Requirements for a Reference Solar Spectrum for Lunar Calibration Applications

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Applications for the solar spectrum in Earth remote sensing

Reflected solar wavelengths

- Generating reflectance data products
  - using reflectance calibrations derived from radiometric calibrations
- A reference for on-orbit calibration methodologies
  - deep convective clouds, Rayleigh scattering, sunglint
  - GSICS inter-calibration (talk by D. Doelling)
- Lunar calibration
  - using sunlight reflected from the Moon as a reference standard

The Moon as a radiometric reference

At reflected solar wavelengths, the Moon acts as a solar diffuser which has exceptionally stable reflectance, $<10^{-8}$ per year.

But the Moon’s apparent brightness is continuously changing. To use it as a calibration reference requires the capability to predict its brightness for any lunar observations made by an instrument.

The inherent stability of the lunar surface means the changing brightness is predictable, dependent only on geometry and the solar irradiance

- key to developing a lunar radiometric reference

The lunar reference is an analytic model, which can be queried for the Sun–Moon–Observer geometry of an instrument’s Moon observations.

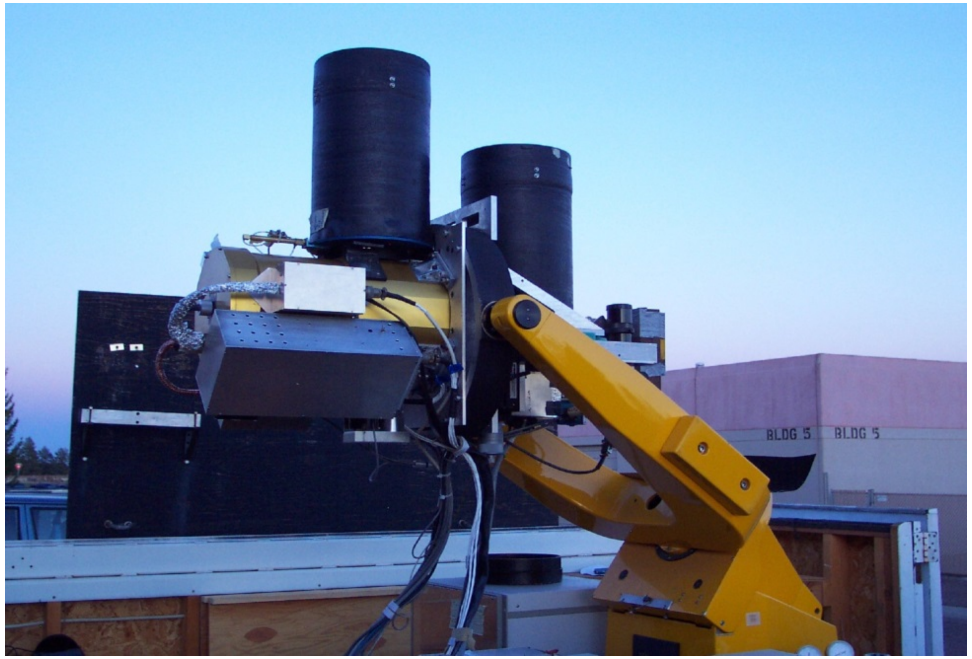
- a lunar reflectance model is valid for any time
  - enables cross-calibration without simultaneous observations
  - has potential to bridge a gap in an otherwise continuous observational data record

The lunar radiometric reference — ROLO development

To build a predictive lunar model requires collecting an extensive set of measurements. ROLO is a dedicated lunar observation facility:

- Located on USGS Flagstaff campus, 2143m altitude
- Twin telescopes, 20cm dia. primary mirrors, Ritchey-Crétien optics
  - 23 VNIR bands, 350−950 nm
  - 9 SWIR bands, 950−2450 nm
- Imaging systems — measure radiance
- Operated more than 8 years
- >110,000 Moon images
  - lunar phases from First Quarter to Last Quarter
- >10^6 Star images
  - used for atmospheric corrections

ROLO telescopes zenith-pointed at dusk



USGS

The lunar radiometric reference — ROLO development

Research and development at USGS determined that the most useful quantity for radiometric calibration is spatially integrated spectral irradiance.

