Extending the spectral range of the RObotic Lunar Observatory (ROLO) model to climate science-relevant wavelengths

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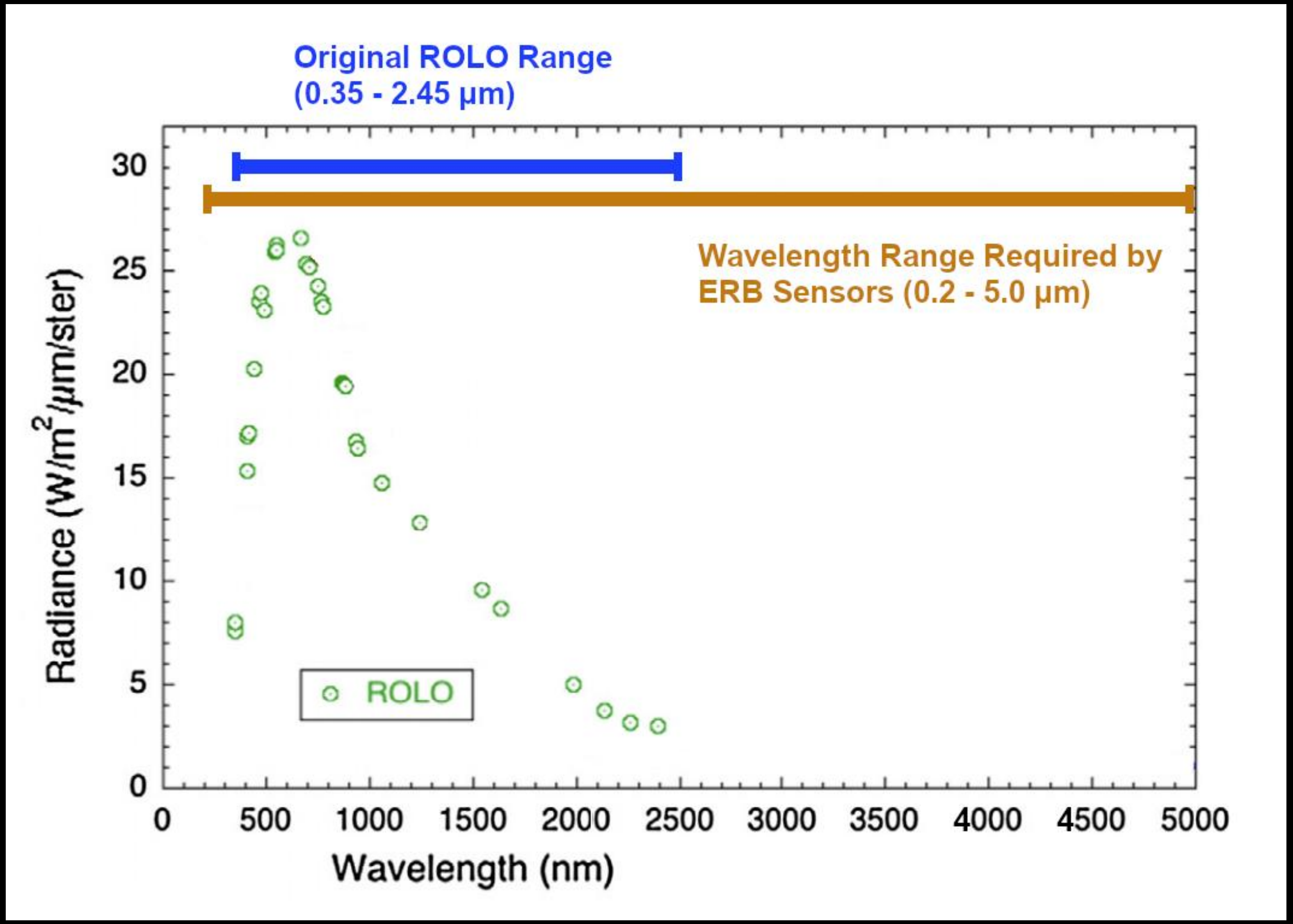
Lunar modeling limitations for Earth Radiation Budget (ERB) sensors

- Uncertainties in the ROLO model currently are too large to use the Moon as an absolute reference, primarily due to errors caused by the atmospheric effects associated with the ROLO ground-based measurements and the lack of SI traceability.
- With new, high accuracy lunar measurements that are expected to be made at high altitude and from low Earth orbit by upcoming missions (i.e., MLO-LUSI, air-LUSI, ARCSTONE, and CLARREO Pathfinder), improvements of at least an order of magnitude over the current uncertainties are possible .
- However, these missions (like the original ROLO telescope observations) will take measurements at reflected solar wavelengths, not the broader shortwave range that is required by ERB sensors (0.2 – 5 µm).
- Expanding the wavelength range of the ROLO model will improve accuracy to the level that the Moon can be practically used as an absolute calibration source for ERB sensors.



