LUnar Spectral Irradiance and radiance (LUSI): instrumentation to characterize the moon as an SI-traceable radiometric standard

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Background

The radiometric accuracy requirements of satellite sensors needed to understand and monitor climate change are very stringent. Measurements spanning the lifetimes of many instruments must be combined with low uncertainties to detect small changes over decadal time periods. Observing such small climatic changes is complicated by the significant changes in optical sensor performance due to launch and operation in space. A reflected solar wavelengths a low uncertainty absolute on-orbit reference standard is needed to mitigate such sensor changes and to put all sensors on the same radiometric scale. With further development the moon could be that reference.

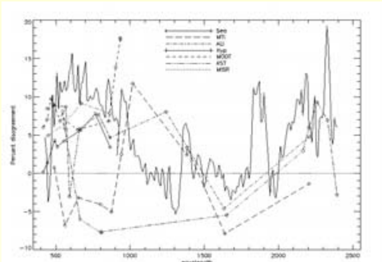
Some identified radiometric accuracy requirements of satellite sensors

Climate Variable	Spectral Range	Accuracy*	Per Decade Stability
Temperature: Tropospheric	Microwave/IR	0.5 K	0.04 K
Stratospheric			
Water Vapor			
Ozone: Total Column	UV/VIS	2% (abs) 1% (rel)	0.2%
Stratospheric		3%	0.6%
Tropospheric		3%	0.1%
Aerosols	VIS	3%	1.5%
Carbon Dioxide	IR	3%	1%
Clouds	VIS/NIR	2-5%	0.5-2%
	IR	1 K	0.2 K
Surface: Snow/Sea Ice	VIS	12%	10%
Ocean Color	VIS	5%	1%
Vegetation	VIS	1%	0.8%
Sea Surface Temp	IR	0.1 K	0.01 K

Source: *Satellite Instrument Calibration for Measuring Global Climate,* Report of a Workshop at the University of Maryland Inn and Conference Center, College Park, MD, November 12-14, 2002, Edited by George Ohring, Bruce Wielicki, Roy Spencer, Bill Emery and Raju Datla, March 2004. NISTIR 7047

*Accuracy has been defined as the difference between measurement and the truth. Here, this is interpreted conservatively as an uncertainty with a coverage factor k=2.

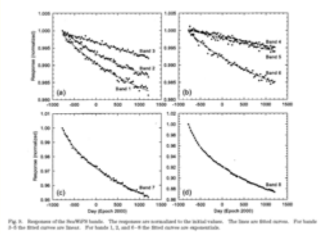
Satellite inter-comparisons show that many of the above requirements are unmet by the current generation satellite sensors. Below is the result of one intercomparison by several instruments that viewed the moon. Disagreements between sensors range from several percent to greater than ten percent—well in excess of the above accuracy and stability requirements.



Lunar cross calibration of remote sensing instruments and the USGS lunar model. The instrument names are abbreviated as follows: Sea = Sea viewing Wide Field of view Sensor (SeaWiFS); MTI = Multispectral Thermal Imager; ALI = Advanced Land Imager on EO-1; Hyp = Hyperion on EO-1; MODT = MOderate resolution Imaging Spectrometer (MODIS) on Terra; ASTER = Advanced Spaceborne Thermal Emission and reflectance Radiometer (ASTER); and MISR = Multiangle Imaging Spectroradiometer on Terra. The ordinate is the percent discrepancy between the irradiance observed by the instruments and that predicted by the model.

At present the uncertainties of best existing lunar model developed at the USGS by Kieffer and Stone [1,2] are too high for its use as a low uncertainty absolute reference suitable for climate study. So far, use of the moon has focused on detecting instrument degradation over time. The SeaWiFS [3] and MODIS [4] sensors have used the moon very successfully in this way.

SeaWiFS Instrument Trend Removal Using the Moon as a Stable Reference. Changes at the 0.1% level can be detected.



Band	Wavelength (nm)
1	412.0
2	444.1
3	490.1
4	510.3
5	554.2
6	608.8
7	763.8
8	866.4

USGS Lunar Model

The USGS lunar model was developed from extensive ground-based lunar observations of the RObotic Lunar Observatory (ROLO) located in Flagstaff Arizona. It is a photometric lunar irradiance model covering 32 filter bands of interest to Earth-observing instruments. The absolute scale is derived from observations of Vega, its published irradiance, atmospheric corrections, and the reflectance of lunar samples retrieved from the Apollo space program.

