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Use of the Moon for in-flight calibration stability monitoring

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1 Abstract

This document describes a procedure for monitoring the stability of radiometric calibration of an Earth Observing (EO) sensor in orbit using the Moon as a source of luminous intensity. This procedure applies to visible to shortwave infrared wavelength (i.e., solar band) instruments, 0.35 to 2.5 microns. The Moon is visible to a spacecraft instrument for more than half of every orbit; however, its use as a calibration light source is complicated by its widely varying brightness with the geometry of illumination and viewing, primarily the lunar phase. Accommodating the lunar geometry in a general way for spacecraft observations mandates the use of a photometric model, which in turn requires a measurement database that captures the cycles of lunar intensity variations sufficiently for model development. The procedure described here uses a model for the quantity of lunar spectral irradiance, involving spatially integrated measurements over the entire lunar disk regardless of its illuminated fraction. The foundation for the usability of the Moon and durability of the lunar photometric model is the inherent stability of the lunar reflecting surface, considered better than one part in 10^8 per year. This characteristic has led to endorsement by the CEOS WGCV of the Moon as a reference standard for calibration stability. Trending a sensor's response over time is accomplished with a series of Moon observations taken by the instrument and compared against the lunar model. Because the model predicts the spatially integrated irradiance quantity, each observation by the instrument must capture the entire lunar disk in some fashion, often oversampled. Instruments in low Earth orbit (LEO) usually require a spacecraft attitude maneuver to observe the Moon, or viewing through a space-view port. Instruments in geostationary orbit can capture the Moon in the margins of their field of regard.

2 Scope

This document explains the procedures to use observations of the Moon to monitor instrument radiometric response over time, and thus assess the stability of the instrument calibration. The lunar calibration technique described here applies to solar-band wavelengths, roughly 350 to 2500 nm. The materials presented are intended to enable instrument teams to evaluate the potential for lunar calibration to meet their sensor stability needs, particularly instruments in orbit.

A description of the lunar technique explains the suitability of the Moon as a calibration target. The lunar calibration system enables the Moon to be considered a consistent source despite its continually varying brightness. It is the capability for precise prediction of the lunar irradiance, underpinned by the inherent stability of the Moon itself, that permits using the Moon for calibration stability monitoring.

Contained in this document are the procedures for interchange between the lunar calibration system and instrument teams. This includes the tasks of the instrument team and the needed data inputs, and the results generated by the system. An example is provided that demonstrates how the results have been used and the level of precision achievable by the technique. Individual results have relative precision ~1%. Given a sufficient series of Moon observations by an instrument, calibration stability at a level better than 0.1% per year has been achieved.

The current lunar technique provides calibration *stability* monitoring, validated by the relative precision of the outcomes. Current uncertainties in the absolute lunar irradiance preclude consideration of the Moon as an absolute radiometric standard. Consequently, absolute calibration using the Moon is outside the scope of the procedure documented here.

3 Terminology

Some key terms used in this document are listed below, with context-related supplementary definitions where appropriate.

Stability: Used here in two contexts, pertaining to 1) an instrument's radiometric calibration and 2) the reflecting surface of the Moon. Calibration stability for an instrument is assessed by having precise knowledge of changes in the sensor responsivity over time and the ability to quantitatively characterize any such changes to produce consistent measurement data for a given input signal (e.g., Earth scene). The photometric stability of the lunar surface is inferred from studies of the rates of fresh cratering and bombardment by cosmic particles and micrometeorites. At the spatial resolutions of current and anticipated future EO imaging instruments, the rate of observable change to the surface reflectance properties is considered to be less than one part in 10^8 per year. Direct measurement at this level of accuracy cannot be achieved with present-day instrumentation.

Solar band, or solar reflectance wavelengths: The wavelength range spanning roughly 300 nm (near-UV) to 2500 nm (SWIR), encompassing the majority of the Sun's radiant output in terms of photon flux, the key quantity for reflectance-based EO measurements.

Irradiance: As referenced in this document, the radiometric quantity of photon flux per unit area. For the purposes of the current lunar calibration technique, the Moon is considered an irradiance source, i.e. effectively a point source, typically realized by underfilling an instrument's field of view (FOV).

Photometric: Here referring quantitatively to the particular circumstances of light scattering from a diffuse reflecting surface.

Libration: The variation in the hemisphere of the Moon that is viewed by an observer on Earth or in orbit. Lunar librations are both apparent, arising from viewing from different vantage points, and caused by actual physical rotation of the Moon. The librations experienced from points on the Earth allow about 59% of the lunar surface to be viewed over time.