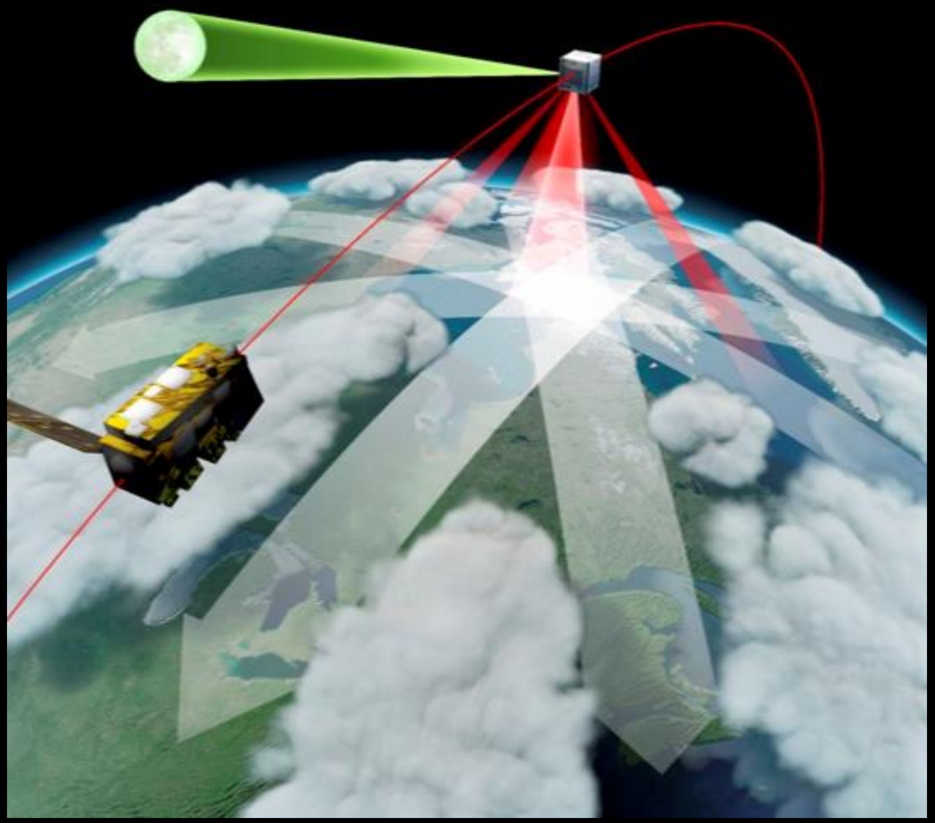
Lunar radiance for the Mare Serenitatis region from ROLO earth-based telescope observations [*Pieters et al.*, 2013].

Objective and expected significance

Overall objective: *Expand the spectral range of the lunar calibration reference from the current 0.35 µm UV limit to 0.2 µm, and from the current 2.45 µm infrared limit to 5.0 µm, to allow for high-accuracy on-orbit shortwave broadband calibration of Earth Radiation Budget sensors using the Moon.*

Science Impacts:

- Increase calibration accuracy of ERB instruments
  - Enable high accuracy recalibration of sensors that observed the Moon, allowing for consistent and continuous records spanning decades
  - Impactful for multiple satellites (including upcoming ERB missions)
- Provide the expanded broadband spectral range to enable utilizing the Moon as an absolute calibration reference for ERB sensors before the data from ARCSTONE, air-LUSI, MLO-LUSI, and CLARREO Pathfinder arrive
- Contribute towards the next generation of ERB sensors
  - Reducing mass, cost, and risk, and enabling small satellite free-flier concepts with improved accuracy over conventional onboard solar calibration techniques
- Ease of future lunar model improvements and community accessibility



The *Trutinor* small-satellite radiometer concept for measuring ERB, exploiting the Moon as an absolute calibration target in the shortwave broadband [*Young et al.*, 2020].

Project Goals and Brief Methodologies

Replication of ROLO model (Completed) →

The lunar reference has been reconstructed from the ROLO model according to equations in *Kieffer and Stone* [2005].

Solar Spectral Irradiance (SSI) Update (Completed) →

Updated the solar spectral irradiance using measurements from the Total and Spectral Solar Irradiance Sensor (TSIS-1) mission; Currently using Hybrid Solar Reference Spectrum (HSRS)

UV Expansion of ROLO Model (Completed) →

Utilized the SOLar-STellar Irradiance Comparison Experiment (SOLSTICE) on the SOlar Radiation and Climate Experiment (SORCE) to expand the ROLO wavelength range in the UV

IR Expansion of ROLO Model (Future Work) →

Assess a data-driven approach to arriving at the effective temperature of the lunar disk using gridded surface temperature maps at each lunar phase from the Lunar Reconnaissance Orbit's (LRO's) Diviner

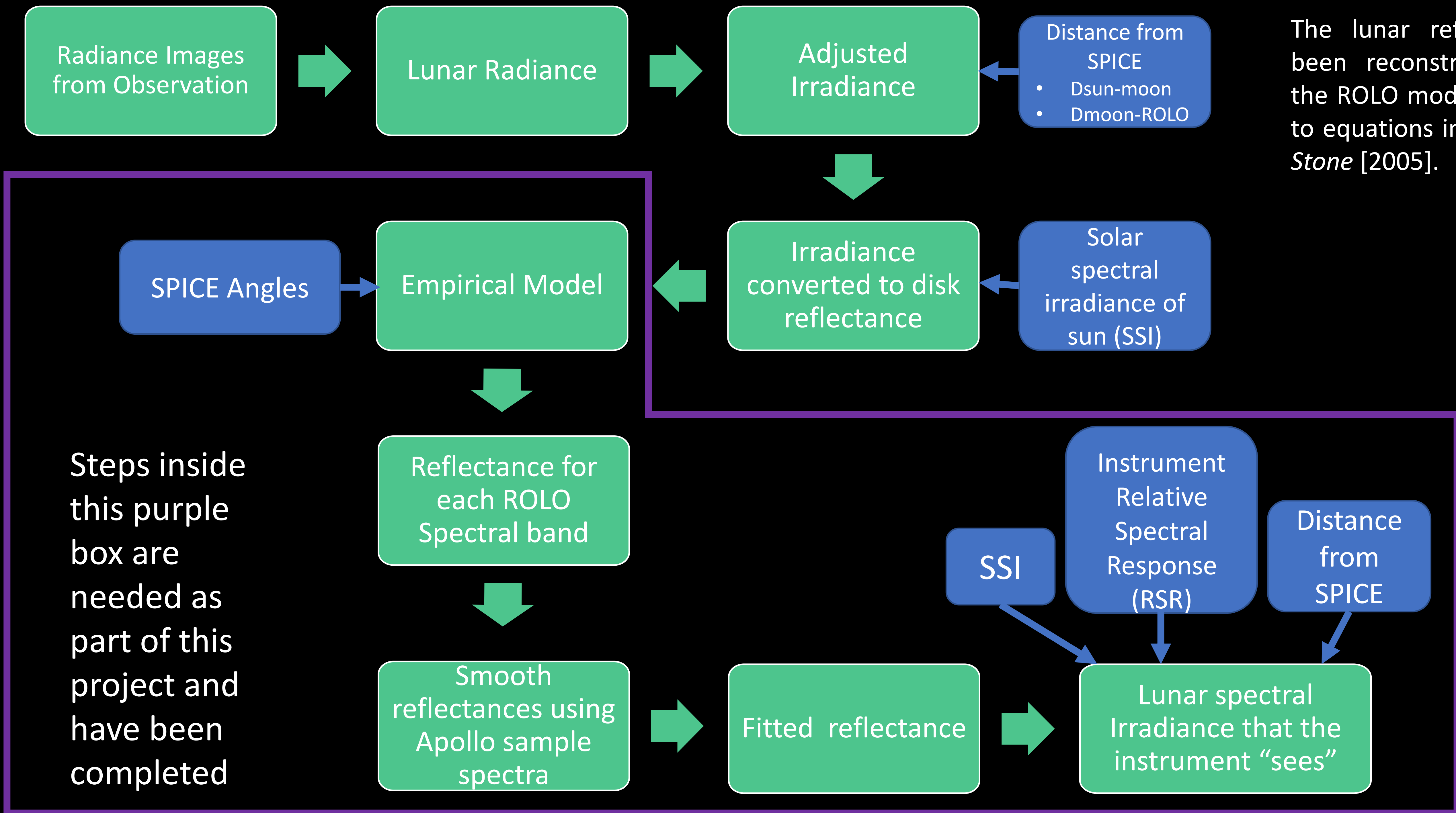
Comparison of ROLO Disk Irradiances to those of CERES (Future Work)