- increases signal-to-noise by summing multiple radiance measurements (pixels)
- eliminates the need for co-registration of images with the reference (model)

The ROLO model that generates lunar spectral irradiance was developed and operates in terms of disk-equivalent reflectance:

$$\ln A_k = \sum_{i=0}^{3} a_{ik} g^i + \sum_{j=1}^{3} b_{jk} \Phi^{2j-1} + c_1\phi + c_2\theta + c_3\Phi\phi + c_4\Phi\theta$$
$$+ d_{1k} e^{-g/p_1} + d_{2k} e^{-g/p_2} + d_{3k} \cos((g - p_3)/p_4)$$

– a function of only the photometric geometry variables of phase angle g and librations as selenographic sub-observer longitude θ and latitude φ and sub-solar longitude Φ

The lunar radiometric reference — ROLO development

The fundamental model outputs (A_k) at 32 ROLO bands are fitted with a lunar reflectance spectrum, which is then convolved with the instrument band spectral response functions and the solar spectrum to give the lunar irradiance (E_M) at the sensor band wavelengths:

$$E_{\mathrm{M}} = \frac{\Omega_{\mathrm{M}}}{\pi} \frac{\int A_{\mathrm{fit}}(\lambda)\, E_{\mathrm{Sun}}(\lambda)\, S(\lambda)\, d\lambda}{\int S(\lambda)\, d\lambda}$$

A_{fit} = lunar reflectance spectrum
E_{Sun} = Solar spectral irradiance
S = spectral response function
$\Omega_{\mathrm{M}} = 6.418 \times 10^{-5}$ sterad

The model computations (A_{fit}) and Ω_{M} are for standard Sun-Moon and Moon-observer distances of 1 AU and 384400 km

Apply distance corrections:

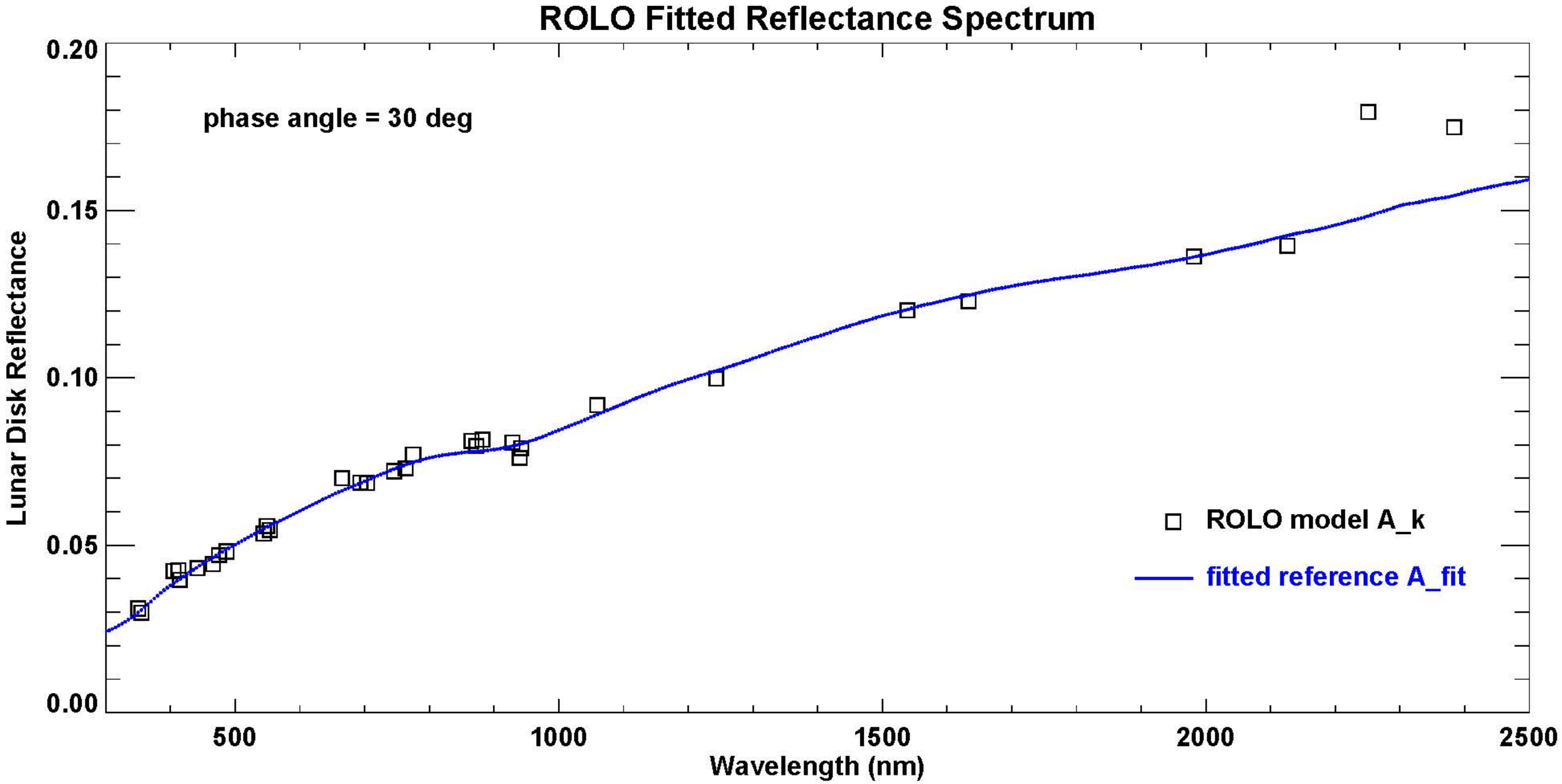
$$E'_{\mathrm{M}} = E_{\mathrm{M}} \left(\frac{1\ \mathrm{AU}}{d_{\mathrm{Sun-Moon}}}\right)^2 \left(\frac{384\,400\ \mathrm{km}}{d_{\mathrm{Moon-Obs}}}\right)^2$$

