# High Resolution Reference Solar Spectrum for TEMPO/GEMS and beyond

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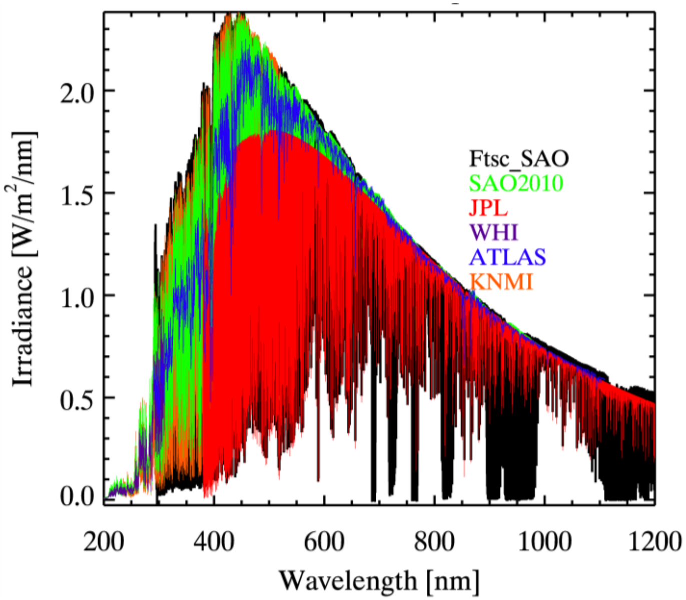
# Reference Solar Spectra

- No absolutely calibrated solar reference spectrum from single source due to limitations
  - Differs depending on the sources of data (sampling, resolution, SRF and accuracy)

- High resolution reference solar spectrum is important for the calibration of the hyperspectral instrument such as TEMPO and GEMS

- As the calibration is sensitive to the choice of high resolution solar reference, we would like to improve over existing high resolution reference spectra

Reference Solar Spectra



# Reference Solar Spectra

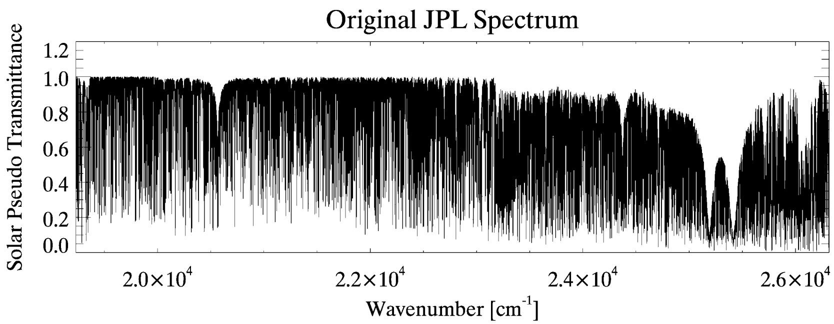
- Reference solar spectra available for TEMPO/GEMS
  - Considering the radiometric, spectral accuracy, spectral sampling and resolution for TEMPO & GEMS (high-resolution spectrometer)
    - ✓ Few high-resolution reference spectra are available

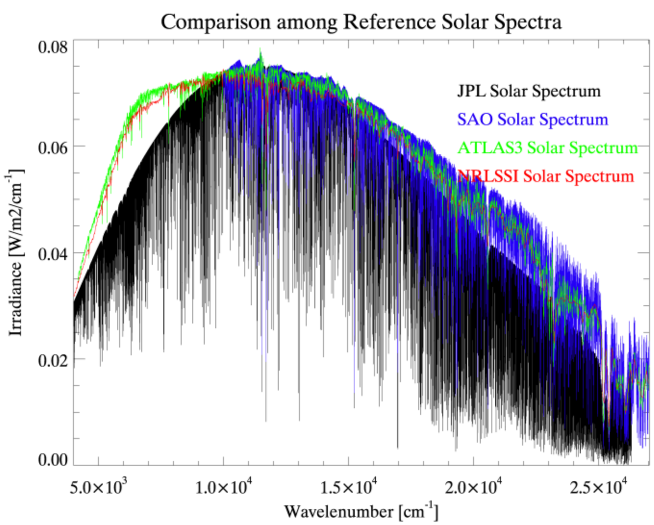
Table. Examples of currently available reference solar spectra and their characteristics

| | Spectrum | Wavelength range [nm] | Spectral resolution [nm] | Spectral sampling [nm] | Uncertainty [%] | references |
|---|---|---|---|---|---|---|
| Low resolution references | NRLSSI2 | 115.50-99999.50 | 1.00 | 1.00 | 2-4 | Coddington *et al*. (2015) |
| | ATLAS | 120.00-2400.00 | 0.25-0.50 | 0.05-0.60 | 2-4 for 120-2400 nm | Thuillier *et al*. (2004) |
| | WHI | 0.10-2400.00 | 1.00-30.00 | 0.01 | 2-4 for 116-2400 nm | Woods *et al*. (2008) |
| High resolution references | **KNMI** | 235.00-520.00 | 0.025 | 0.01 | <4 for 300-500 nm | Dobber *et al*. (2008) |
| | **SAO2010** | 200.07-1000.99 | 0.04 | 0.01 | < 5 for 300 -1000 nm | Chance and Kurucz (2010) |
| | **Ftsc SAO** | 293.00-1626.57 | | 0.003 | | Chance and Kurucz (2010) |
| | **JPL (transmittance)** | 380.00-2400.00 | | 0.00014 | | Toon (2014) |

# Reference Solar Spectra

- JPL transmittance
  - Newly derived solar linelist
  - Very high resolution (0.01 $cm^{-1}$) with broad wavelength range (600-26316 $cm^{-1}$ , 2400 -378 nm)
  - not radiometrically calibrated



# Spectral Calibration

- Sensitivity tests for GEMS wavelength calibration

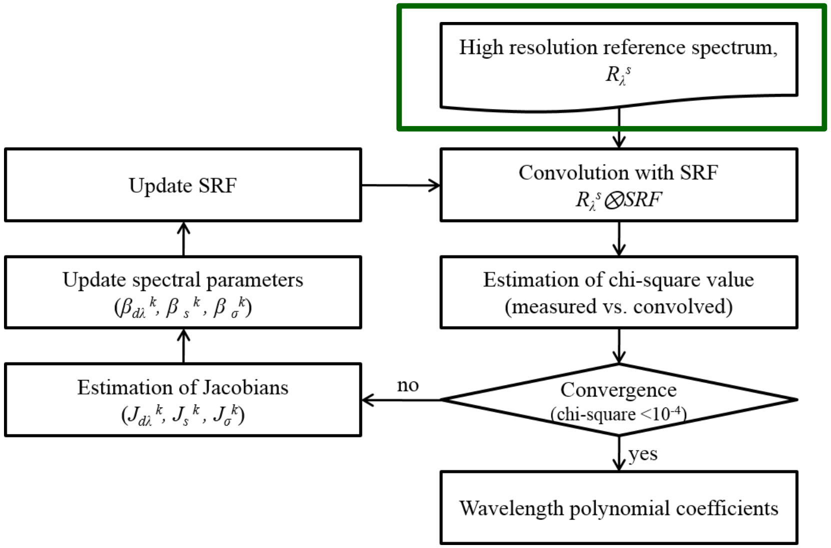



Figure . Flow chart of spectral calibration algorithm for GEMS

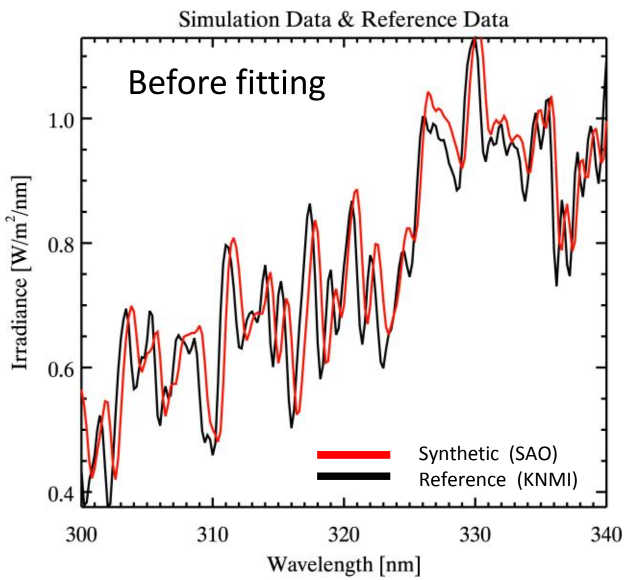
- Tested for the GEMS ozone retrieval range (300 to 340 nm)
- Input perturbation