Compare irradiances from the expanded ROLO model and original ROLO model to the Clouds and the Earth's Radiant Energy System (CERES) disk irradiances at the available lunar phase angles

The outcome of this project will be a new lunar model.

Codes will be archived at the completion of the project by the PI using NASA's Earth Data repository: *earthdata.nasa.gov.*

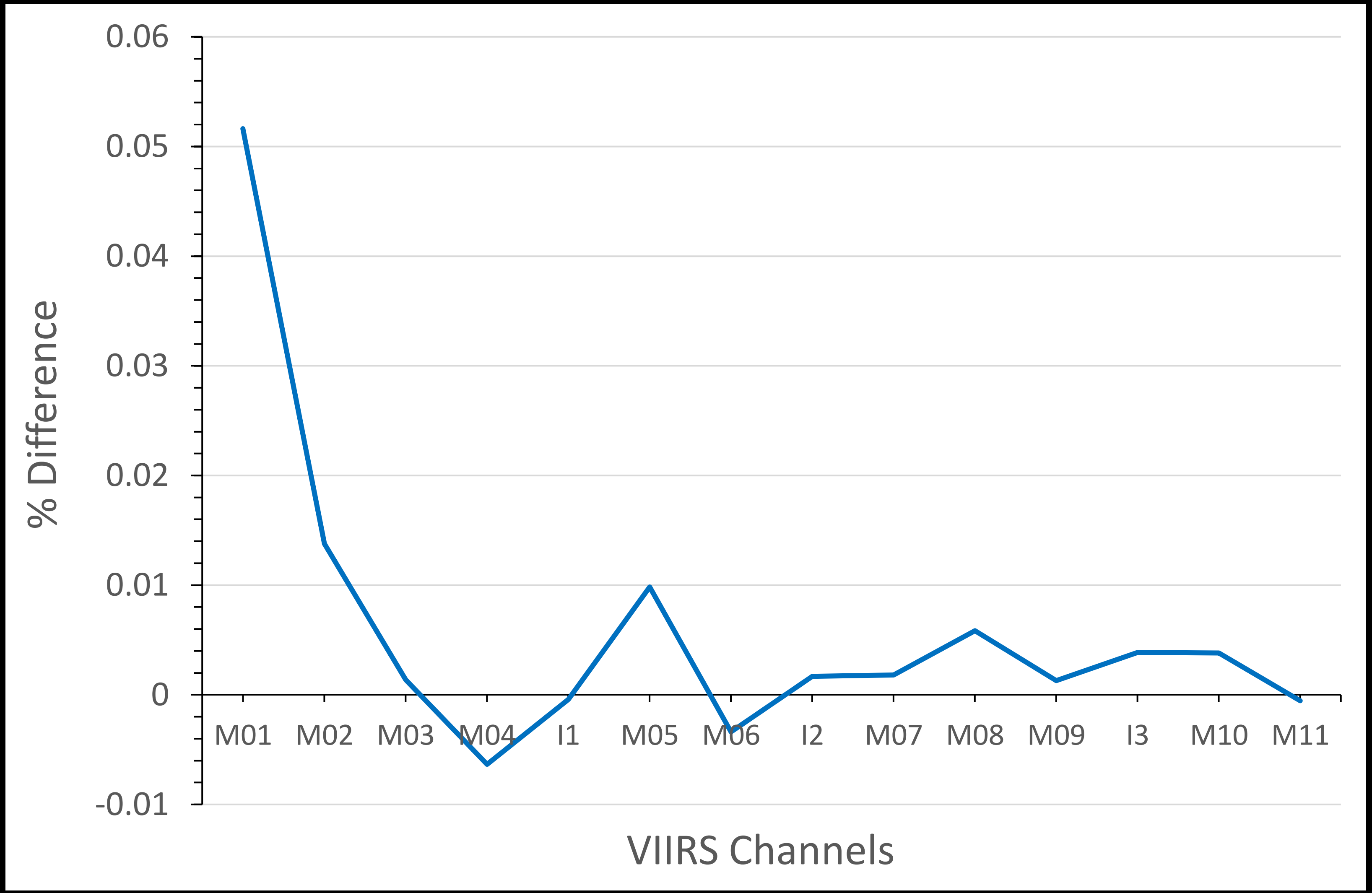
Reproducing and improving the ROLO model



The lunar reference has been reconstructed from the ROLO model according to equations in *Kieffer and Stone* [2005].