It accounts for changes in the Sun-Moon-observer geometry to an uncertainty of approximately 1% across differing lunar phases and below 1% across different librations with a restricted range of phase angles.

When interpolating to cross calibrate instruments with differing spectral bands the uncertainty can increase to approximately 3%.

The uncertainty of the absolute irradiance is significantly larger, approximately 10%.

Recent improvements in calibrating spectro-radiometers coupled with observations taken from high-altitude balloon platforms and mountaintops should result in significantly lower sensor calibration uncertainties when using the moon as an on-orbit reference.

1. H. H. Kieffer and Thomas C. Stone, *Astr. J.*, **129**, 2887 (2005)
2. T. C. Stone, H. H. Kieffer and J. M. Anderson, *Proc. SPIE* **4483**, (2002)
3. R. A. Barnes *et. al.*, *Appl. Opt*. **38**, 4649 (2004)
4. J. Sun, X. Xong, B. Guenther, and W. Barnes, *Metrologia* **40**, S85-S88 (2003)

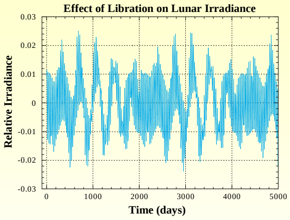
Goals of LUSI

To further develop the moon as an absolute on-orbit SI-traceable reference:

- Reduce the uncertainty of predicting the absolute lunar irradiance to 1% (k=1)
  - This is the best way to ensure a low uncertainty relative spectral scale that is needed for a cross-platform reference
  - A low uncertainty absolute scale allows validation of instrument performance and models used to deduce climate variables
- Increase the spectral resolution—320 nm to 2500 nm continuous with a resolution of approximately 0.3 %.
  - Continuous coverage allows SI-traceable calibration for all satellite instrument bands
  - High spectral resolution reduces sampling/interpolation errors when comparing sensors with different spectral bands
- Measure the lunar radiance to facilitate calibration and characterization of high spatial resolution sensors
- Use Earth-based instrumentation deployable to high-altitude balloon platforms and high-altitude mountaintop observatories to mitigate the effects of the atmosphere. Such an instrument can be based on the latest technology and calibrated in a laboratory frequently unlike satellite sensors that must use space-qualified components and are difficult to retrieve.

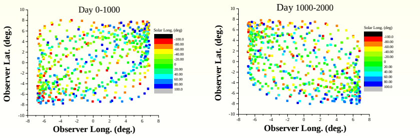
Modeling the Moon

Although the moon can be observed at most of its phases each month, the illuminated surface of the moon facing the Earth is not the same at each monthly phase (the lunar libration effect) . To fully model the effect of lunar libration on the lunar irradiance to better than one percent requires several years of observation.



Previous lunar work has shown that libration affects the lunar irradiance by only a few percent.

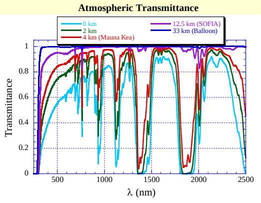
Observations over a 3 year period are expected to provide adequate sampling of the observer seleno-graphic longitude and latitude and the solar selenographic longitude (approximately the signed lunar phase) to develop an irradiance model.



Developing a complete radiance model, one that covers all surfaces of the moon viewable from the Earth will take longer than 3 years. However a partial model one with limited spatial coverage or higher uncertainties could be developed sooner and would be of value.

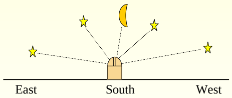
Atmospheric Effects

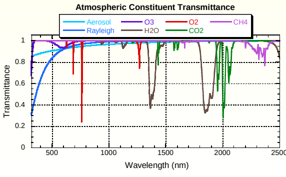
Perhaps the best sub-orbital observation location is the platform of a high-altitude balloon where atmospheric transmittance is greater than 99% over most bands of interest. But, balloon launches are a limited resource and regular lunar observations are needed to fully model the effects of phase and libration. To make the most of balloon flights, observations from high altitude mountaintops through atmospheric window bands are planned. The balloon flights are to extend wavelength coverage and provide validation of the atmospheric corrections and uncertainties developed from the mountaintop measurements.



Even from the best astronomical observatories there is still significant atmospheric extinction through window bands. Therefore accurate atmospheric corrections are needed. Development of accurate corrections and equally importantly their uncertainties is expected to come primarily from observations of stars through varying air masses combined with an atmospheric model.