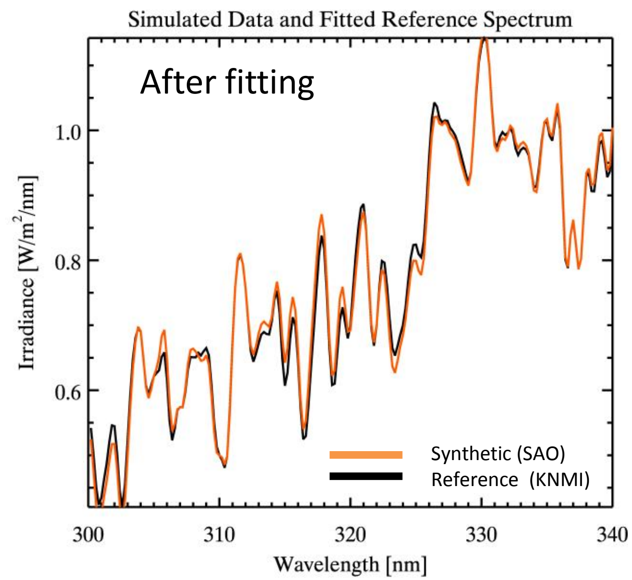
| Shift | Squeeze | FWHM |
|---|---|---|
| 1 (%) | 0.5 (%) | +0.1 (nm) |

- Considered spectral parameters
  - ✓ Reference solar spectrum
  - ✓ SRF
  - ✓ SNR
- Check the algorithm performance due to uncertainty of spectral parameter

# Spectral Calibration

- What if we use a different reference spectrum?




| Algorithm input | | | | | Algorithm output | | | |
|---|---|---|---|---|---|---|---|---|
| Shift | Squeeze | FWHM | Ref. Solar spectrum | True solar spectrum | Shift | Squeeze | FWHM | Chi square |
| -0.0100 | 0.0050 | 0.7000 | SAO2010 | SAO2010 | -0.0102 | 0.0050 | 0.6987 | $5.456e^{-6}$ |
| -0.0100 | 0.0050 | 0.7000 | KNMI | KNMI | -0.0102 | 0.0050 | 0.6989 | $4.887e^{-6}$ |
| -0.0100 | 0.0050 | 0.7000 | SAO2010 | KNMI | -0.0132 | 0.0050 | 0.6988 | $2.563e^{-4}$ |
| -0.0100 | 0.0050 | 0.7000 | KNMI | SAO2010 | -0.0068 | 0.0050 | 0.7018 | $2.751e^{-4}$ |

# Spectral Calibration

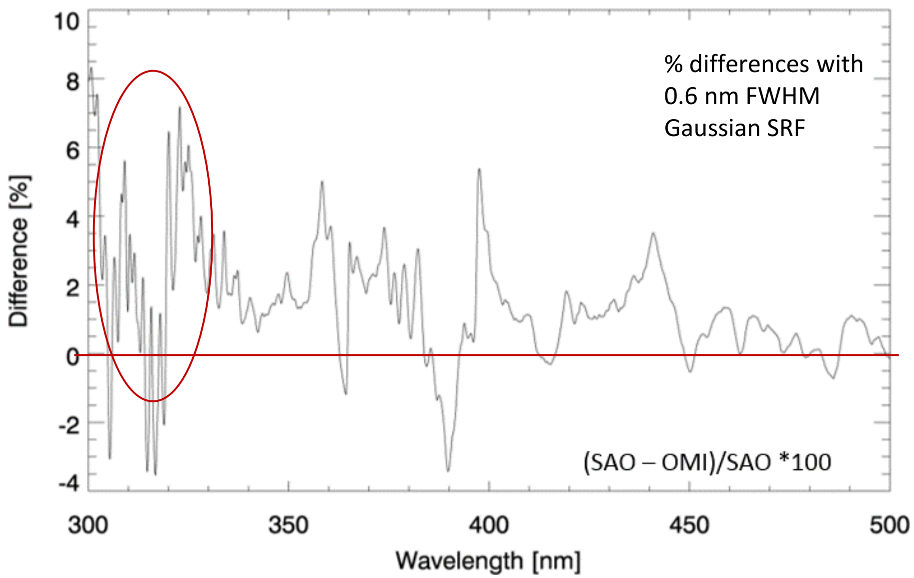
- Sensitivity tests results
  - It is highly sensitive to the reference solar spectrum
    - ✓ Due to the uncertainty of reference solar spectrum,
      - Calibration performance could be considered as lower than actual performance
      - The derived shifts could be different from actual wavelength variability
    - ✓ Minimum chi-square value increases more than an order

| Algorithm Input | | Algorithm Output | |
|---|---|---|---|
| Reference spectrum | Assumed measurement | $X^2$ ($e^{-6}$) | ΔR (%) |
| KNMI | KNMI | 4.89 | 0.012 |
| SAO2010 | SAO2010 | 5.46 | 0.014 |
| KNMI | SAO2010 | 275 | 0.077 |

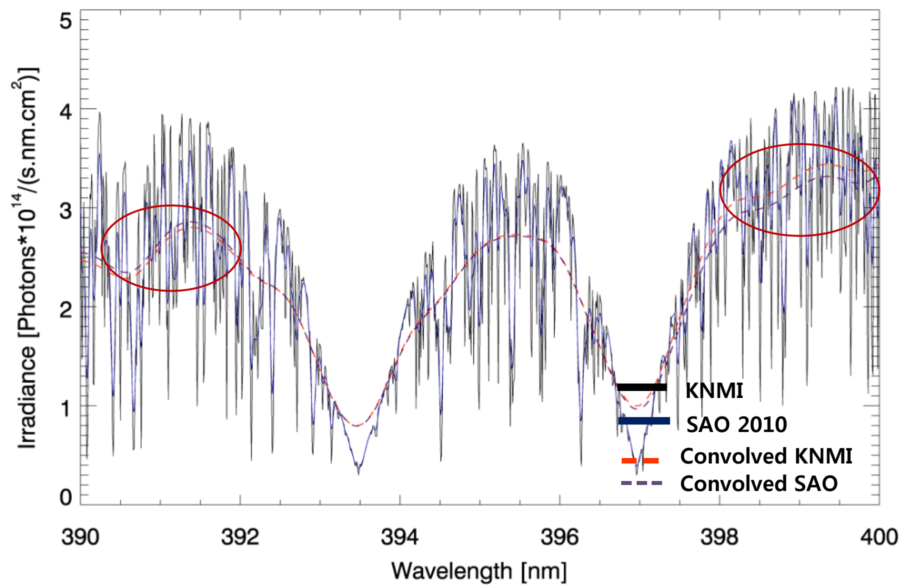
(ΔR is mean differences of radiance)