Validating a Reproduction of the ROLO Model

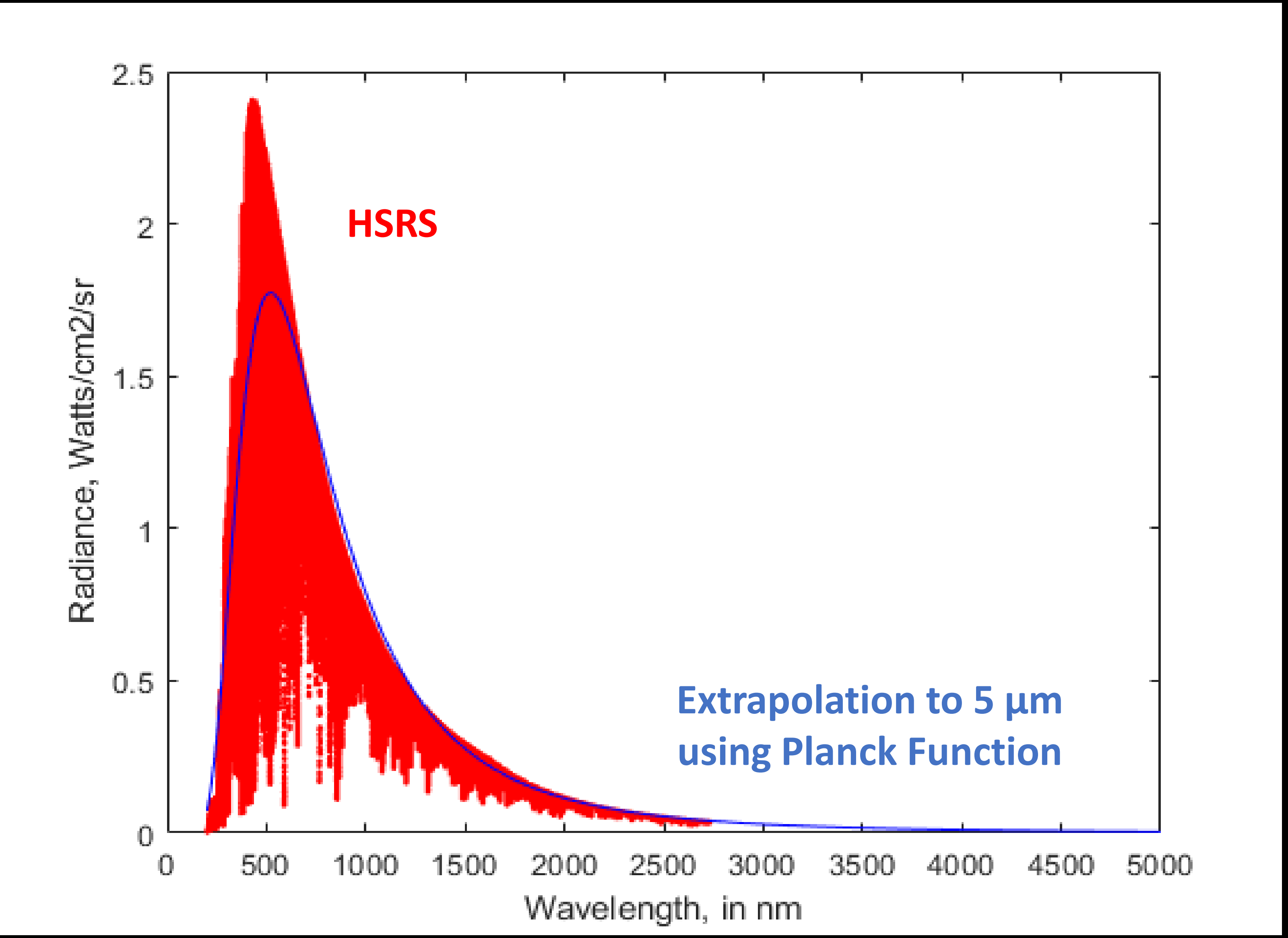
Using an instrument Relative Spectral Response (RSR) from the Visible Infrared Imaging Radiometer Suite (VIIRS) and an example lunar observation, the Matlab reproduction of the ROLO model was validated with the version being used by Collaborator Stone at USGS to within the overall accuracy of the lunar model.



Percent difference between T. Stone and C. Young lunar spectral irradiance that the instrument "sees" for each VIIRS spectral band using solar spectrum from *Wehrli* [1985].

Solar Spectral Irradiance (SSI) Update

- Solar spectral irradiance measurements from the Total and Spectral Solar Irradiance Sensor (TSIS-1) are now available at unprecedented accuracy, 0.2 – 0.5%, k =1 [*Richard et al.*, 2020].
- Since the lunar reflectance is convolved with the solar spectral irradiance, obtaining the solar irradiance spectrum in the expanded wavelength range is required.
- For the time being, Hybrid Solar Reference Spectrum (HSRS) 'p005nm' average SSI is being used [*Coddington et al.*, 2021].
- Future plans to use time series SSI from the Spectral Irradiance Monitor (SIM) instrument on TSIS-1.