Saros cycle: The 18.6 year cycle of precession of the Moon's spin axis, which directly affects the libration state for a given location and lunar phase angle.

Reference standard: Defined in the CEOS QA Framework guidelines as "measurement standard used for the calibration of working measurement standards in a given organization or at a given location"; in the context of lunar calibration, the Moon is considered a reference standard for stability due to the inherent photometric stability of the lunar surface.

4 Introduction/Context

This document provides guidance on a method to assess sensor calibration stability for EO instruments in orbit to facilitate establishing a Quality Indicator for the data products delivered by that instrument. Calibration stability is essential for the interoperability of datasets to enable long-term environmental monitoring from space-based remote sensing platforms. The method described here is applicable to solar band radiometric instruments, which commonly employ solar diffusers or onboard lamps to maintain calibration on orbit. Assessing calibration stability with diffuser systems requires accurate monitoring of the diffuser surface reflectance over time to evaluate the progressive degradation that occurs in the space environment. The reliability of lamps operated in space as radiance standards has not been demonstrated unequivocally. An alternative approach considers the Moon as a solar "diffuser". The reflectance of the lunar surface has stabilized through eons of weathering by exposure to solar radiation and pulverization of the regolith by micrometeorite bombardment. The extent of fresh cratering on the Moon is virtually undetectable by the highest resolution sensors in Earth orbit.

The main obstacle to using the Moon for calibration purposes is its constantly changing appearance, primarily the familiar lunar phases, but also the lunar librations and its non-uniform albedo and non-Lambertian reflectance. However, the photometric stability of the lunar surface enables these cyclic variations to be characterized with high precision, and durable models to be developed, given sufficient observational measurement coverage. At least ¼ of a Saros cycle is needed to capture the extremes of libration.

A set of ground-based observations spanning more than 6 years was acquired by the lunar calibration program at the U.S. Geological Survey (USGS), from which a model was developed for the spectral irradiance of the Moon [Astronom. J. 129, 2887-2901, 2005]. The USGS lunar model has the form of an analytic function that predicts the irradiance for a specified lunar phase and libration state and thus accommodates the geometries of observations from space-based instruments. Operation of the USGS lunar calibration system is presumed in the procedure described here. A description of this system can be found at http://www.moon-cal.org.

The lunar calibration system provides model results directly corresponding to satellite instrument observations. The positions of the Sun and Moon are determined from precision ephemeris computations, from which appropriate corrections for distances (Sun-Moon and Moon-observer) are generated. The instrument spectral response is accommodated by interpolating along the modeled lunar reflectance spectrum, which is smooth. To avoid the complications of the spectral structure of sunlight, the irradiance model was developed and operates in the (unitless) quantity of disk equivalent reflectance. This involves conversion using a model for the solar spectral irradiance, which contributes uncertainty to the lunar model, but affecting only the absolute scale of irradiance.

5 Outcomes

The outcomes of this procedure are: for a given set of observations of the Moon acquired by an instrument, data on the equivalence of the instrument-measured lunar irradiance to the corresponding modeled irradiance. The model results effectively normalize the variable brightness of the lunar source, thus providing known input signals for the instrument Moon observations. The observed/modeled comparisons for a time series reveal temporal trends in the sensor's responsivity.

For a given instrument band, the lunar model results have relative precision ~1% over the range of geometries within the model coverage. This value is derived from analysis of the residuals (absolute deviations) of fitting an extensive observational database as part of the model development. This precision relates to the model's capability to predict variations in the lunar irradiance with photometric geometry; it is independent of accuracy in the modeled irradiance on an absolute scale.

6 Inputs

Inputs to this procedure include 1) the instrument response to the lunar irradiance source and 2) time and location information needed to compute the lunar ephemeris and the photometric geometry corresponding to the instrument Moon observations. Establishing calibration stability using the lunar technique requires a time series of lunar measurements acquired by the instrument.

The sensor response for each Moon observation should be calibrated to radiometric units using appropriate coefficients for the time of the observation and applying all usual corrections for detector effects. For imaging instruments, the spatial extent of the Moon image should be integrated to an irradiance value to include both the sunlit and dark portions of the lunar disk. These integrations can be oversampled or corrected for oversampling. Additionally, the spectral passband of the sensor must be provided (typically once, unless this is known to change). The ephemeral data needed for each Moon observation include the date/time and the spacecraft location in celestial coordinates; the current lunar calibration system works with J2000 cartesian coordinates.