# Current References

- SAO2010 vs. KNMI reference spectrum
  - There are non-negligible differences between the two at TEMPO/GEMS resolution (FWHM = 0.6 nm)



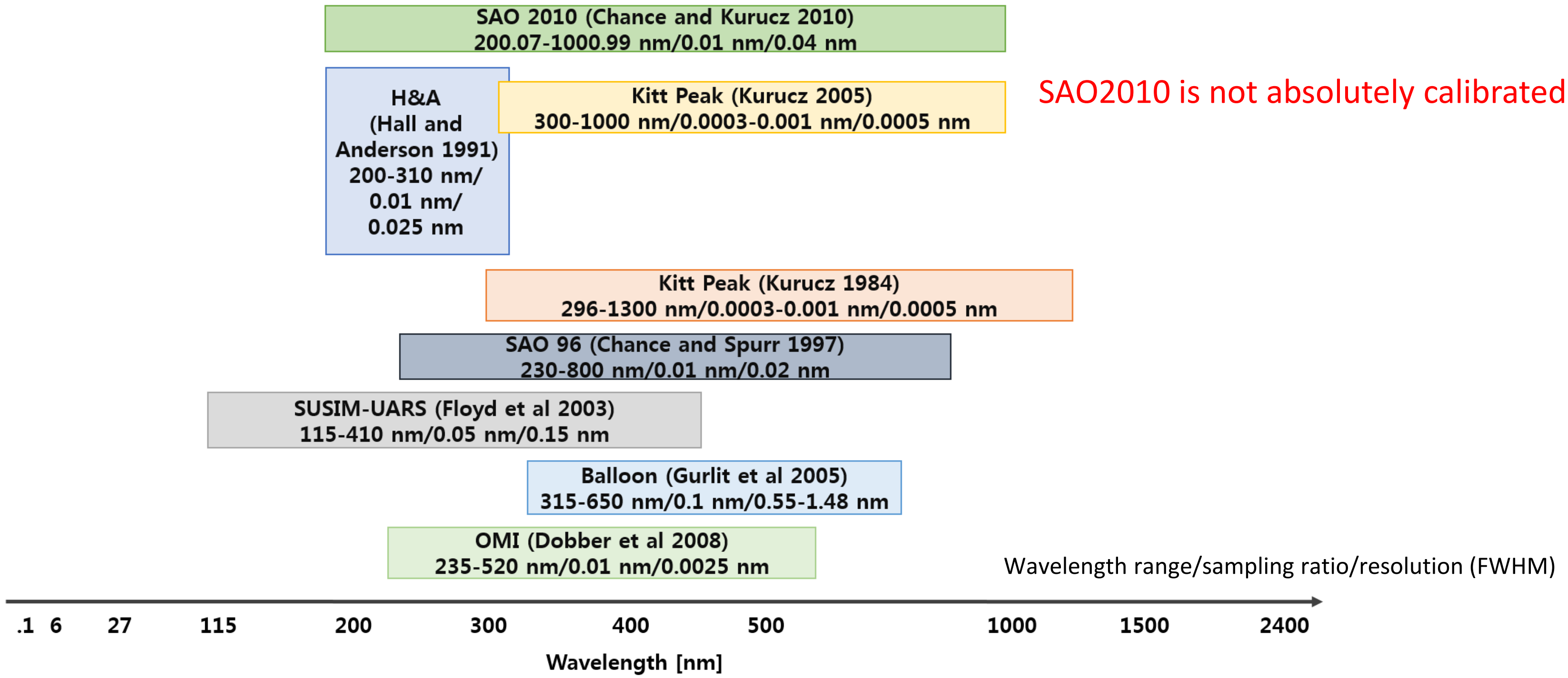

Differences between SAO2010 and KNMI (FWHM= 0.6 nm)




Comparison between SAO2010 and KNMI at initial resolution and lower resolution (FWHM= 0.6 nm)

# Current References

- SAO2010 vs. KNMI reference spectrum
  - Differences between two are mainly caused by using of the different data sources



# Requirements for Update

- Preparation of reference spectrum for TEMPO/GEMS
  - TEMPO/GEMS top-level requirement

| | TEMPO | GEMS |
|---|---|---|
| Observational Range [nm] | 290 -740 | 300 - 500 |
| Spectral Sampling [nm] | 0.2 | 0.2 |
| Spectral Resolution [FWHM, nm] | 0.6 | 0.6 |

  - Reference solar spectrum requirement
    - ✓ Absolute radiometric accuracy < 3-4% (Dobber et al.,2008)
    - ✓ Original spectral resolution > TEMPO/GEMS resolution
    - ✓ Fully *Nyquist* sampled (Chance et al.,2010)

**SAO2010 and JPL (over 380 nm) are only great references for TEMPO&GEMS and beyond after calibration with low resolution (WHI below 310 nm & ATLAS over 310 nm)!!**

# Method

- Updating SAO2010/JPL

  ① **Fitting the SAO2010/JPL** with reference (WHI/ATLAS) to obtain SRF of reference & scaling factors;
  **same spectral feature**

  ② Convolution of the SAO2010/JPL spectrum with the derived function ;**same spectral resolution**

  ③ Calculating the ratio between convolved spectrum with reference (R)

  ④ Obtaining the new convolved SAO2010/JPL applied ratio (R’) to SAO2010/JPL;

  new convolved SAO2010/JPL
  = convolved SAO2010/JPL * R

1. *Spectral fitting* (OE method)

$$I_{ref} = \frac{\int I_{SAO}\phi_{ref}\,d\lambda}{\int \phi_{ref}\,d\lambda} \times scaling\ factors$$

2. *Obtain SAO to reference grid & resolution*

$$I_{SAO'} = Regrid\left[\frac{\int I_{SAO}\phi_{ref}\,d\lambda}{\int \phi_{ref}\,d\lambda}\right]$$

3. *Calculate ratio*

$$R_{low} = \frac{I_{ref}}{I_{SAO'}}$$

4. *Obtain Ratio to SAO grid & resolultion*

$$R_{high} = Regrid(R_{low})$$

5. *Obtain updated SAO*

$$I_{new\ SAO} = I_{SAO} \times R_{high}$$

Figure. Process for updating SAO2010

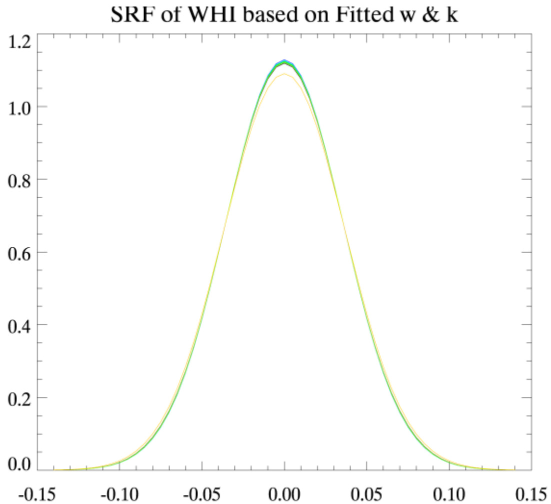
# Method

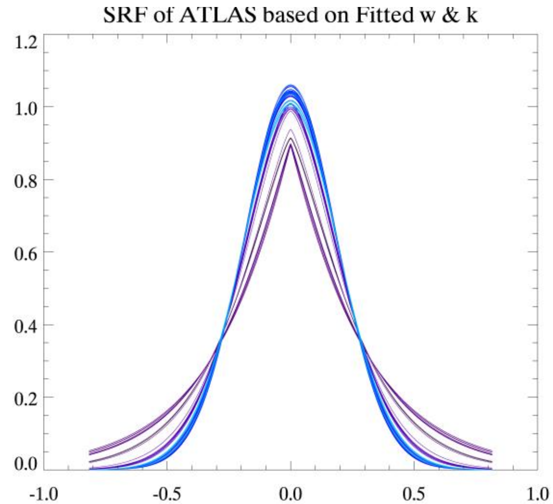
- Deriving the SRF of references based on Super-Gaussian function (Beirle et al.,2016)

$$1.\, Spectral\ fitting\ \text{(OE method)}$$
$$I_{ref} = \frac{\int I_{SAO}\phi_{ref}\, d\lambda}{\int \phi_{ref}\, d\lambda} \times scaling\ factors$$

$$\boldsymbol{S(x) = \frac{k}{2\varpi\Gamma(1/k)} e^{-\left|\frac{x}{\omega}\right|^{k}}}$$