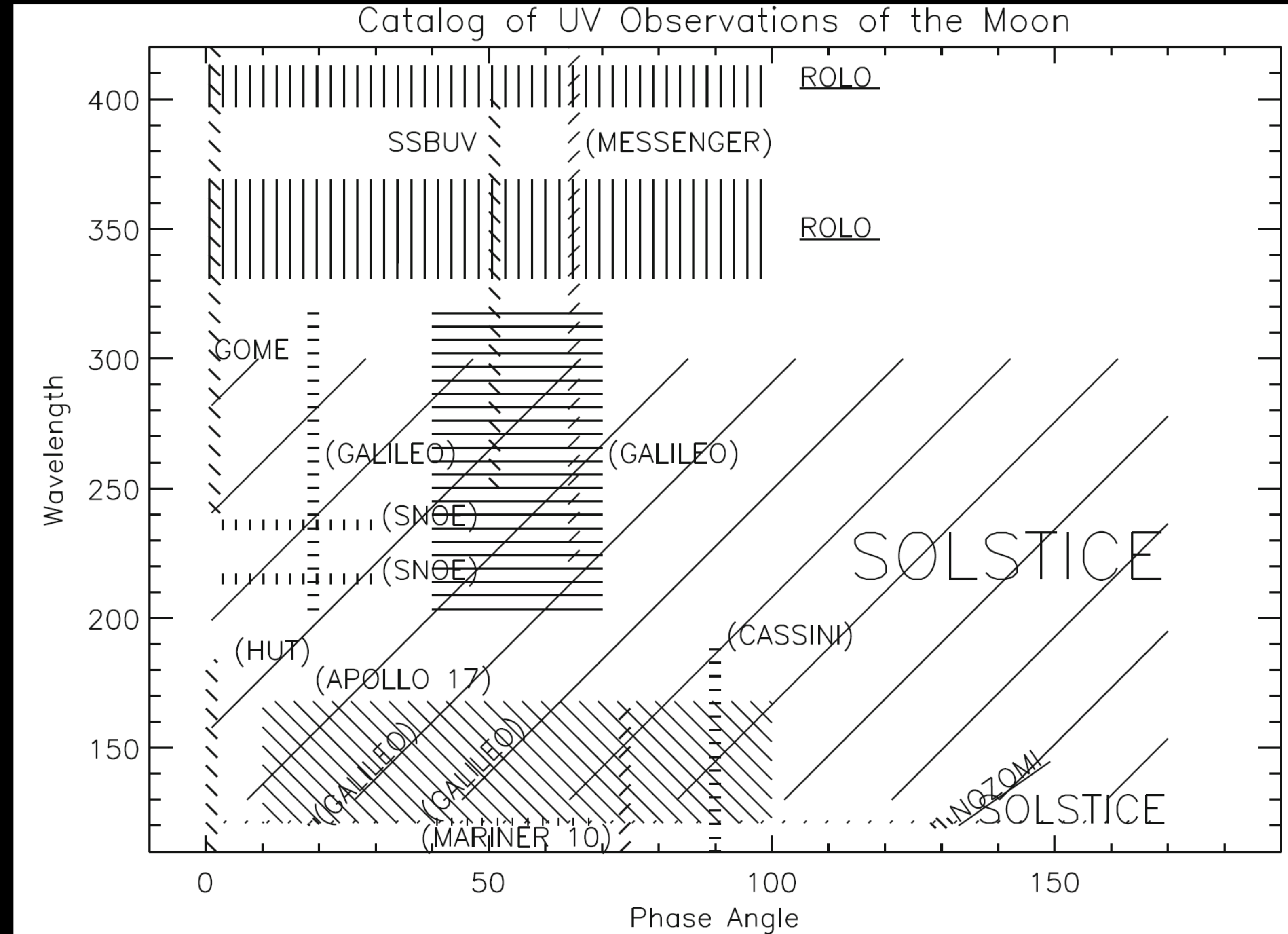


In the SWIR wavelength range of 2.4 – 5 µm, the solar spectrum is smooth, and has been extrapolated to 5 µm using a Planck Function fit at ~5600 K.

UV Expansion

- SOLar-STellar Irradiance Comparison Experiment (SOLSTICE) on the SOlar Radiation and Climate Experiment (SORCE) provides lunar measurements at a wide range of lunar phase angles and at required wavelengths, and these qualities are unmatched by other instruments that have viewed the Moon.

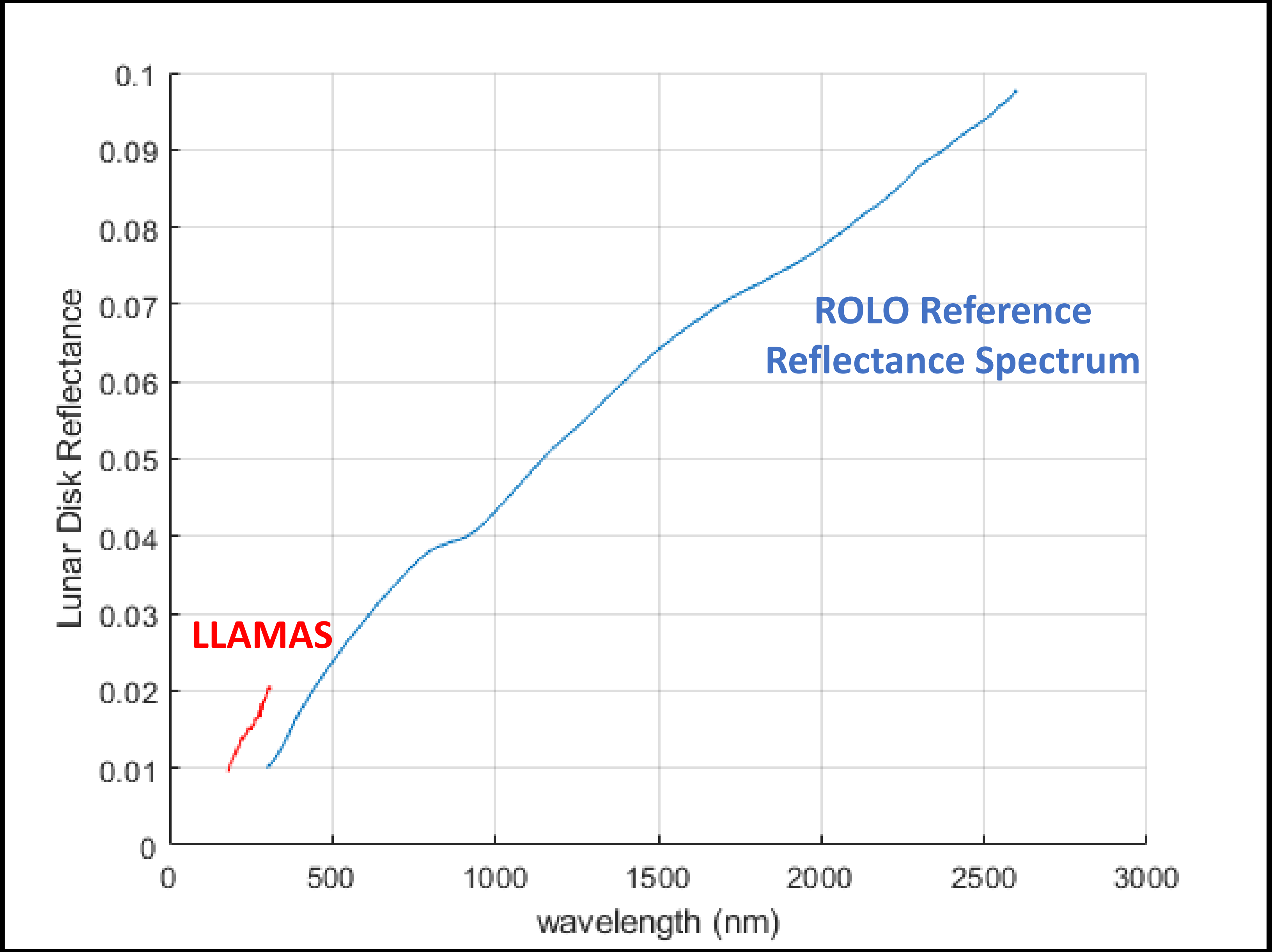
- SOLSTICE was used to expand the ROLO wavelength range from 0.35 to 0.2 µm by bootstrapping to the ROLO reference lunar disk reflectance spectrum.