The final output E'_{M} is the lunar spectral irradiance present at the instrument location at the time of the observation, in each sensor spectral band.

The lunar radiometric reference — ROLO development

Example of fitting the reference lunar reflectance spectrum

reference is mixture of RELAB spectra for Apollo returned samples 62231 (soil, 95%) and 67455 (breccia, 5%)



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Advances in lunar modeling and the solar spectrum

- the lunar model kernel is a spectral reflectance model ($A_{\mathrm{k}} \rightarrow A_{\mathrm{fit}}$)
- the fitted lunar reflectance spectrum is smooth, with only weak absorption structure
  - continuous, thus straightforward to interpolate and convolve with sensor band RSRs

A high-accuracy specification of lunar disk reflectance A, coupled with SI-traceable SSI, can yield an SI-traceable lunar irradiance reference

- this is the goal for lunar calibration development efforts
  - a lunar reflectance specification with tenths-percent accuracy is technically feasible
- SI-traceable solar spectral irradiance data are available, e.g. TSIS SIM

Lunar calibration must accommodate spectrometer instruments with line widths of a few nanometers

- requires SSI with higher resolution than e.g SIM instruments provide

Construction of a static solar spectrum

Objective: sufficiently high spectral resolution with accuracy close to absolute SSI data

Approach: reduce an ultra-high res (FTS) spectrum to the desired resolution, then scale to an absolute reference spectrum

