Briefing paper on new measurements of the Moon to improve lunar calibration capabilities


Introduction and Background

The Moon presents a useful light source for calibration of Earth-observing sensors in orbit, but its constantly changing brightness (primarily the familiar lunar phases) requires special techniques to use it. These techniques have been developed by the U.S. Geological Survey’s Lunar Calibration project in Flagstaff, Arizona. The procedure involves predicting the lunar disk-integrated irradiance for the specific conditions of an instrument’s observations of the Moon by computing an analytic model. Lunar calibration has successfully been utilized with a number of NASA research instruments and with imagers on operational meteorological satellites having sensors in the reflective solar wavelength range. The USGS lunar irradiance model [1] is considered the international reference standard for calibration against the Moon.

The USGS Robotic Lunar Observatory (ROLO) was developed as a proof-of-concept for lunar calibration. The observatory telescopes operated for more than eight years, and the ROLO lunar model was built from thousands of lunar measurements in each of 32 wavelength bands. This analytic model is the key to using the Moon as a calibration reference—it allows accommodating the various geometries of solar incidence and sensor viewing for any Earth-orbiting instrument’s observations. The model predicts with high precision the changes in the lunar brightness due to varying phase angle and the lunar librations (i.e. the particular hemispheres of the Moon that are illuminated and viewed). These predictions enable quantitative evaluation of sensor response changes over time with sub-percent precision, as demonstrated for the Visible-Infrared Imaging Radiometer Suite (VIIRS) on the S-NPP satellite [2] and the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) [3], among many others. The efforts dedicated to these instruments attest to lunar calibration being essential for space-based ocean color measurements, in particular.

The need for new measurements: limitations of the current lunar calibration system

Currently the Moon is rarely used as an absolute calibration reference. This can be attributed to the 5-10% uncertainty in the absolute scale of the ROLO model, which traces back through the telescope image database. The absolute scale of the ROLO database is derived from observations of the star Vega. Since these calibration measurements were acquired with ground-based telescopes, they require correction for atmospheric transmission, which constitutes the largest source of uncertainty in ROLO data. The ROLO measurements of Vega are scaled to published stellar energy distributions, and the end-to-end calibration process lacks robust traceability to Système International (SI) units.

Some Earth remote sensing instruments launched in recent years have exhibited capabilities for very high quality lunar imaging (e.g. PLEIADES) and lunar radiometry (e.g. S-NPP
VIIRS). The application of lunar calibration techniques to these instruments’ Moon observations has revealed some residual geometry dependencies in the ROLO model, which were masked by noise levels in earlier instruments. These findings are the subject of ongoing studies within the USGS Lunar Calibration project, and some dependencies may be mitigated by a reprocessing of the ROLO lunar database, anticipated to occur in 2015.

But the ROLO database, although extensive and unique, has some inherent limitations. Foremost among these is the range of observation zenith angles for stellar data acquisitions, which are used to derive atmospheric transmission corrections for the Moon and Vega measurements. This operational constraint ultimately limits the accuracy that is achievable for the atmospheric corrections of ROLO data, and thus the absolute accuracy of the ROLO lunar model.

To utilize the Moon as an absolute calibration source requires reducing uncertainties in the lunar reference to under 1% (k=1) over the entire reflected solar spectral range, with assured traceability to SI. The current best lunar radiometric reference, the ROLO irradiance model, cannot meet these standards. To meet this objective requires acquiring a new lunar measurement database.

The current limitations of lunar calibration are attributes of the ROLO lunar model, not the Moon itself as a reference. The reflectance properties of the lunar surface are exceptionally stable, and the variations in photometric geometry (the phase and librations) are periodic and predictable. Thus the Moon’s constantly changing brightness can be characterized quantitatively to the limits of accuracy achievable for field radiometric measurements, considered to be at the sub-percent level. Once the lunar reflectance function is parametrized in a model (built from the measurement database), the Moon’s inherent stability means this model is valid for any time, including the past. It then follows that any calibrations derived from observations of the Moon can be improved post-facto using the improved lunar model.

Key requirements for a new lunar measurement dataset

The experience gained from the ROLO project has shaped the approach to acquiring new lunar characterization measurements. Multiple independent requirements drive the need for both a ground-based facility, for long-term acquisitions, and a flight component, for absolute scale validation.