SOLSTICE UV measurement capabilities compared to other instruments that have collected lunar UV data [*Snow et al.*, 2013].

UV Expansion

- NASA Grant: LASP Lunar Albedo Measurement and Analysis from SOLSTICE (LLAMAS)
- POCs: Martin Snow and Gregory Holsclaw
- Observing campaign: June 2006 – Dec 2010
- Added Moon to schedule of eclipse observations
- On average, observed one disk-integrated spectrum per day in each channel
- Over 1000 complete spectra in each channel
- Relevant wavelength range: MUV 180 – 309 nm
- Data are grouped into 180 Lunar geometries from phase angles -90.5° – 90.5° and include libration geometry at each phase angle



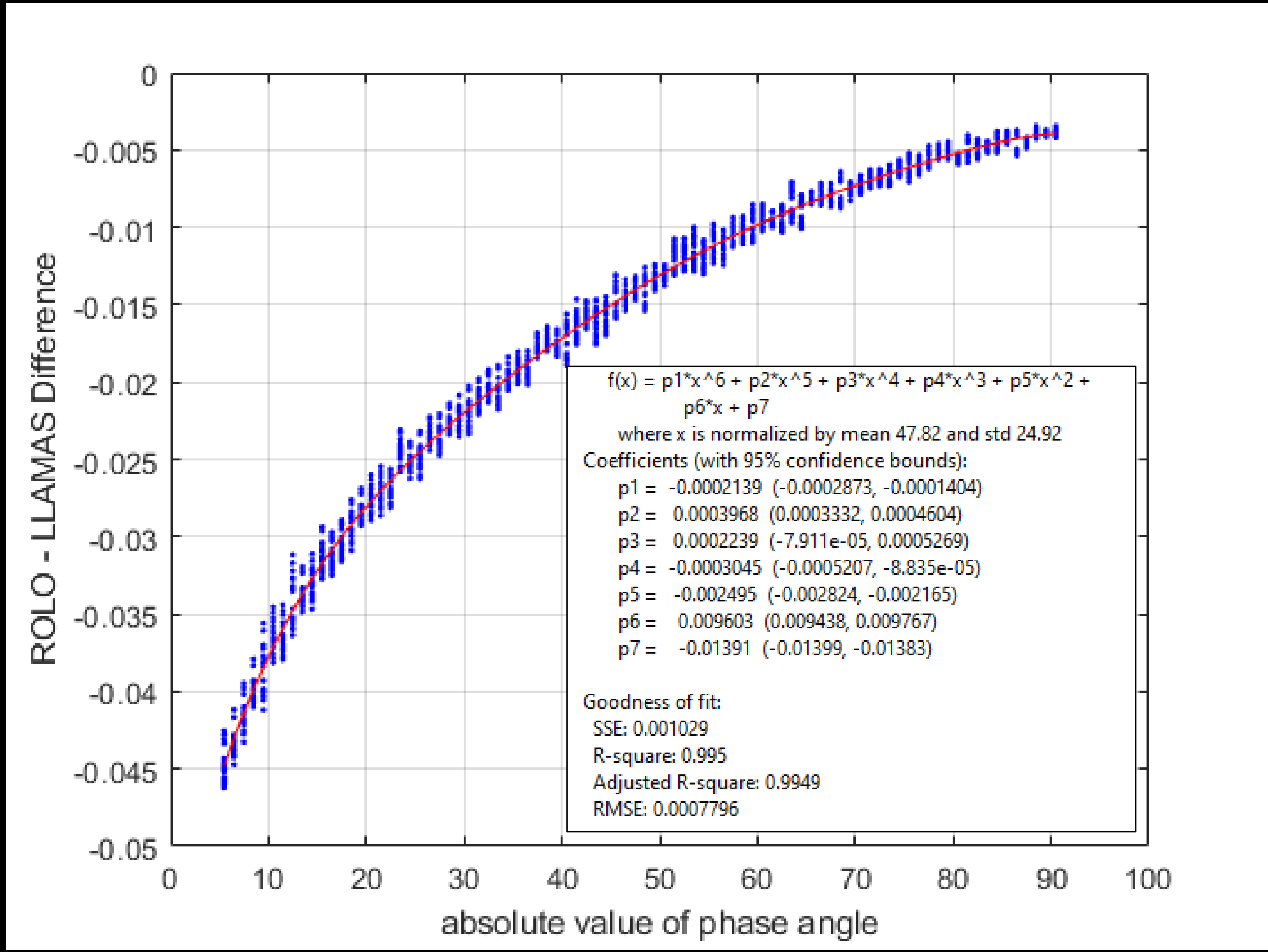
There is an offset between LLAMAS and ROLO (both datasets shown here at -60.5° phase angle)

UV Expansion

1. Operated the ROLO model at all 180 geometries to get a fitted reflectance spectrum at each geometry.

2. Calculated the difference between this fitted ROLO reflectance spectrum and LLAMAS at the overlapping wavelengths between LLAMAS and ROLO (300-309 nm) at all 180 geometries.