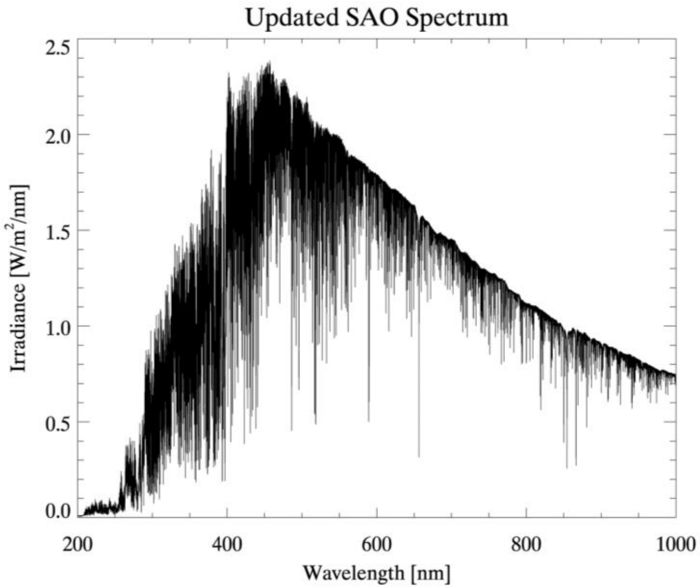
ϖ is for the width k is for the shape of S



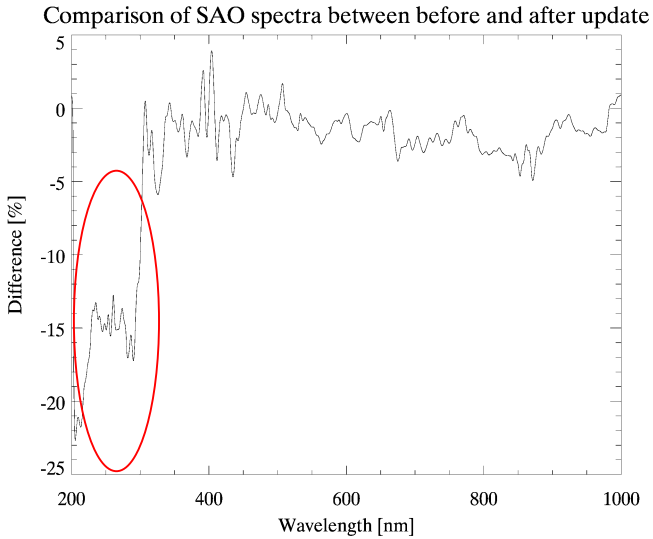



# Result

- A significant improvement in the shorter wavelength range is evident




Updated SAO spectrum




Comparison between before and after update
$(= \frac{updated\ SAO2010 - SAO2010}{updated\ SAO2010} * 100(\%))$

# Result

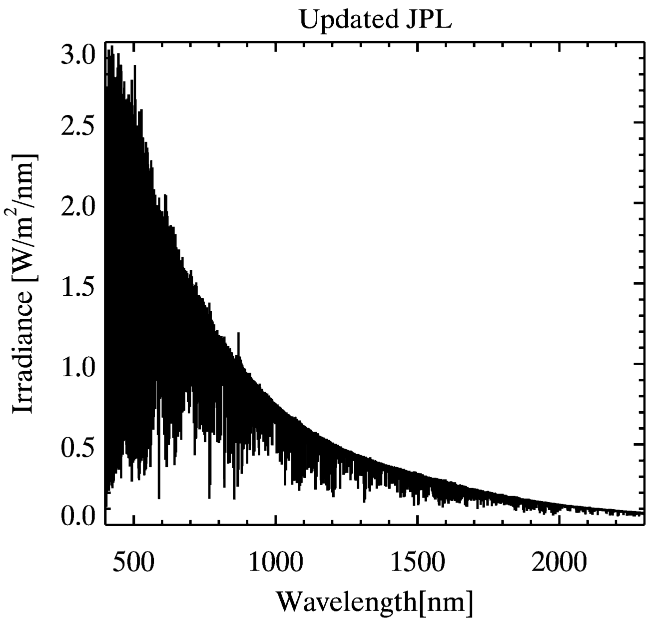
- Comparison new SAO2010 with other reference solar spectra
  - Increased consistency among the spectra with the decreased mean radiometric differences

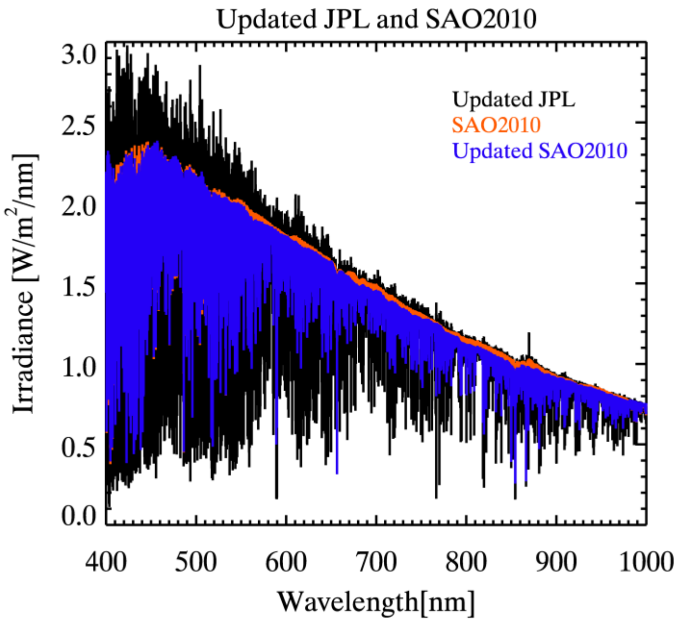
Comparison among reference spectra for 300 -500 nm range at FWHM 1.0 nm

| Reference Spectrum | Correlation Coefficient | Mean Radiometric Differences [%] |
|---|---|---|
| SAO2010/NRLSSI2 | 0.9659 | 1.7275 |
| SAO2010/ATLAS3 | 0.9738 | 0.3223 |
| SAO2010/KNMI | 0.9464 | 1.6985 |
| NewSAO2010/NRLSSI2 | 0.9754 | 1.4045 |
| NewSAO2010/ATLAS3 | 0.9899 | 0.0854 |
| New SAO2010/KNMI | 0.9689 | 1.0593 |

# Result

- Calibrated JPL




  - We would compare calibrated JPL with SAO2010 within oxygen air band A & B to figure out which is better

