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

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ABSTRACT

The wealth of data generated by the world's Earth-observing satellites, now spanning decades, allows the construction of long-term climate records. A key consideration for detecting climate trends is precise quantification of temporal changes in sensor calibration on-orbit. For radiometer instruments in the solar reflectance wavelength range (near-UV to shortwave-IR), the Moon can be viewed as a solar diffuser with exceptional stability properties. A model for the lunar spectral irradiance that predicts the geometric variations in the Moon's brightness with $\sim$1% precision has been developed at the U.S. Geological Survey in Flagstaff, AZ. Lunar model results corresponding to a series of Moon observations taken by an instrument can be used to stabilize sensor calibration with sub-percent per year precision, as demonstrated by the Sea-viewing Wide Field-of-view Sensor (SeaWiFS). The inherent stability of the Moon and the operational model to utilize the lunar irradiance quantity provide the Moon as a reference source for monitoring radiometric calibration in orbit. This represents an important capability for detecting terrestrial climate change from space-based radiometric measurements.

Index Terms— Moon, Calibration, Radiometry, Measurement standards

1. INTRODUCTION

The archive of environmental monitoring data from space-based remote sensing instruments now spans decades in time, leading to efforts toward assembling the multitude of observations into long-term records of the Earth's climate. Building a self-consistent environmental record from the data and products of many different instruments on different platforms requires development of methods to verify calibration accuracy over the instruments' lifetime, often exceeding the specifications to which they initially were designed. For radiometer instruments in the solar reflectance wavelength range, roughly 350 nm to 2.5 μm, maintaining calibration in orbit is complicated by the lack of reliable, SI-traceable standards suitable for flight use, and the degradation of on-board calibration apparatus in the space environment. Dedicated field campaigns involving simultaneous measurements of uniform ground sites have achieved high-accuracy point calibrations, but the stability of uninstrumented ground sites cannot be assured — an important consideration for long-term calibration efforts.

The Moon provides a luminous target that is accessible to spacecraft in any Earth orbit. However, the complex nature of the Moon's reflectance and appearance means that its use requires special methods for both characterization of the source and acquisition and analysis of lunar views by instruments in orbit. But the exceptional stability of the lunar reflecting surface combined with the absence of intervening atmosphere has led to the Moon being considered a reference standard for stability calibration of solar-band radiometer instruments.

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2. THE MOON AS A REFERENCE SOURCE

Although the Moon is a well-known luminous celestial object, only recently has it been measured with sufficient breadth of coverage to enable precise prediction of the brightness variations with Sun-Moon-Observer geometry. These variations arise from primarily the familiar phases, but also the lunar librations and the distinctly non-Lambertian lunar reflectance behavior. Practical use of the Moon requires a continuous predictive capability in order to accommodate the particular conditions of lunar observations made by spacecraft instruments. Such a capability takes the form of an analytic model.

The Moon presents a spatially extended radiance target, whose brightness falls within the dynamic range of Earth reflectance measurements. Figure 1 shows histograms of pixel values for two identical-sized subsamples extracted from a full-Earth visible channel image taken from geostationary orbit (GOES-12, 2004 August 30 17:45:14). The Moon was captured in overscans of the Earth disk, in the corner of the field of regard. The Moon subsample (top) has a large peak at the space background level of 29 DN, clipped in the figure by the scaling. The terrestrial subsample (bottom) shows response peaks corresponding to ocean $\sim$70 DN, clear land $\sim$100–260 DN, and cloud $\sim$270–400 DN.

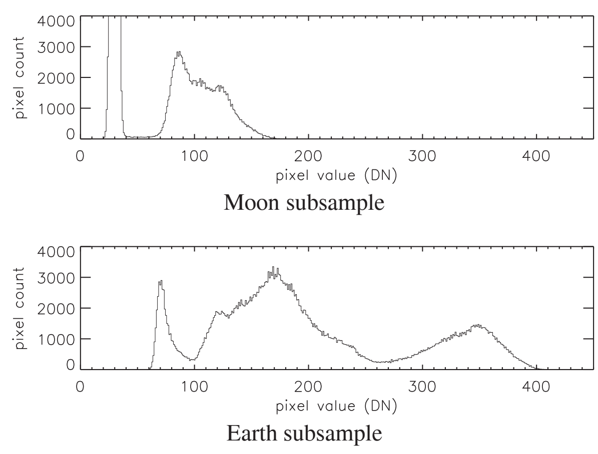

Fig. 1. Histograms of raw sensor counts for two identical-sized subsampled regions of a GOES-12 full-Earth image. The space-level counts have been clipped by the scale for clarity.

