# THE MOON AS A RADIOMETRIC REFERENCE SOURCE FOR ON-ORBIT SENSOR STABILITY CALIBRATION

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## 1. INTRODUCTION

The increasingly extensive history of Earth observations from space has enabled the development of climate records and seeking the signatures of climate change through assimilation of data products from multiple space-based remote sensing instruments. Among the data Quality Assurance needs to accomplish this task is for the sensors to maintain consistent calibration over time and between instruments. A particular difficulty for on-orbit calibration of radiometer instruments in the visible to near-infrared wavelength range arises from the lack of reliable, SI-traceable standards suitable for spaceflight use. One mitigating approach utilizes common observations by satellite instruments of stable and/or well-characterized ground targets, e.g. the Antarctic Dome-C comparison campaign of Dec. 2008–Jan. 2009, initiated by the Committee on Earth Observation Satellites (CEOS) (cf. `http://calvalportal.ceos.org` → Projects → Dome C Campaign 2008).

The Moon provides a common target that is available to all Earth-orbiting instruments. As a calibration source, the Moon has many favorable properties, including the absence of intervening atmosphere, but it requires special methods for its use. This paper describes current capabilites of lunar calibration to meet instrument calibration consistency needs.

## 2. THE MOON AS AN ON-ORBIT CALIBRATION SOURCE

Although the Moon is a well-known luminous object, only recently has its brightness been characterized sufficiently quantitatively for consideration as a radiometric reference. Because the amount of light received from the Moon varies continuously with Sun-Moon-Observer geometry, primarily the familiar phases but also due to the lunar librations and its non-Lambertian reflectance properties, practical use of the Moon requires the ability to accommodate the particlar conditions of lunar observations made by spacecraft instruments. This is accomplished through photometric modeling. Reasonable model accuracy can be attained only with an extensive set of basis measurements spanning several years[1].

The lunar surface reflectance is effectively invariant[2], the result of eons of exposure to the space environment. This means that a lunar model, once established, is valid for any time — a key consideration for its use for long-term sensor calibrations. An additional effect of the highly weathered lunar surface is the near-obliteration of spectral absorption features of the soil constituent minerals, thus the fine structure of the reflected solar spectrum is largely preserved. At visible wavelengths, the sunlit lunar surface presents a range of radiance levels similar to those of clear land observed from space.

## 3. UTILIZING THE MOON FOR CALIBRATION PURPOSES

### 3.1. The USGS lunar spectral irradiance model

The measurements needed to specify the lunar brightness have been acquired and a model for the lunar spectral irradiance has been produced by the lunar calibration program at the US Geological Survey in Flagstaff, AZ, under NASA sponsorship. Utilizing the irradiance quantity simplifies the modeling and its application, and takes advantage of the improved signal to noise gained through spatial integration of radiance imagery. The model analytic form is an empirically derived function of the geometric variables of phase and lunar libration[3]. For each of 32 wavelength bands $k$, spanning 350 nm to 2450 nm:

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

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where $A_k$ is the disk-equivalent reflectance in band $k$, $g$ is the absolute phase angle, $\theta$ and $\phi$ are the selenographic latitude and longitude of the observer, and $\Phi$ is the selenographic longitude of the Sun. There are 18 coefficients for each band, eight of which are common across all bands ($c_n$, $p_n$). The 320 wavelength-dependent coefficients are available in electronic form (ascii table) to individuals wishing to replicate the model by contacting the author.

### 3.2. Capability for calibration stability monitoring

The ability to use the Moon as a stable source for spaceflight instrument calibration derives from the inherent stability of the Moon's reflectance and the precision with which the lunar irradiance model can predict the variations in brightness with geometry (illumination and viewing). At the spatial resolution of typical Earth-observing imagers, the lunar surface is considered stable at better than one part in $10^8$ per year[2]. Development of the lunar model has fitted the set of ground-based measurements with a mean residual $\sim$1%; this value represents a measure of the model's relative predictive capability.

Sensor calibration stability is derived from analysis of multiple observations of the Moon over time, where the variations in the observed lunar irradiances are offset using lunar model prediction results. With a time series of Moon observations collected by an instrument, sensor calibration stability with sub-percent per year precision can be achieved. This has been demonstrated by the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) instrument, which has acquired monthly lunar observations since November, 1997. Calibration corrections for all eight SeaWiFS bands have been developed from fitting analytic functions to the SeaWiFS lunar irradiance measurements, normalized by the lunar model results. The corrected sensor calibrations are stable at better than 0.1% over the 9+ year lifetime of the instrument[4].

### 3.3. Spacecraft operations for lunar observations

Earth-observing instruments in low-Earth orbit (LEO) typically must view the Moon by turning the spacecraft. The OrbView-2 satellite, which carries the SeaWiFS payload, has performed pitch-over maneuvers nearly 200 times to view the Moon. Small roll maneuvers of both the Terra and Aqua spacecraft allow the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments to view the Moon about 9 months of each year at nearly the same phase angle through a space-view port.

For calibration stability monitoring, viewing the Moon once per month is a recommended minimum frequency. Establishing a baseline for trending can be accomplished during a satellite's post-launch pre-commissioning phase, or combined with other major calibrations events such as deployment of a pristine solar diffuser. Best practices dictate multiple observations for baseline data, and for regular observations, if possible, to smooth random errors in the irradiance comparisons.

## 4. CONCLUSIONS

Using the Moon for on-orbit calibration requires special methods, both for initially establishing the lunar source as a reference and for the acquisition and processing of lunar observations made by spacecraft instruments. An analytic model is used to provide the calibrated brightness of the Moon corresponding to the geometries of spacecraft lunar views. In effect, the model becomes the reference standard.

Viewing the Moon under favorable conditions (i.e. large illuminated fraction, from the shadowed portion of the orbit) typically requires an attitude maneuver for LEO spacecraft, which can be problematic for those not designed with this capability. Because lunar calibration can meet calibration stability requirements for climate measurements from space, adding specifications to allow viewing the Moon may become necessary for the designs of future Earth observing instruments and spacecraft, possibly through a mandate by funding agencies.

## 5. REFERENCES


[1] H. H. Kieffer and R. L. Wildey, "Establishing the Moon as a spectral radiance standard," *J. of Atmospheric and Oceanic Technology*, vol. 13, no. 2, pp. 360–375, 1996.

[2] H. H. Kieffer, "Photometric stability of the lunar surface," *Icarus*, vol. 130, pp. 323–327, 1997.

[3] H. H. Kieffer and T. C. Stone, "The spectral irradiance of the Moon," *Astronom. J.*, vol. 129, pp. 2887–2901, 2005.

[4] R. E. Eplee Jr., S. W. Bailey, R. A. Barnes, H. H. Kieffer, and C. R. McClain, "Comparison of SeaWiFS on-orbit lunar and vicarious calibrations," *Proc. SPIE*, vol. 6296, pp. 629610–1–7, 2006.