# Discussion and Further Study

- Radiometric calibrated high resolution reference solar spectra (SAO2010 & JPL spectra) have been derived based on low resolution reference spectra (WHI & ATLAS) with Super-Gaussian function
- Additional optimization and detailed analysis among reference solar spectra is in progress
- We will derive high resolution solar reference spectra from 200-2400 nm at various spectral resolution (e.g., 0.01 nm, 0.01 $cm^{-1}$)

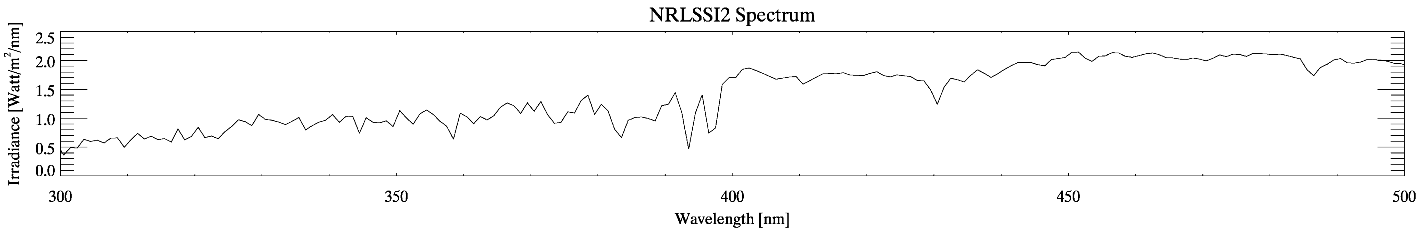
# Thank You

# Reference Solar Spectra

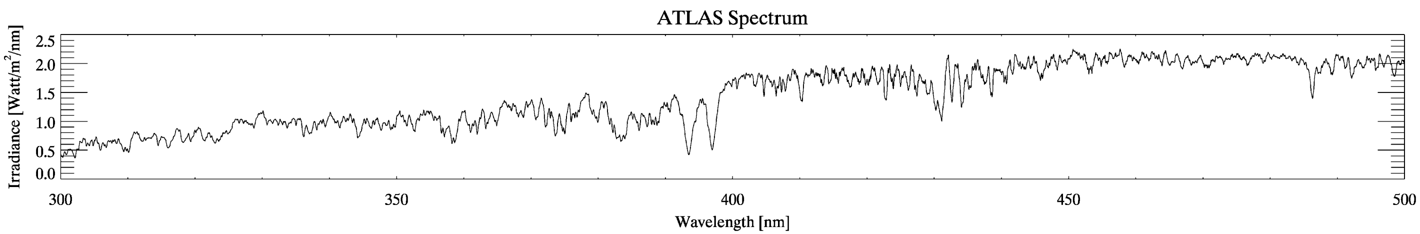
**Low resolution references**

**Different sampling, resolution, magnitude**

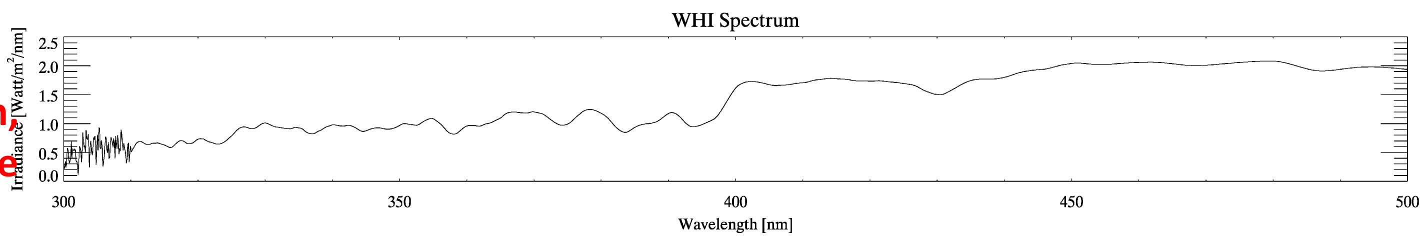
**High resolution references**



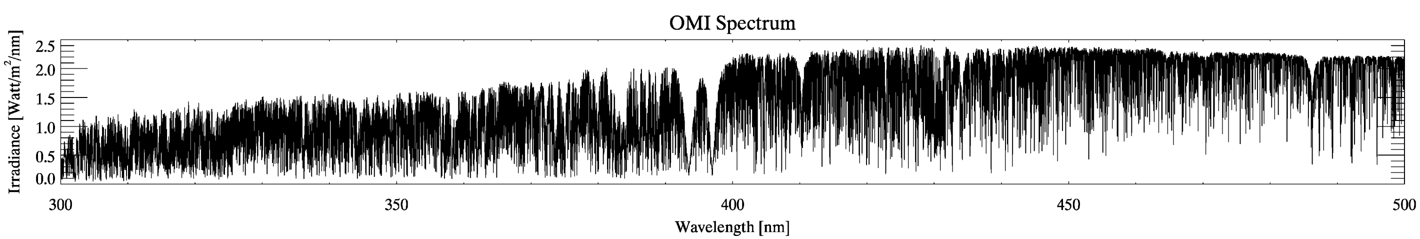

NRLSSI
Coddington *et al.* (2015)



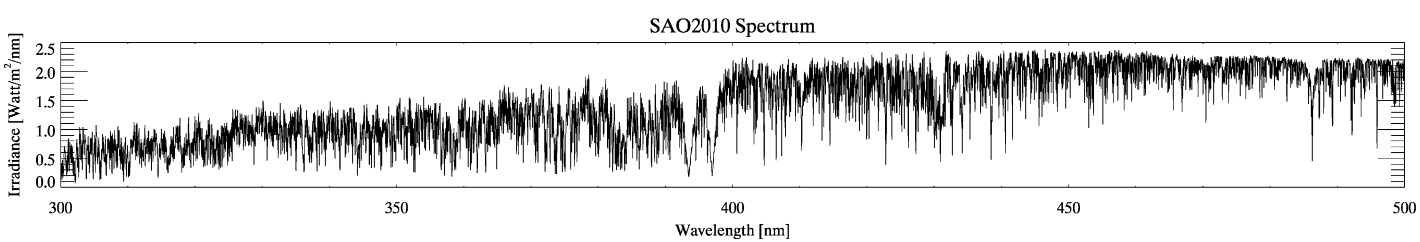

ATLAS
Thuillier *et al.* (2004)




WHI
Woods *et al.* (2008)




KNMI
Dobber *et al.* (2008)

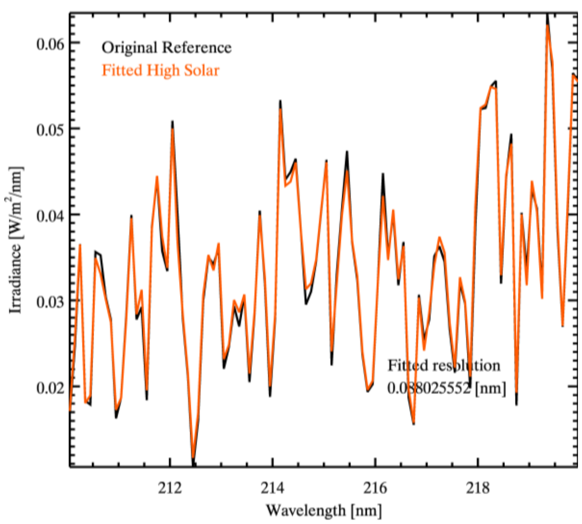



SAO2010
Chance & Kurucz (2010)