The reflectance properties of the lunar surface are relatively invariant, the result of eons of exposure to the space environment. At the spatial scales of typical Earth-observing instruments, the Moon is considered photometrically stable to better than one part in 10^8 per year[1]. Additionally, the impact of ionizing radiation and pulverization of the lunar soils by micrometeorite bombardment has nearly obliterated significant spectral absorption features of the soil constituent minerals, thus largely preserving the fine structure of the reflected solar spectrum. The inherent stability of the Moon means that a lunar model, once established, is valid for observations acquired at any time — a key consideration for long-term sensor calibrations. A further consequence, in consideration of the necessity to use a model to accommodate instrument lunar views, is that the model becomes the *de facto* reference standard — an analytic representation of the physical artifact (the Moon).

3. UTILIZATION OF THE MOON FOR ON-ORBIT CALIBRATION

Because observations of the Moon by satellite instruments may be acquired at arbitrary view angles (within the constraints of orbital mechanics), lunar calibration utilizes an analytic model that is continuous in the geometric variables of illumination and viewing. The precision of such a model is governed by the extensiveness of the measurements used in its formulation. For the Moon, adequate coverage of both phase and the lunar librations can only be achieved with measurements spanning an appreciable fraction of the 18.6-year lunar phase-repeat cycle[2].

3.1. Lunar model development

Providing the foundation for an analytic model of the lunar spectral irradiance, a set of radiance images of the Moon covering phases from First Quarter through Full Moon to Last Quarter for more than 8 years has been collected by the lunar calibration program at the U.S. Geological Survey (USGS) in Flagstaff, AZ. The irradiance quantity was chosen to simplify the model development, but it also has a signal-to-noise advantage gained from summation of many image (radiance) pixels. However, this means the entire Moon should be captured in the field of regard of spacecraft instruments in order to have meaningful comparisons to the model predictions.

The USGS development of the lunar spectral irradiance model is described in detail in [3]. The empirical disk-equivalent reflectance function has terms to characterize basic phase, asymmetry of the surface albedo, librations in longitude and latitude, and the backscatter increase at small phase angles known as the opposition effect. The 320 coefficients of the wavelength-dependent model terms are available in ASCII text format by request to the author. Figure 2 shows the modeled disk-equivalent reflectance for $\sim$1200 fitted data points at 550 nm. The mean absolute residual from fitting 32 wavelength bands in the range 350 nm to 2450 nm is $\sim$1%; this is a measure of the precision with which the model can predict the variation in lunar irradiance over the range of the geometric variables.

3.2. Spacecraft operations for lunar observations

Earth-observing instruments in low-Earth orbit typically must view the Moon by turning the spacecraft. The OrbView-2 satellite, which carries the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) payload, has performed pitch-over maneuvers nearly 200 times to date to view the Moon. Small roll maneuvers of both the Terra and Aqua

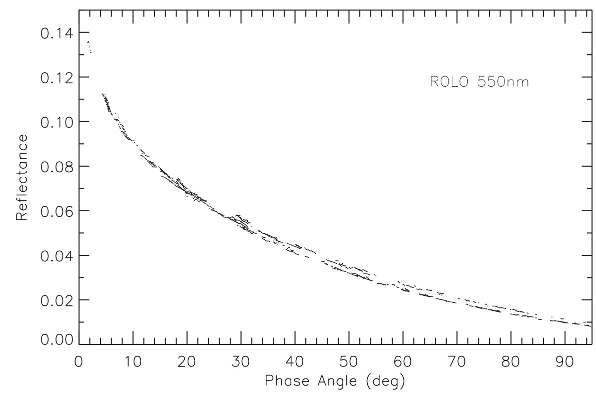

Fig. 2. Modeled lunar disk-equivalent reflectance. Data points are model results corresponding to $\sim$1200 observations acquired by the USGS Robotic Lunar Observatory (ROLO), in the 550 nm band. The two distinct branches show the asymmetry in waxing and waning lunar phases due to the distribution of mare and highland terrain types. The deviations from a smooth phase curve show the effects of the different libration states of the observational data.

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. Imagers on meteorological satellites in geostationary Earth orbit can capture the Moon in the margins and corners of a rectangular field of regard. These chance observations allow calibration of the visible channel sensors, which typically do not have on-board calibration systems, if the off-Earth image pixels have been preserved in archived data.