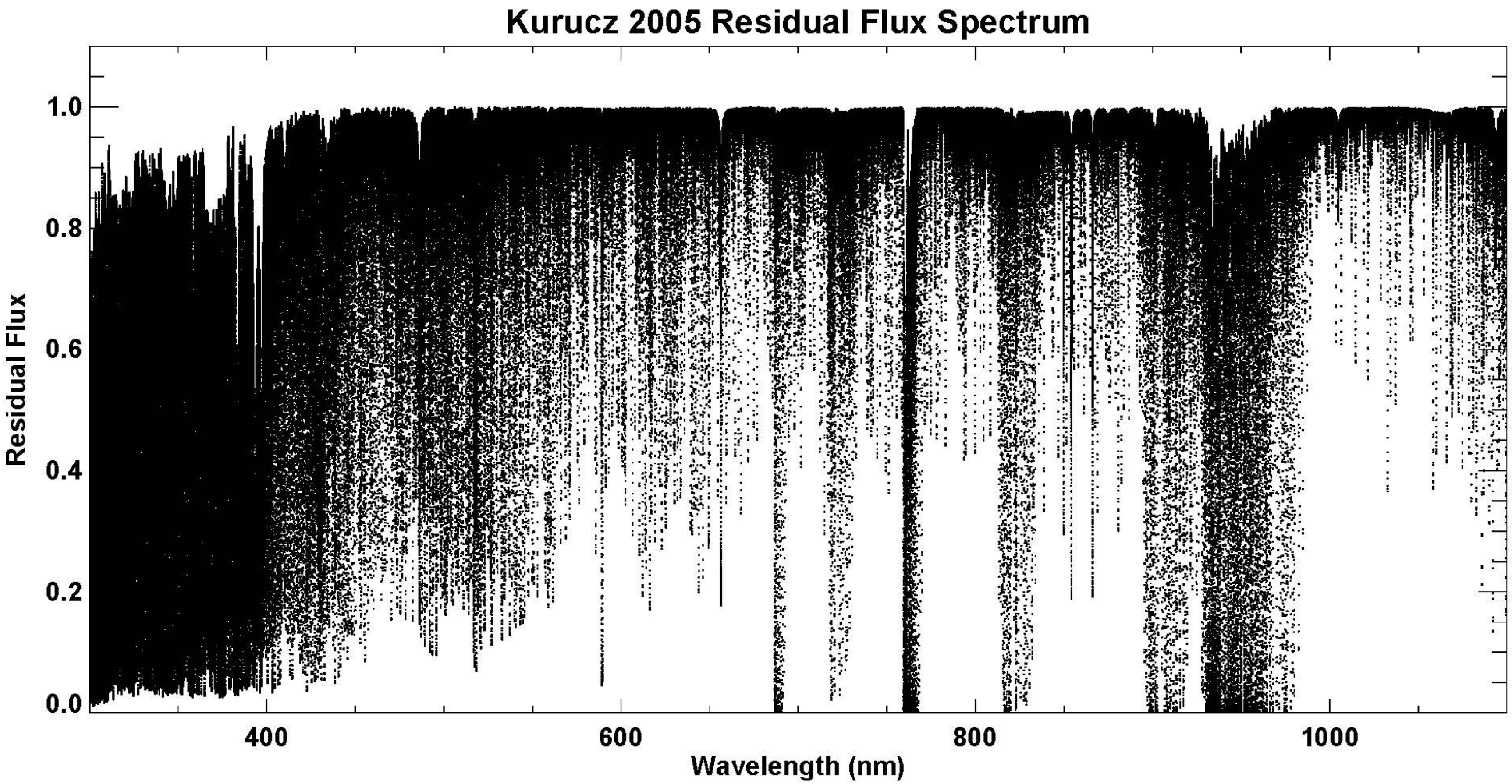
For efforts at USGS-ROLO:

- high res spectrum = Kurucz et al. (1984) Solar Flux Atlas “residual flux”
  - normalized to lamp irradiances, ~0.00187 nm resolution
- absolute reference = Wehrli (1985) solar irradiance, PMOD publication 615
  - Thuillier (2003) spectrum was not yet published at the time of ROLO development
  - recent work used SORCE SIM data — median of 3 years centered on the 2008 solar minimum

Construction of a static solar spectrum

Kurucz residual flux spectrum — 2005 reprocessing, effort to correct telluric contamination features

http://kurucz.harvard.edu/sun/fluxatlas2005/fluxspliced.2005



Construction of a static solar spectrum

- apply Gaussian filter to residual flux spectrum
  - for each reduced-resolution wavelength λ_{out} :
  - choice for output resolution = 0.005 nm
  - choice for half-width = 0.005 nm

$$f'(\lambda_{out}) = \frac{\sum_i f(\lambda_i) \cdot \exp\left[\frac{-(\lambda_i - \lambda_{out})^2}{2\sigma^2}\right]}{\sum_i \exp\left[\frac{-(\lambda_i - \lambda_{out})^2}{2\sigma^2}\right]}$$

λ_{out} = output center wavelength
λ_i = original function wavelengths
σ = Gaussian half-width