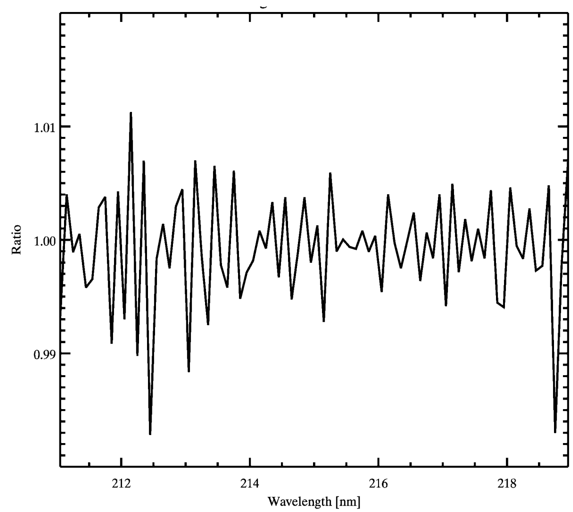
# Result

- Updating SAO2010

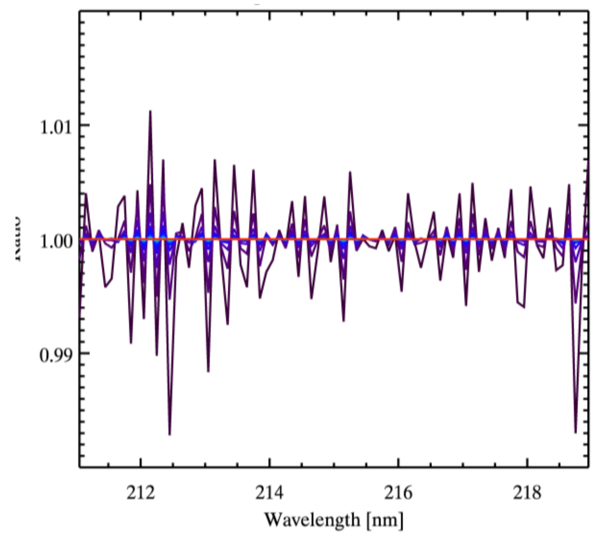
Fitting SAO based on WHI




Ratio btw fitted SAO & WHI




Ratio for each iteration step



# Whole Heliosphere Interval (WHI) (Mar-Apr 2008)

- obtained from simultaneous observation during solar cycle minimum conditions
- 0.1-6 nm: XPS-TIMED
  - Thermosphere, Ionosphere, Mesosphere, Energetics, and Dynamics
  - XUV (X-ray UV) Photometer System (XPS)
    - ✓ 0.1-nm resolution from spectral model fitted to 7-nm broad band XPS measurement
- 6-105 nm: MEGS (rocket)-EVE
  - Multiple EUV Grating Spectrograph
  - EUV Variability Experiment (EVE)
    - ✓ 0.1-nm spectral resolution measurement binned down to 0.1-nm intervals higher resolution spectrum (0.01-0.025 nm intervals) also available rocket launched on 14-Apr-08
- 105-116 nm: SEE-TIMED
  - Solar EUV Experiment (SEE)
    - ✓ 0.1-nm intervals, but 0.4-nm spectral resolution
- 116-310 nm: SOLSTICE-SORCE
  - Solar Radiation and Climate Experiment (SORCE)
  - Solar Stellar Irradiance Comparison Experiment
    - ✓ .1-nm spectral resolution measurement binned down to 0.1-nm intervals
- 310-2400 nm: SIM-SORCE
  - Spectral Irradiance Monitor
    - ✓ low-resolution prism measurement is interpolated to 0.1-nm intervals
    - ✓ SIM resolution is about 1 nm at 300 nm and about 34 nm at 1200 nm

# Thuillier et al 2004

- widely used for the low resolution solar reference
- 0.5-120 nm: Rocket
- 120-200 nm: SUSIM-UARS/SOLSTICE-UARS
- 200-400 nm
  - SUSIM-UARS/SOLSTICE-UARS/
  - SUSIM-ATLAS1-3/SSBUV-ATLAS1/
  - SOLSPEC-ATLAS1-3/SOLSTICE-ATLAS1-3
- 400-870 nm: SOLSEPC-ATLAS1-3
- 870-2400 nm: SOSP-EURECA

- An empirical solar linelist has been generated by simultaneous fitting of ATMOS, MkIV, Kitt Peak, Denver U, and TCCON spectra. The telluric absorptions were fitted using the HITRAN linelist and any remaining, airmass-independent absorptions were attributed to the sun. Together with a simple lineshape function, this linelist allows the computation of a solar pseudo-transmittance spectra, for disk-center, disk-integrated, or intermediate cases. These spectra have been validated using MkIV, Kitt Peak, ACE, and GOSAT spectra.

# Solar Update

- SAO 96
  - 230-800 nm, 0.01 nm resolution/0.02 FWHM
  - Based on ground-based measurements (Kurucz 1984) & balloon measurements (Hall and Anderson 1991)
    - ✓ Converted to vacuum wavelengths.
    - ✓ Ground data was recalibrated using 4 O2 lines (accuracy of better than 0.001 nm)
    - ✓ Balloon data were recalibrated in wavelength using 20 selected atomic reference lines. (accuracy of 0.003 nm)
    - ✓ Spectra were resampled at even 0.01 nm increments, employing a triangular filter of 0.02 nm FWHM and linearly merged over the 300-305 nm

| Spectrum | Wavelength/Sampling (nm) | Resolution (nm) | Sources | Accuracy |
|---|---|---|---|---|
| **Kitt Peak** | **293.09-1627.02** vacuum nm derived from the Fourier transform spectroscopy measurements of the Sun **0.0003 – 0.001** | **0.0005** | Kurucz R. L., I. Furenlid, J. Brault, and L. Testerman, *Solar Flux Atlas from 296 to 1300 nm* (National Solar Observatory, Sunspot, New Mexico, 1984) 240 pp.<br><br>http://kurucz.harvard.edu/sun.html | |
| **Hall and Anderson** | **200-310**<br>**0.01**<br>measured near 40 km in the stratosphere in 1978 and 1983, have been combined and extrapolated to zero optical depth to provide a reference spectrum in 0.1-Å | **0.025** | Hall L. A. and G. P. Anderson (1991), High-resolution solar spectrum between 200 and 3100 Å," *J. Geophys. Res.* 96, 12, 927–12,931 | within 0.04 Å. |

# Solar Update

- SAO produce the calibrated solar spectrum (235-1100 nm) as part of OMPS instrument and algorithm development
  - SOLSTICE and SUSIM (Woods et al., 1996)+ LOWTRAN/MODTRAN
  - Linearly merged 405.6-410.6 nm
- OMI spectrum (Dobber et al., 2006)
  - Kitt peak (Kurucz 1984) and Hall & Anderson 1991
  - Use combined low resolution spectra
    - ✓ SUSIM from UARS (Floyed et al., 2003) up to 410 nm, 0.15 nm resolution
      - Triangular slit
    - ✓ Balloon spectrum for SCIAMACHY validation (Gurlit et al., 2005) from 400 nm
      - Square shaped slit function

# Solar Update

- SAO 2010
  - Use updated kitt peak (agreement with Thuillier et al., ; better than 1% at 20 nm spectral resolution)
    - ✓ Large scale features by O3, O2-O2 were computed and divided out.
    - ✓ The computed line spectrum were adjusted for an match to the observed spectra
    - ✓ Artifacts from wavelength mismatches, deep lines, etc, were removed by hand.
  - Updated kitt peak data and H&A spectra are each convolved to a Gaussian FWHM of 0.04 nm and sampled to 0.01 nm
  - Linearly merged to 300 to 305 nm