A number of spacecraft regularly view the Moon near 7 degrees phase angle. This choice provides a high irradiance signal while avoiding the increased backscatter of the opposition effect region and its associated increase in lunar model uncertainty. Acquiring multiple observations within a narrow range of phase angles can effectively reduce uncertainty in the series of model results and comparisons to instrument observations, by both limiting the dynamic range of the predicted irradiances and allowing greater consistency in the computation of instrument irradiance measurements. However, restricting the phases to a narrow range is not a requirement; the model precision of $\sim$1% extends over the full range of valid phase angles.

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 measured irradiance computations.

3.3. Comparison of measured and modeled irradiances

In operation, the USGS lunar calibration system provides the spatially integrated lunar irradiance corresponding directly to observations taken by spacecraft instruments. Model results are interpolated or convolved to the instrument wavelength bands, and account for the $1/r^2$ dependence on Sun–Moon and Moon–spacecraft distances.

For imaging systems, instrument irradiances are derived from radiance measurements (i.e. pixels) on the lunar disk. The detector response to the background of deep space surrounding the Moon is needed, usually taken to be zero radiance, although many sensors have sufficient dynamic range to detect stars in the space field. The irradiance is computed from the sum:

$$I = \Omega_p \sum_{i=0}^{N} L_i$$

where Ω_p is the solid angle of a detector element, L_i is the detector response to the Moon, calibrated to radiance, and N is the count of elements determined to be on the lunar disk. In practice, this number often includes signal from the scattered light around the bright disk.

4. CAPABILITY FOR CALIBRATION STABILITY

The inherent stability of the Moon's surface reflectance enables precise characterization of its cyclic brightness variations. A high-precision analytic model provides the Moon as a stable reference against which to compare lunar measurements taken by radiometer instruments. Sensor calibration stability is derived from temporal analysis of multiple observations of the Moon compared against the lunar reference.

Given a series of Moon observations by an instrument spanning a sufficient length of time, calibration stability with sub-percent precision can be achieved, as has been demonstrated by the SeaWiFS instrument. SeaWiFS has acquired lunar observations monthly since November, 1997. Using computations of the USGS lunar model to offset the variations in the observed irradiance due to geometry (phase, libration, etc.), sensitivity degradations were revealed in all 8 SeaWiFS bands, particularly noticeable in bands 7 (765 nm) and 8 (865 nm), as shown in Figure 3 (top). The SeaWiFS radiance calibration now includes a time-dependent correction to the sensor responsivity, developed from the lunar calibration results. Applying this trend-corrected calibration to the SeaWiFS lunar irradiance measurements gives the model comparisons shown in Figure 3 (bottom). The corrected SeaWiFS radiometry is stabilized to better than 0.1% over the 9+ year lifetime of the instrument[4].

The successful stabilization of SeaWiFS calibration using the Moon as a reference has shown the value of acquiring lunar observations as part of standard flight operations. Since 2006 the U.S. National Oceanic and Atmospheric Administration (NOAA) has instituted a program of regular observations of the Moon by the U.S.-observing pair of Geostationary Operational Environmental Satellites (GOES-East and GOES-West). The JAXA Greenhouse Gases Observing Satellite "IBUKI" (GOSAT), launched in January, 2009, has viewed the Moon during its post-launch initial calibration and verification operations. A number of upcoming missions have included lunar calibration as part of their on-orbit calibration plans, e.g. the Landsat Data Continuity Mission (LDCM) and METEOSAT Third Generation.

5. CONSIDERATIONS FOR LUNAR CALIBRATION AT INFRARED WAVELENGTHS

Although the current lunar calibration program at USGS provides the Moon as a radiometric reference for solar-band instruments, there is considerable interest in extending the technique to mid-wave and thermal infrared (IR) wavelengths. The development efforts required would be similar to those of the shortwave system,