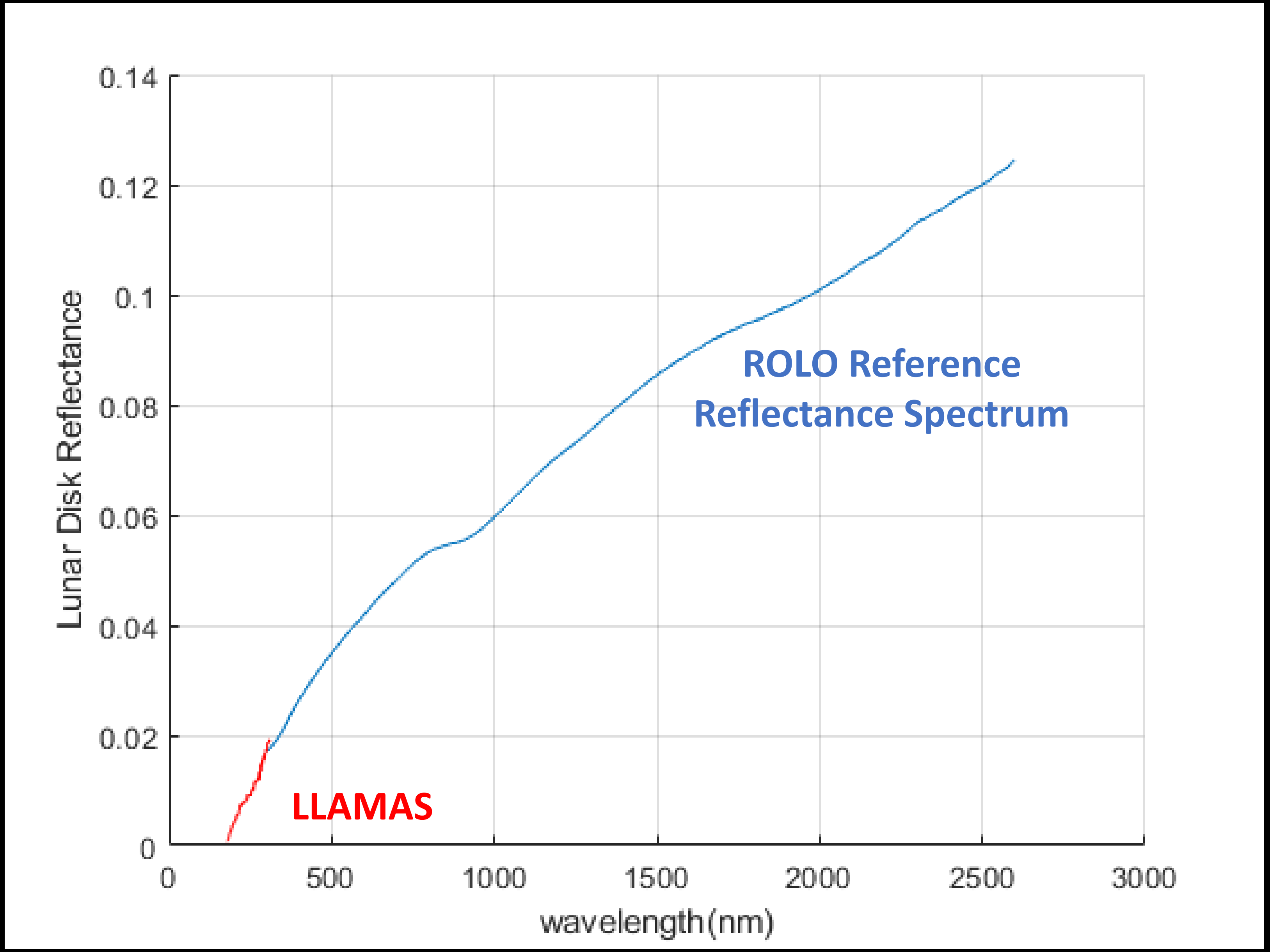
3. Developed an analytic function to fit the difference between ROLO and LLAMAS and calculated coefficients for this fit function (R-square = 0.995)