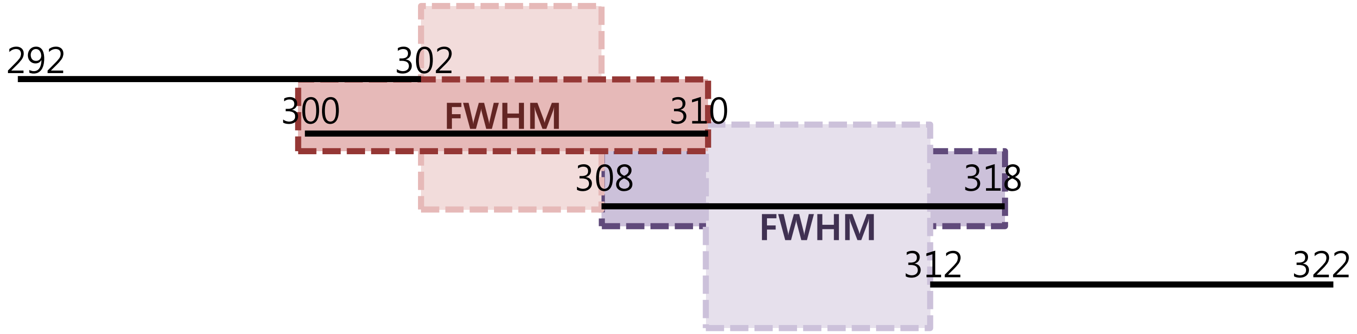
# Solar Update

- Compare SAO 2010 & OMI

| | Range (nm) | Sampling (nm) | Resolution (nm) | High resolution | Low resolution | issues |
|---|---|---|---|---|---|---|
| SAO 2010 | 200.07-1000.99 | 0.01 | 0.04 | Kitt peak (2005) Hall & Anderson | | Radiometric calibration |
| OMI | 250-550 | 0.01 | 0.025 | Kitt peak (1984) Hall & Anderson (SAO 96) | SUSIM (~410 nm) (Floyd et al 2003) Balloon (400 nm ~) (Gurlit et al 2005) | Under-sampling |
| Updated SAO | 200.07-1000.99 | 0.01 | 0.04 | SAO 2010 | WHI (~310 nm) (Woods et al 2009) ATLAS1&3 (300 nm~) (Thuillier et al 2004) | |

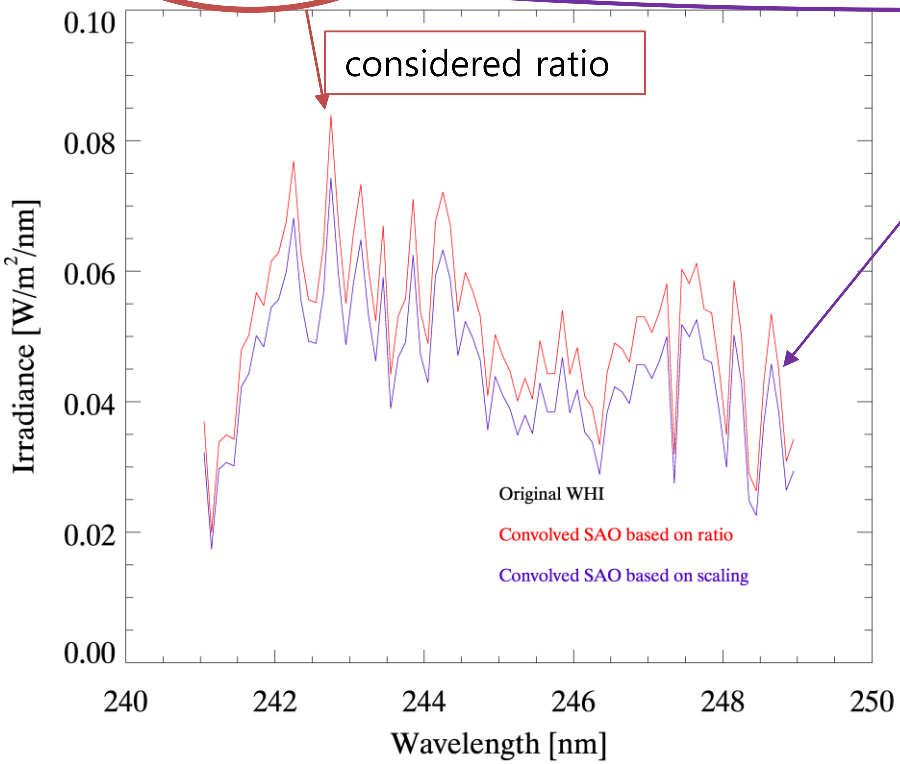
# Solar Update

- Allow overlapping between adjacent windows.
  - For example, if each window is 10 nm, then fit 292-302 nm, 300-310 nm, 308-318 nm and only apply the results to non-overlapped regions, i.e., results from fitting 300-310 nm to 302-308 nm.



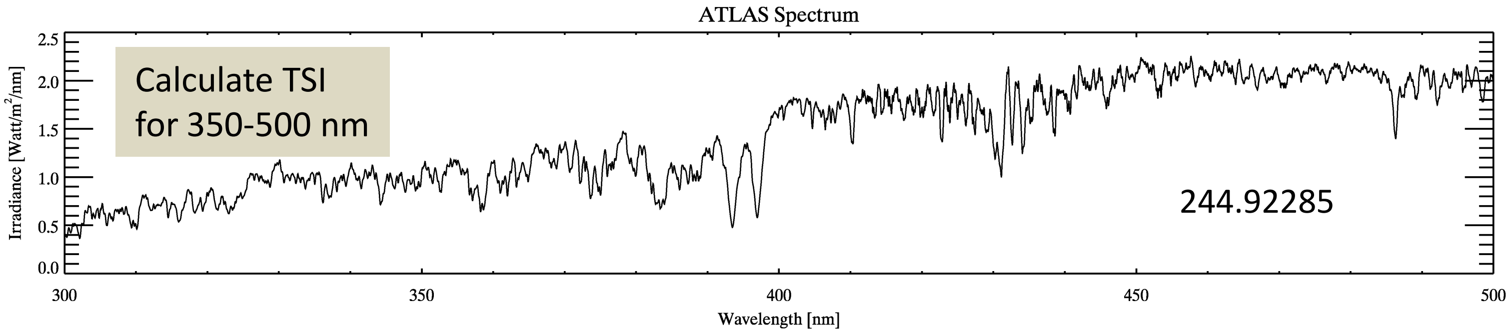
$$I_{WHI} = \left(\frac{\int I_{SAO} \times \phi_{WHI} d\phi}{\int \phi_{WHI} d\phi}\right) \times \left(a_o + a_1(\lambda - \lambda_{avg}) + a_2(\lambda - \lambda_{avg})^2 + a_3(\lambda - \lambda_{avg})^3 + a_4(\lambda - \lambda_{avg})^4 + a_5(\lambda - \lambda_{avg})^5\right)$$