Observations of stars as their light passes through varying air masses (nearer the horizon) provide atmospheric corrections and a catalog of top-of-the atmosphere stellar irradiances. Once known, the latter can provide atmospheric transmittance with an observation through a single air mass.



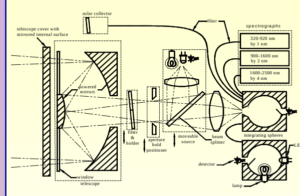


High spectral resolution measure-ments will be invaluable in develop-ing atmospheric corrections due to molecular species. Each has distinct transmittance spectra that, when combined with high spectral resolution data, allows testing of the atmospheric model as the problem is over specified.

Modeling aerosols is more difficult as they are spectrally smooth and highly variable. These problems can be addressed using LIDAR and observation locations with minimal aerosol extinction, such as the observatories at Mauna Loa and Mauna Kea where the aerosol optical depth is below 1 % on many days (according to AERONET).

Irradiance Instrumentation

Design of the lunar irradiance instrument is simplified by the existence of commercially available spectrographs. These spectrographs can be stable and the sub-components are readily available to make a custom instrument. To account for their non-uniform response and the non-uniformity of the lunar image, the spectrographs are illuminated by an integrating sphere at the focus of a conventional 25 cm diameter telescope.

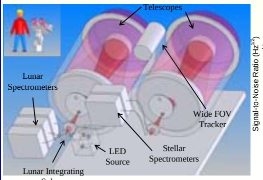


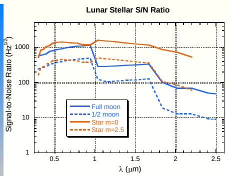
Stability monitors, LEDs, lamps and detectors are to detect changes in the optical through-put and spectrograph responsivity.

A filter wheel is to contain band pass filters for end-to-end validation, a wavelength standard, and linear polarizers to measure the lunar polarization.

A solar collector is to measure the sun during the day to provide lunar reflectance as a secondary data product.

A similar simpler instrument that observes stars is to provide atmospheric corrections. In this instrument starlight is directly coupled into the spectrographs. Both instruments together are compact enough to fit on a single mount and to fly on a high-altitude balloon.

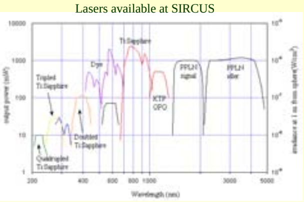




Calibration and Characterization

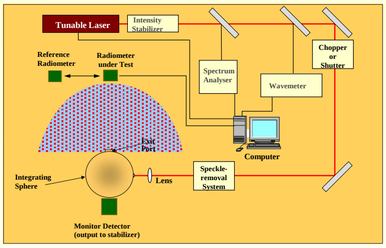
Extensive calibration and characterization of the instruments would be performed at the facility for Spectral Irradiance and Radiance responsivity Calibrations with Uniform Sources [5,6]. This is a detector based facility, whose fundamental scale is optical power that is set by cryogenic Active Cavity Radiometers. Laser sources transfer the power scale to reference detectors which in-turn are used to derive irradiance and radiance responsivity scales using laser fed integrating spheres (uniform sources) together with precision apertures and known illumination geometry.

Lasers available at SIRCUS



Reference detectors to cover the reflected solar range

- Si 210-950 nm
- InGaAs 900-2500 nm
- Pyro-electric 210-2500 nm



Laser fed integrating sphere sources generate uniform illumination at high flux levels of known wavelength. They can be viewed directly or with a collimator to measure system level spectral radiance or irradiance responsivity.

Characterization of the lunar instrumentation is to include:

- End-to-end spectral responsivity including out of band spectral response—allows correction of spectrograph stray light
- Point spread function of the imaging instrument
- The stability of internal monitors and responsivity with temperature and pressure changes

Uncertainties of the lunar measurements are expected to be dominated by the instrumentation stability and the atmospheric corrections. Uncertainties in calibration transfer from SIRCUS scales should be relatively small:

- Scale transfer to lunar instruments 0.2 %
- Stability of instrumentation on deployment 0.3 %
- Atmospheric Corrections 0.5 %
- Total uncertainty 0.6 % (k=1)

5. S. W. Brown, G. P. Eppeldauer and K. R. Lykke, *Metrologia* **37**, 579 (2000)
6. G.P. Eppeldauer *et. al.*, *Metrologia* **37**, 531 (2000).