7 Standards and Traceability

As explained above, this guideline pertains to a technique to monitor calibration *stability*. Although the lunar calibration system is attached to an absolute radiometric scale, use of the Moon as an absolute calibration source is outside the scope of the procedure documented here.

The metric standard for stability relates, somewhat intangibly, to consistency. There are two essential components of the lunar calibration system that embody consistency metrics: the inherent photometric stability of the Moon and the quality of fitting the lunar model basis data.

In the context of a radiometric target for Earth observing sensor systems, the Moon is considered photometrically stable at a level of 10^{-8} per year. This is far below the threshold of direct measurement of reflectance; the value is determined from a study of the youngest cratering events (magnitude and rate) on the Moon [Icarus 130, 323-327, 1997]. Although the cratering analysis assigns an uncertainty in the stability value of a factor of two, this nonetheless exceeds the most stringent performance goals of EO instruments by several orders of magnitude.

A consequence of the inherent stability of the Moon is that its photometric properties can be known with high precision, given extensive measurements. Further, a parametric description of these properties, i.e. a model, developed from such a measurement set is valid for any time (in the current geologic era). Therefore, the validity of comparisons of lunar irradiance measurements taken by an instrument at different times to the corresponding model results derives from the photometric stability of the Moon.

The irradiance model at the core of the current lunar calibration system was developed from fitting thousands of measurements acquired by the Robotic Lunar Observatory (ROLO). The analytic expression that constitutes the model kernel was formulated empirically, as a function of the geometric variables of phase and libration, with the goal to minimize the residuals in the fit. The current form has 18 adjustable parameters for each of 32 ROLO bands, 8 of which are constant across all bands. There were ~1200 data points fitted for each band, thus the system of equations is vastly over-determined. The mean absolute fit residual over all bands is 0.0096, or ~1%. Since the model kernel is a function of the geometric variables of Moon observations, this value effectively represents the precision of the model's predictive capability with regard to variations in the observed lunar irradiance with geometry. The standard underpinning this precision is adherence to accepted principles of statistical interpretation of data.

8 Task Description

Providing lunar irradiance comparisons as described in the Outcomes above involves established protocols for interfacing with the lunar calibration system. Currently, this is done via individual communications with the lunar calibration program at the U.S. Geological Survey. This process is moving to a web services-based method, now under development. The current procedures are documented at http://www.moon-cal.org under the header Spacecraft Calibration; additional details are provided below. An obvious requirement is that the spacecraft instrument observes the Moon. Some practical aspects of Moon capture are discussed in the final subsection below.

An overview of the procedural steps for lunar calibration:

- initial setup of the lunar calibration system (done once, for each new instrument)
- the instrument team provides measured lunar irradiances, the times of the observations, and the instrument location for each observation
- the lunar calibration system generates the precise location of the Sun and Moon, the distances and photometric geometry for each observation, and modeled lunar irradiances
- outputs are provided: the lunar ephemeris/geometry for each observation (phase angle, lunar libration state, angular size of the Moon), the Sun-Moon and Moon-instrument distances and distance correction factors, and the model lunar irradiances interpolated to the instrument spectral bands and corrected to the observation distances.

8.1 Initial System Setup

An essential preliminary activity is a discussion with the spacecraft instrument team to establish the suitability of the lunar calibration technique for the instrument. Given an affirmative outcome, the lunar calibration software system must be set up to accommodate the instrument. This involves offline processing of the sensor relative spectral response. Spectral response functions must be provided by the instrument team for each instrument band, including each element of a hyperspectral sensor. For the eventual web services interface, initial setup will include granting a login for access to the server site.

8.2 Instrument-measured Irradiances

Processing Moon observations to irradiance for lunar calibration inputs is the responsibility of the instrument team. Presuming level-1 data, calibrated to radiometric quantities, the basic procedure is spatial integration of the sensor signal attributed to the Moon. For imaging instruments, this means summing all pixels on the lunar disk. The lunar irradiance model explicitly accounts for the lunar phase as the fractional illumination of the entire Moon; therefore, the whole disk is integrated, including the unlit portion.

The extent of the Moon in a sensor's field of regard can be somewhat ambiguous, the effective size being affected by stray light contamination, imaging quality (MTF), and other factors. These effects also can change with time on orbit. For calibration stability, the key to achieving high-quality results is consistency of determining the Moon extent for all observations.