The primary requirement is absolute accuracy of the lunar radiometry, with assured SI traceability. This in turn requires that the radiometer instruments be calibrated frequently, and must allow for the field calibration test equipment to be re-calibrated (in the laboratory) periodically. Thus practical considerations point to a ground-based facility to be used for the majority of observations. Acquiring lunar radiometric measurements from a ground site constrains the observing to local nighttime, imposing a limitation on the phase and libration geometries that can be acquired on a given night. It also requires corrections for observing through the atmosphere. To minimize the error contribution from atmospheric correction, the measurements are best acquired from a high-altitude astronomical observatory site. It is anticipated that the Mauna Loa Observatory in Hawaii may be used for this ground-based
Extensive coverage of the lunar phases and librations is critical for conversion of the new measurement dataset into a radiometric reference (lunar model) that is valid and usable for satellite calibration. Since the geometric coverage is governed by the Moon’s orbit and its availability to be observed from a terrestrial site at night, several years of observations are required to fill out the geometric parameter space. The minimum duration is estimated to be three years [4]; ROLO operated for more than eight years, from a site on the USGS campus in Flagstaff. However, the high-accuracy measurements acquired in the interim period are immediately useful for improving the existing lunar calibration system, by bootstrapping to the ROLO dataset and re-formulating the lunar models. But the goal is to enable modeling based solely on the new measurements.

The new measurements must cover the reflected solar spectrum continuously from the atmospheric UV cutoff near 0.32 µm to 2.5 µm. Continuous spectral coverage at moderate resolution (e.g. 0.3 nm) will improve the accounting for differences in the spectral response functions of various instruments, which is an important consideration for cross-calibration. Additionally, spectral measurements will provide significantly improved atmospheric corrections than are possible with ROLO’s multi-band sensors. It is anticipated that the new measurement instrumentation can achieve at-telescope radiometric accuracy at the sub-percent level. Thus corrections to top-of-atmosphere measurements remain the largest sources of error.

To reduce the uncertainty in atmospheric correction to the minimum possible, actual measurements taken from above the atmosphere are needed. Acquisitions from a flight instrument can be infrequent, sampling a small subset of phases and librations. The purpose is to anchor the absolute scale of the lunar measurements and models. This can be done in terms of lunar disk reflectance with an instrument capable of observing the Sun and Moon in rapid succession, such as demonstrated by the LASP HyperSpectral Imager for Climate Science. An essential requirement for the flight instrument is pre- and post-flight laboratory calibration, thus a balloon or sounding rocket platform is needed; deployment on a free-flying satellite is not appropriate.

**Summary of the key requirements:**

- high-accuracy measurements, with frequent on-site calibration to assure SI traceability
- long-term ground-based measurement campaign, to provide sufficient phase and libration coverage for modeling
- location at a high-altitude astronomical observatory site
- continuous spectral coverage over the entire reflected solar wavelength range
- flight observation component, for absolute validation measurements above the atmosphere
Benefits of an improved lunar calibration system

With a high-accuracy, SI-traceable absolute lunar reference, all sensors that have viewed the Moon can be calibrated to the same standard, and thus cross-calibrated with each other. This capability has important implications for climate monitoring and detecting climate change. It enables merging archived Earth imaging data from a series of instruments into contiguous records by placing them on a common radiometric scale. These datasets extend back many years, decades in the case of meteorological satellites. For example, geostationary operational imagers routinely capture the Moon by chance in the margins and corners of a rectangular field of regard. Hundreds of Moon images have been found in the archives of Meteosat imager data. Lunar calibration analysis provides a common link to develop climate data records from these archives; research activities to this end are ongoing at the Meteosat operations agency, EUMETSAT.

An accurate absolute lunar reference also can serve a critical function for bridging a gap in otherwise continuous observations made by a series of research satellites, where the objective is long-term monitoring of Earth environmental variables, and a break in the series could be terminal.

Considered as a calibration target, the Moon is an exceptionally stable diffuse reflector of sunlight, and it is observable from all Earth orbits. For reflected solar instruments, lunar calibration may be the only feasible solution for transfer-to-orbit calibration consistency. The challenges of on-orbit calibration at these wavelengths are significant — on-board solar diffusers suffer degradation from operating in the space environment, and sources of illumination that are reliable and stable in vacuum and zero gravity are still under development.