Analytic fit function: 6 term polynomial

UV Expansion

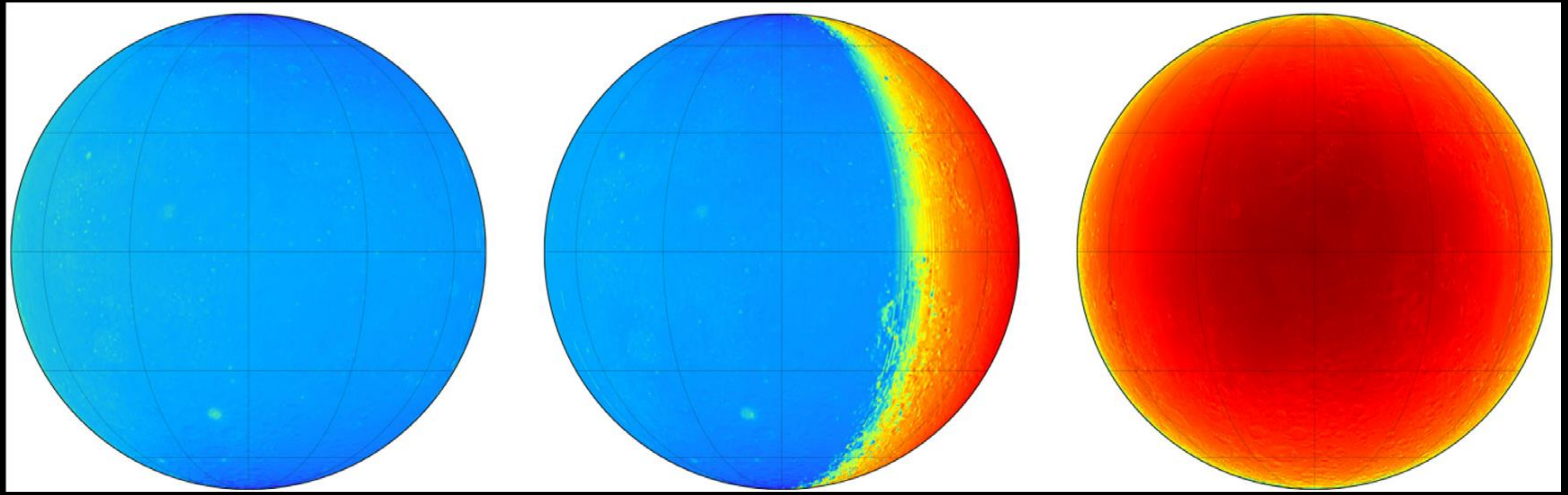
1. Operated the ROLO model at all 180 geometries to get a fitted reflectance spectrum at each geometry.
2. Calculated the difference between this fitted ROLO reflectance spectrum and LLAMAS at the overlapping wavelengths between LLAMAS and ROLO (300-309 nm) at all 180 geometries.
3. Developed an analytic function to fit the difference between ROLO and LLAMAS and calculated coefficients for this fit function (R-square = 0.995)
4. Used this fit function to apply the shifted correction factor to the LLAMAS data at each of the 180 geometries to place them on the same scale as the ROLO data.
5. Averaged the resulting spectra to generate a static LLAMAS UV reference reflectance spectrum that can be bootstrapped onto any ROLO fitted reflectance spectrum by applying offset function for a given phase angle.



Appended LLAMAS data to ROLO reference reflectance spectrum (here, both datasets are averaged over all phase angles and Lunar geometries from LLAMAS)

Future Work: IR Expansion

- Original ROLO spectra were not thermally corrected– will do correction as part of this project.
- Will account for the remaining reflected signal and thermal signal emitted by the sunlit Moon.
- For reflected signal, will do extrapolation of thermally corrected lunar spectral reflectance.
- Will use gridded surface temperature (T) maps at each lunar phase derived from the Diviner instrument to get effective T of lunar disk.
- Wavelength-dependent whole disk radiances for each phase will be computed using the Planck function, and thermal emission will be calculated according to:



Global instantaneous temperatures of the Moon in orthographic projection, with subsolar longitude equal to 180 °, 120 °, and 0 °, respectively [*Williams et al*., 2017].

$$r_s{}^2\, eB_0(T)/F_{Sun}$$

r_s = distance from the Sun to the Moon's surface in astronomical units (AU)

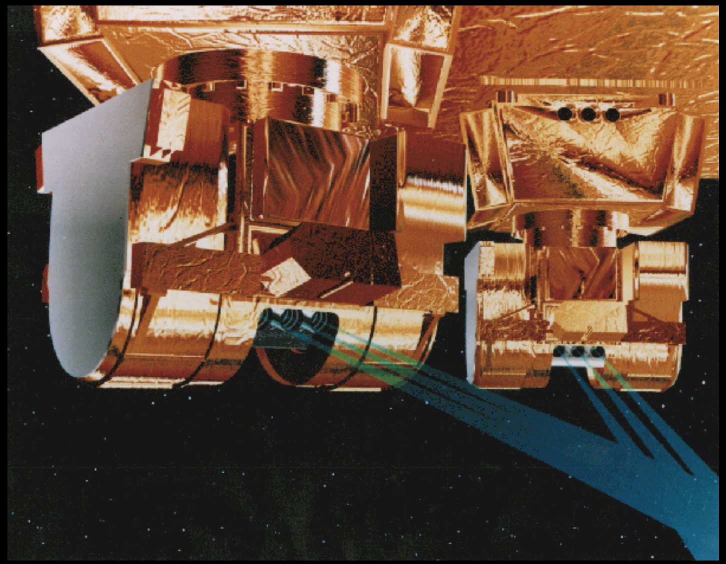
e = spectral emissivity of the Moon

B_o = Planck blackbody equation (T in kelvin)

F_{Sun} = solar flux /π at 1 AU

(e, B_o, and F_{Sun} are each a function of wavelength)

Future Work: CERES comparison



- The CERES instruments are broadband radiometers designed to accurately measure the radiation budget of the Earth and routinely view the Moon to monitor stability.

- We will compare irradiances from the expanded ROLO model and original ROLO model to CERES disk irradiances at the available lunar phase angles.

- The CERES instruments have adequate spectral range with which to compare to the expanded lunar model disk irradiances in the shortwave channel (0.3 – 5.0 μm), and to quantify the thermal contribution from the longwave (5 – 35 μm) and window channels (8 – 12 μm).

Summary

The ROLO lunar reference wavelength range must be expanded to 0.2 – 5 µm to allow for future absolute calibration of ERB sensors!

Important science benefits:

1. Increase calibration accuracy of ERB instruments that have viewed or will view the full lunar disk (enabling earlier detection of trends that are crucial to inform climate policy decisions)

2. Allow NASA & the climate science community to derive additional benefit from missions collecting high accuracy lunar measurements (by providing the expanded lunar model and framework before the data from those missions arrive)

3. Contribute towards a new generation of higher accuracy, measurement-gap-tolerant ERB sensors (with lunar calibration capabilities built-in to the design)

4. Easily enable improvements in the future, and a more user-friendly interface will broaden the impact of lunar calibration

The ROLO model replication, SSI update, and UV expansion portions of this project are completed.
Future work will include the IR expansion and comparison to CERES lunar observations.

A publication detailing the work presented today is being drafted.

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