Instruments in orbit have available the dark background of deep space for a zero-radiance reference. An established technique available to imaging sensors uses the contrast of the bright limb against dark space, first to locate the disk in the image. The direction to the Sun is found independently from ephemeris computations and matched with the instrument pointing information to define the lunar bright limb direction. An arc extending from this location is found by fitting multiple positions of high contrast along the limb. Typically no more than 170 degrees of arc are useful for this determination. The limb arc is then extended to encircle the entire lunar disk and to refine the center location. Concentric annuli are formed for cumulative summation of pixels. The slope of this sum vs. radius can be used to specify the upper limit of integration. This method can accommodate certain types of degradation in optical systems, providing consistent irradiance measurements.

The oversampling factor must be determined in some fashion for each lunar irradiance measurement. Preferably this can be extracted from the spacecraft attitude telemetry and the sensor sampling rate. In some cases, oversampling must be determined from measurement of the down-track size of the Moon in an image, presumed a round target. This incurs the complication of the usually oblique relation between the lunar bright limb and the instrument tracking directions, or image frame. Inputs for lunar calibration can be oversampled irradiances, or corrected for oversampling.

8.3 Observation Parameters

Required inputs include the time and location corresponding to each observation. Observation times are specified in UTC. Typically the Moon is scanned through the instrument field of regard with some degree of oversampling. The time when the geometric center of the Moon is crossed should be used for the input. The instrument location must be provided in the J2000 geocentric coordinate system. For instruments in orbit, the spacecraft location at the observation time usually is found by propagating the orbit from an extant set of Keplerian orbital elements.

Based on the time and instrument location, the lunar calibration system generates the photometric geometry for the observation. The positions of the Sun and Moon are computed from a double-precision ephemeris, and the instrument location determines the phase angle, the distance to the Moon, and its angular size. The ephemeris also provides the lunar libration state, which is explicitly accommodated in the lunar irradiance model.

8.4 Irradiance Model Results

Currently, lunar calibration results are provided through direct interaction with the USGS program personnel. A forthcoming web-based system is intended for operational applications, providing direct lunar calibration results to registered users. In either case, initial observations are processed interactively to confirm the standard formatting of inputs.

Post-processing of lunar model results provides outputs suitable for direct comparison to measurements made by instruments. The lunar model kernel produces the disk-equivalent reflectance in 32 wavelength bands from 350 to 2450 nm (i.e. the ROLO bands), corresponding to the instrument observation geometry. These values are interpolated along a smooth reflectance spectrum and convolved with the spectral response function for each instrument band. Conversion to irradiance involves a solar spectral model, also convolved with the instrument bands. Last, distance corrections are applied to translate the modeled irradiance values to the instrument location.

Since cumulative lunar calibration results are the most useful to reveal sensor performance trends, it is recommended that all observations are included each time an instrument team submits inputs for processing. This does not incur an unreasonable burden of computing time. The program at USGS archives the instrument team inputs and model results data for tracking usage and for system and (limited) instrument performance diagnostics. However, lunar calibration results are not publicized in any form without an explicit release from the instrument team. In case of any major revision to the irradiance model, the lunar calibration program will reprocess the most recent inputs and provide notification and new results to all participating instrument teams.

8.5 Practical Aspects of Viewing the Moon

A common need of instrument teams planning lunar observations is the maximum expected radiance of the target. The capability to predict this quantity is available through the lunar calibration program at USGS to support planning efforts. The inputs required are the sensor instantaneous field of view (IFOV) and the lunar phase of the intended observations, in addition to the relative spectral response.

The most useful lunar calibration results are obtained when the Moon is viewed through an instrument's normal nadir-view optics; however, spacecraft in low-Earth orbit (LEO) must execute attitude maneuvers to accomplish this. The SeaWiFS instrument has viewed the Moon more than 180 times using a pitch-over maneuver. The process begins after the spacecraft enters the Earth's shadow. The usual pitch rate of 360 degrees per orbit is reversed, and the FOV is directed to the Moon. The reverse pitch rate is stabilized and timed to scan the Moon at a constant rate as the spacecraft passes the sub-lunar point on its ground track. The maneuver continues until the instrument again points to Earth, at which time the normal nadir-locked rate is restored. The MODIS instruments on the Terra and Aqua spacecraft view the Moon through a side-viewing optical port, normally used to view deep space to measure instrument dark response. Using modest roll maneuvers, MODIS can capture the Moon about 9 months of the year in this way. The different scan mirror angle that must be used for Moon and Earth observations is a disadvantage of this approach. Accommodating lunar views may be a consideration for the design of future EO instruments and spacecraft.

For instrument stability monitoring, a baseline must be established from a chosen observation or set of observations. A convenient time for this is during post launch testing, or surrounding a major calibration event such as viewing a pristine solar diffuser.