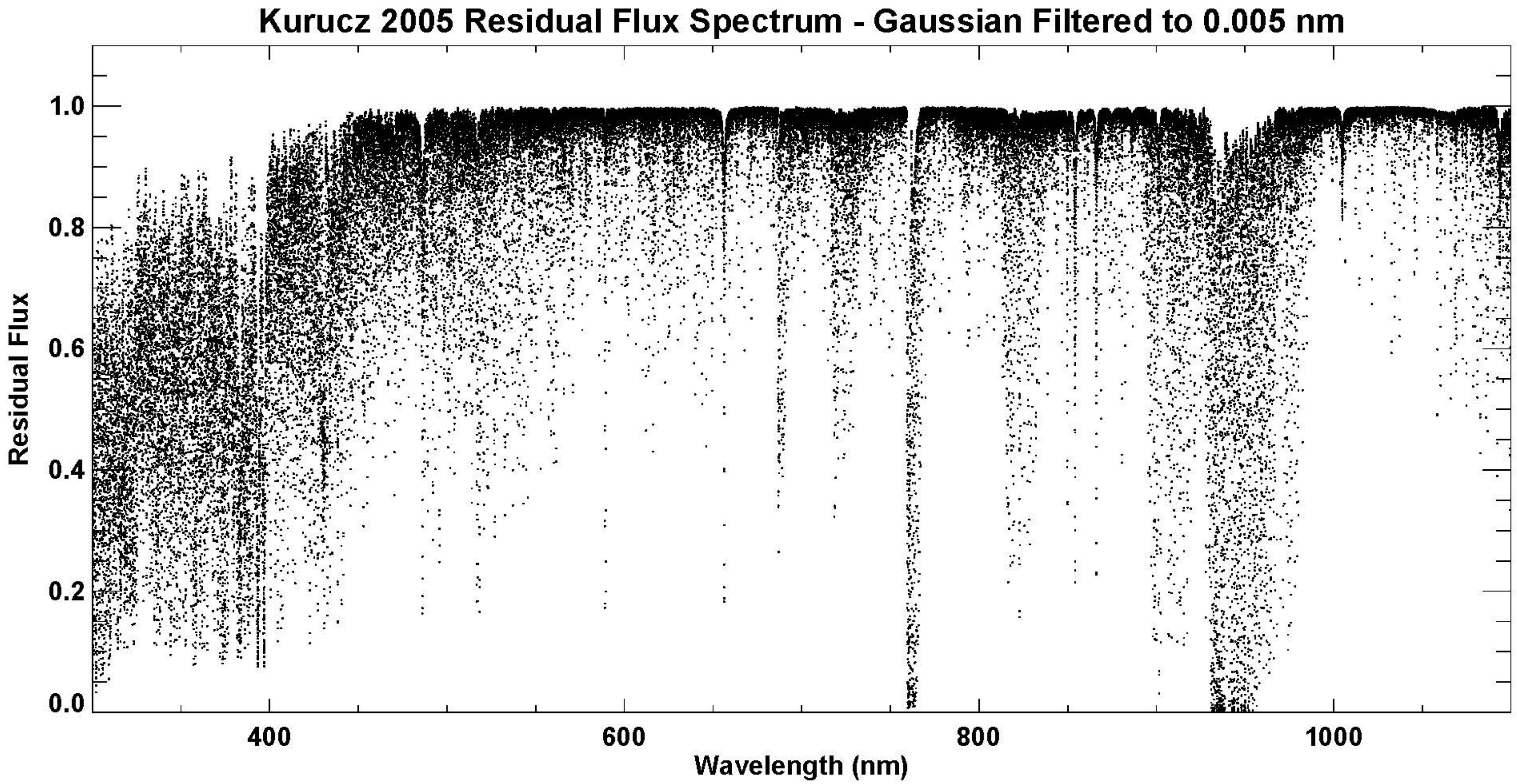
- convolve the output (filtered) spectrum over the absolute reference spectrum bands and integrate to get scaling factors for each band
  - requires knowing the reference spectrum bandpass functions, e.g. SIM trapezoid LSFs
- apply factors to scale the higher resolution spectrum — the final result
  - requires interpolating between reference spectrum bands
  - used linear interpolation — what is the best method?