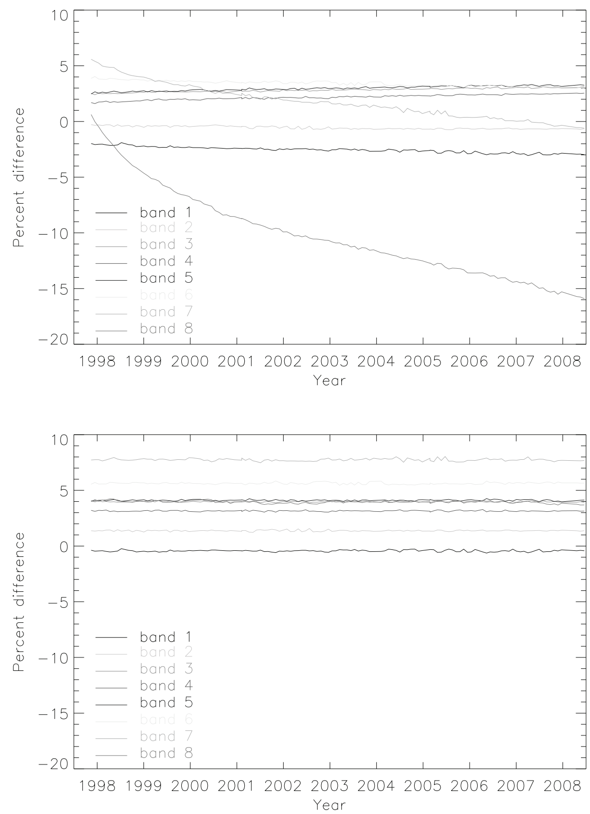

Fig. 3. SeaWiFS lunar irradiance comparisons to model predictions. The difference is given by: $\left[\frac{\text{measured}}{\text{model}} - 1\right] \times 100\%$. (top) Uncorrected measurements show steady changes in the SeaWiFS sensor response over time, particularly band 7 and band 8. (bottom) Results of applying a temporal correction for the sensitivity degradation — the lunar irradiances measured using the revised SeaWiFS calibration are steady to under 0.1% over 9+ years. The inter-band offsets show the difference in absolute calibration between SeaWiFS and the lunar model.

but the IR region poses a number of significant challenges. As with the solar-reflected wavelengths, extensive characterization of the variation in lunar brightness with geometry would be needed. These are difficult measurements to acquire with ground-based instrumentation, due in part to the thermal background signal from the atmosphere.

Establishing an IR lunar reference also would require a model of the thermal properties of the Moon. This is particularly challenging, given the highly variegated and non-Lambertian IR emission characteristics of the lunar surface[5]. The variation in temperature across the sunlit surface can reach 70K–80K, while local variations associated with topography $\sim$5K have been observed. The brightness temperature varies from $\sim$320K near the terminator to close to 400K at the sub-solar point. Additionally, an IR lunar model must account for the thermal inertia across the terminator.

Typical Earth-observing infrared imaging instruments may require gain adjustments in order to observe the Moon for radiometric calibration, since the sunlit lunar surface emits up to 2 times the normal Earth upwelling radiance, while the unilluminated hemisphere can reach temperatures as low as 40K. However, the NASA Clouds and the Earth's Radiant Energy System (CERES) instruments regularly have acquired raster scans of the Moon for spatial response characterizations of their thermistor bolometer sensors. A recent study has developed a methodology to derive calibration stability from the CERES lunar observation data[6].

6. CONCLUSIONS

The task of the current and next generation of Earth-observing satellites to measure climate and detect climate change has led to increasingly stringent calibration requirements for space-based instruments[7], and has focused efforts on achieving these calibration benchmarks. Assuring long-term stability in sensor response is essential for the climate task, but this remains a challenge for radiometric instruments in the solar-reflected wavelength range due to the lack of radiometric standards suitable for spaceflight use, the degradation suffered by on-board calibration systems in the space environment, and the expense and effort required to conduct vicarious calibration campaigns using instrumented ground sites.

Assessment of radiometric calibration stability for instruments in orbit can be accomplished using observations of the Moon. The ability to use the Moon as a reference derives from the inherent stability of its surface reflectance, which allows high-precision modeling of its cyclic brightness variations. A continuous, analytic model is required to predict the brightness corresponding to the specific geometry (Sun–Moon–observer) of spacecraft lunar observations. Thus the model is the lunar reference. A model for the lunar spectral irradiance and the methodology to utilize this quantity for calibration of instruments that view the Moon have been established by the U.S. Geological Survey lunar calibration program (see `http://www.moon-cal.org`).

Because environmental monitoring instruments in low Earth orbit typically must turn to view the Moon, the ability to utilize the lunar reference source is dependent on spacecraft design. Lunar calibration has demonstrated the capability to achieve radiometric calibration stability at the level of precision needed for climate change detection. For solar-band instruments, this may be the only feasible technique available. Thus the ability to acquire views of the Moon should be a consideration for spacecraft design specifications and on-orbit calibration requirements of future Earth-observing satellite missions.

7. REFERENCES

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