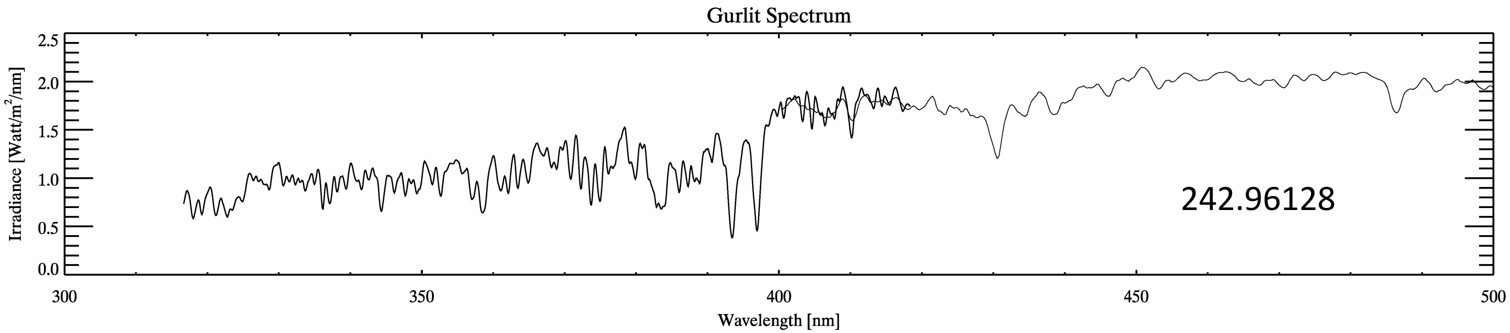
considered ratio

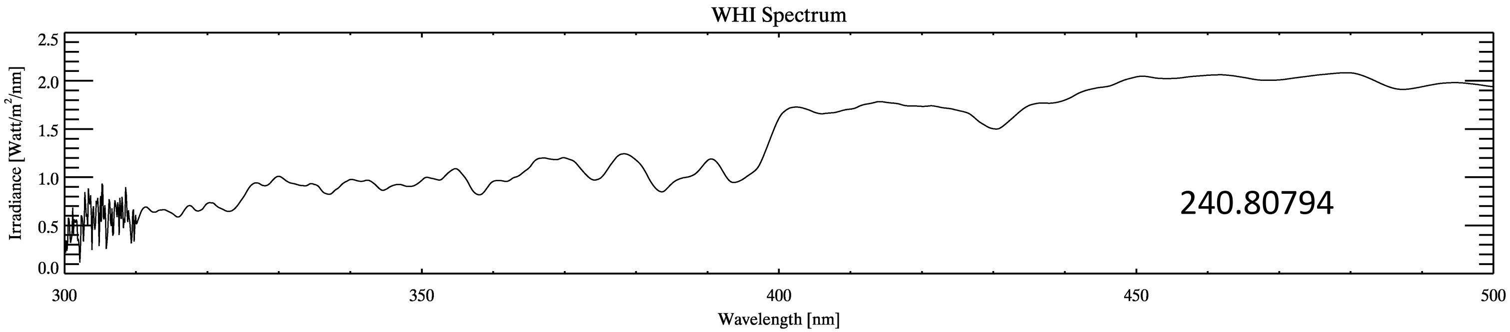



- Convolved SAO based on ratio after iteration
  - ✓ Nearly same as original WHI spectral region
- Convolved SAO based on obtained scaling factors from fitting
  - ✓ Quite different with original WHI the fitted SAO includes the **broad variation of the correction from the scaling parameters**

# Current References



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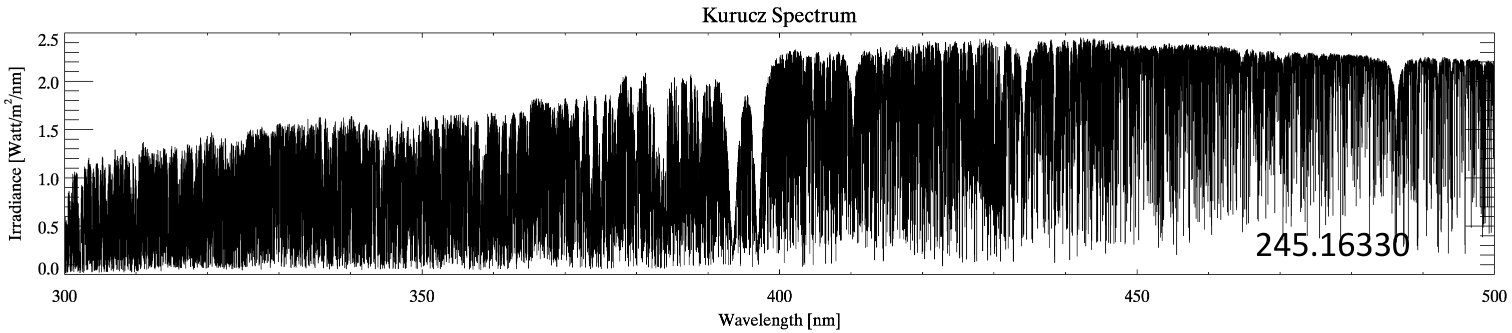
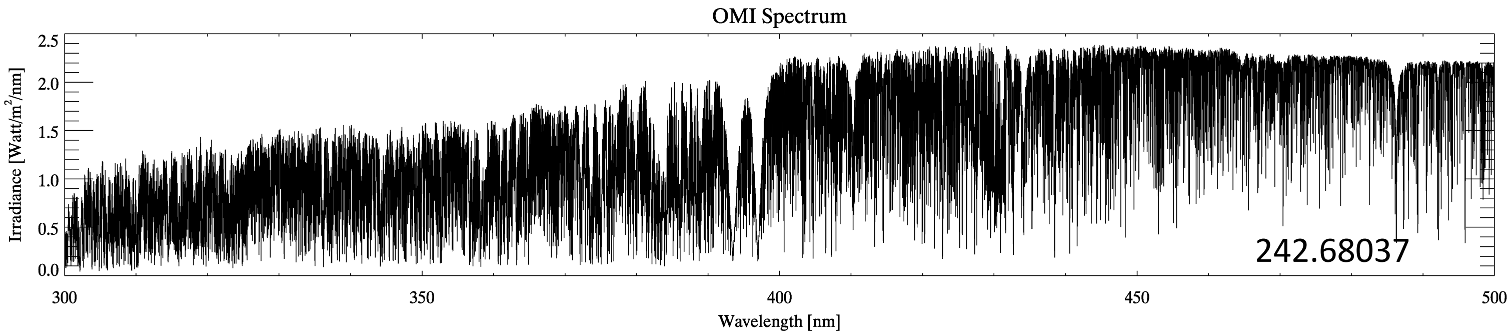
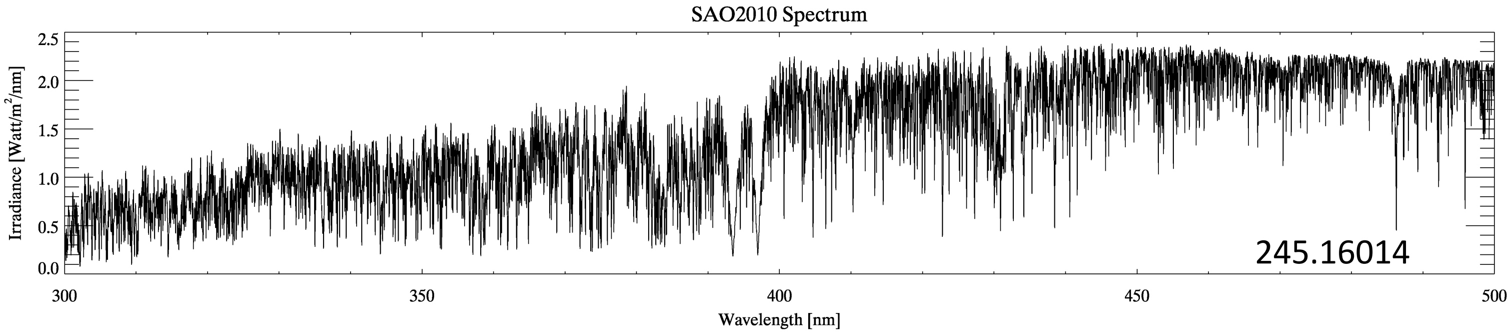



Similar with Gurlit et al




Similar with Kurucz