Example results

Absolute reference input: SORCE SIM median spectrum (processed at USGS)

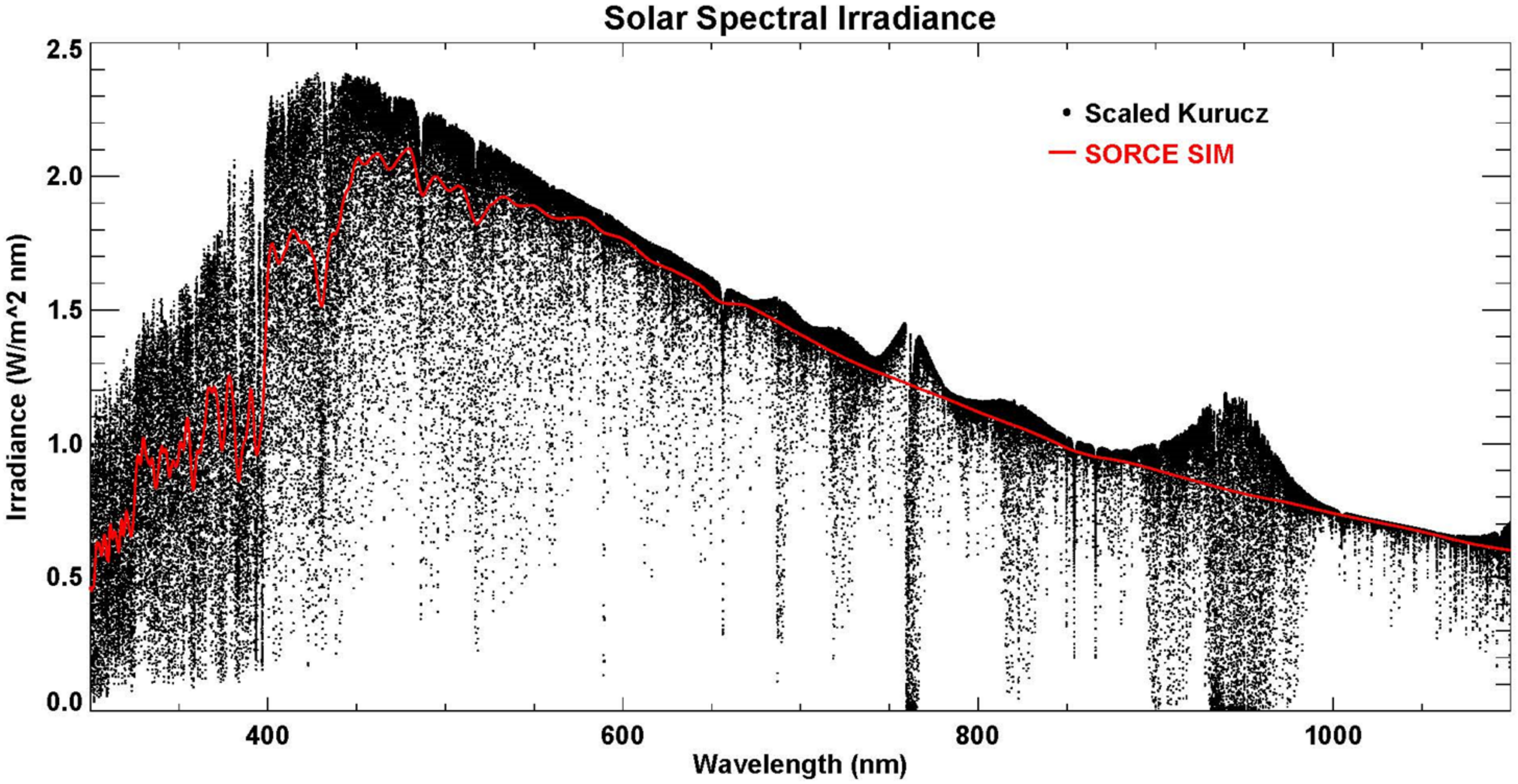
– used TSIS-1 SIM line spread functions for convolutions