Experimental best practices suggest acquiring multiple data collects during each planned Moon view, if possible. Measurements of lunar irradiance often have shown processing sensitivities, e.g. related to background subtraction, that lead to considerable scatter in measurements under otherwise similar observing circumstances.

Oversampling is accommodated explicitly by the lunar calibration system. Undersampled observations incur increased uncertainty due to the spatially variegated surface features of the Moon. For irradiance measurements, the entire lunar disk is integrated, regardless of the fraction of illumination. Observations that are missing a portion of the disk can be accommodated using a simple fractional correction; however, processing partial-disk data in a rigorous manner requires a spatially resolved radiance model, which is a planned feature of the system not yet implemented.

The lunar model has a valid phase angle range from eclipse (~1.5 degrees) to 90 degrees before and after Full Moon. Uncertainties are higher for phase angles smaller than 5-6 degrees, due to the difficulty of modeling the lunar reflectance phase function for narrow angles. Observations near 7 degrees benefit from high irradiance signal while avoiding this increased uncertainty (most SeaWiFS lunar observations have been acquired near 7 degrees). Phase angles before Full Moon are distinguished in the lunar calibration system by assigning negative values.

Instrument calibration stability using the Moon derives from a time series of observations, using lunar model results to offset the varying brightness of the target. Acquiring observations on a monthly schedule can provide consistency of the phase angle and improve the precision of the model predictions. However, the system accommodates any phase angle within the valid range, thus restriction to a narrow range of phase angles is not a requirement.

9 Evaluation of Performance

The merit of calibration stability assessments using the lunar technique derives from the lunar irradiance model predictive precision, underpinned by the inherent stability of the Moon. Quantitative evaluation of a given time series of lunar irradiance comparisons, i.e instrument measurements compared against the lunar model results, involves the relative precision of the lunar model and requires assessment of the random errors associated with generating irradiance values from instrument observations of the Moon.

Testing the lunar model precision may prove inconclusive, since the model is based on a dataset with unprecedented extent of geometric coverage. There are few historical observations of lunar irradiance; however, these were considered during development of the irradiance model form. In virtually all cases, the residuals from fitting historical data were higher than the fits of ROLO data.

The expected behavior of the lunar disk-integrated reflectance is a smoothly varying function of phase and libration angles. The current irradiance model guarantees smooth predictions with geometric variation due to the continuous form of the model kernel expression. The spectral integrity of the model is tied to the absolute calibration of the ROLO data, which still carries significant uncertainty. Expected lunar reflectance spectral characteristics are achieved using a correction applied to the model results at each ROLO wavelength prior to interpolation to instrument bands. This is an acknowledged shortcoming of the lunar model capabilities. For calibration stability measurements, offsets to any bias of the lunar model results typically are developed to match the instrument baseline observations.

To date, lunar observations by instruments have shown relatively high levels of uncertainty in their processing to irradiance, as evidenced by the scatter in the time series of measurement/model comparisons. For example, the SeaWiFS instrument, which relies on lunar calibration for tracking sensor response changes, must determine the oversampling rate for Moon observations from measurements of the down-track size of the disk image. This leads to a temporal jitter that is correlated among all SeaWiFS bands. Nonetheless, smooth response trends have been developed for all SeaWiFS bands with sub-percent uncorrelated error.

10 Evidence to support a Performance Indicator

Lunar calibration is a novel technique. Special operations, e.g. satellite maneuvers, often are required to view the Moon, and a series of lunar observations is needed to assess calibration stability. To date, few instruments have collected sufficient lunar measurement sets.

The lunar calibration system developed by the USGS predicts the Moon's brightness variations with the geometry of illumination and viewing based on an empirical model. The lunar irradiance model was developed from an extensive set of measurements collected by the ground-based ROLO telescope facility. The ROLO dataset is unmatched in the extent of its geometric coverage, which limits the possibility of comparison against external measurements. As a consequence, evaluation of the lunar irradiance model with regard to its geometric precision, which is the critical element for assessing calibration stability using the Moon, has no supporting evidence as specified by CEOS Quality Assurance requirements.

11 Review of Process

Remote sensing of ocean color has stringent requirements on calibration stability, particularly for the short-wavelength visible bands. Vicarious methods at these wavelengths are complicated by increased uncertainty of atmospheric corrections. One ocean color research satellite, SeaWiFS, has based its calibration stability strategy on acquiring regular observations of the Moon and applying lunar calibration methods. From analysis of the series of Moon observations, SeaWiFS has developed sensor response trends that have resulted in calibration stability to better than 0.1% per year. The lunar-based sensor corrections are integrated into the operational processing of SeaWiFS data products.