightness of each solar component is calculated using radiative transfer codes from semiempirical models of different features in the solar atmosphere. This has the advantage of estimating the changes in SSI.
  - A successful example is the SATIRE-S (Spectral and Total Irradiance Reconstructions for the Satellite era) model employing daily solarmagnetograms and continuum images (Ball et al. 2012, Krivova et al. 2003, Wenzler et al. 2006).

References

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Conclusion

- The uncertainty in the SSI at solar minimum is larger than its variability throughout the solar cycle.
  - The uncertainty in a model, such as the SOLID SIRS is on the order of 2-3%
  - The spectral relative uncertainty is on the order of 0.2%
- As improvements in preflight calibration, on-orbit calibration maintenance, and physical models improve, this uncertainty is expected to decrease with time.