High-res input: Kurucz 2005 reduced to 0.005 nm resolution



Example results

Filtered Kurucz (0.005 nm resolution) spectrum scaled to SORCE SIM



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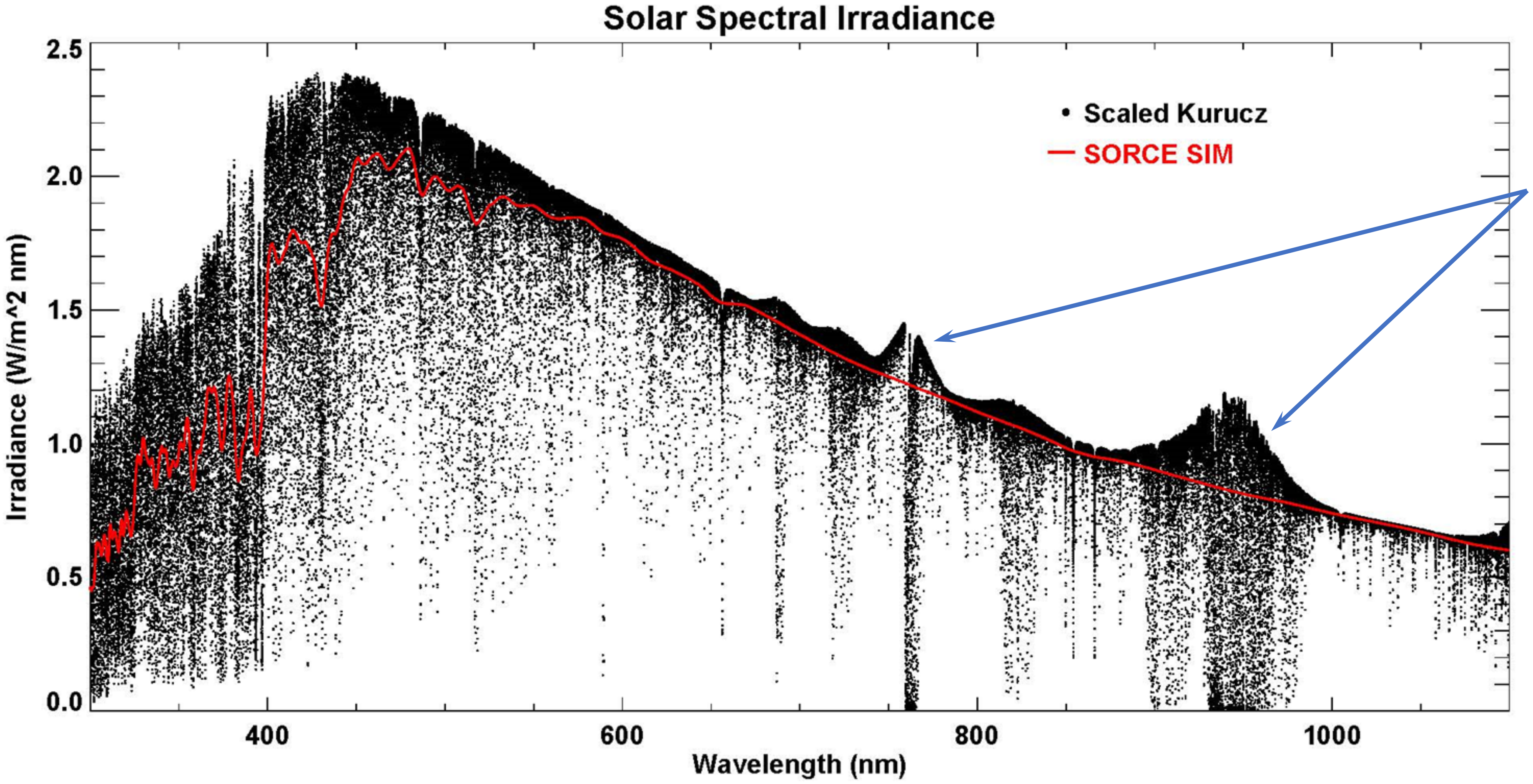

signatures of residual absorption features

check by convolving scaled spectrum with SIM LSFs

- should reproduce SIM spectrum

Conclusions

- A common reference solar spectrum is a critical need for remote sensing instrument calibration at reflected solar wavelengths
  - an essential component of reflectance calibrations and lunar calibration
  - typically used as a static quantity, e.g. in lookup tables
- Calibration applications require both absolute accuracy and a spectrally resolved reference
  - with sufficient resolution to accommodate spectrometer instruments, e.g. ~0.01 nm
- High-accuracy SSI data are available
  - obtaining the needed spectral resolution requires merging datasets
  - this process is sensitive to the actual line spread functions of the SSI instruments
- Further processing of the solar spectral atlas data is needed
  - to separate (and remove) atmospheric absorption structure from Fraunhofer structure

Thank you!