Further Details of Lunar Calibration

Introduction

The goal of the USGS lunar calibration program is to utilize the Moon as an on-orbit standard, both absolute and transfer, for radiometric calibration of remote sensing satellite sensors. There is a recognized need for an on-orbit spectral standard in the solar reflectance wavelength region (0.35 to 2.5 micron): instruments in flight commonly experience changes in responsivity from their pre-launch calibrations, on-board calibration systems typically do not use the same optical path as the Earth view, and on-board systems also degrade in the space environment. For detecting signals of global climate change from space, the long-term stability requirement for solar-band instruments is 1% over a decade (NISTIR 7047). Lunar calibration may be the only practical means for meeting this criterion.

The principal challenges to using the Moon as a light source are the non-uniformity of the lunar surface albedo, the brightness variations arising from lunar phase and libration, and the strong dependence of the surface reflectivity on phase angle. The complexity of these dependencies effectively mandates the use of a lunar radiometric model to compare against spacecraft observations of the Moon. Such a model must be developed from a program of radiometric measurements of the Moon covering a practical range of lunar phases and a sufficient portion of the 18.6-year libration cycle. The USGS lunar calibration program has acquired the necessary observational data for development of operational lunar models.

A basic requirement for lunar calibration is that the instrument must view the Moon. This poses another challenge for nadir-viewing spacecraft in that often an in-flight attitude maneuver is needed. To date, SeaWiFS has made well over 100 lunar observations using a pure-pitch satellite maneuver. The ALI and Hyperion instruments on EO-1 have acquired monthly lunar views for several years. Of the NASA EOS flagship satellites, only Terra has captured the Moon in nadir-view, once.

Observational Database

The basis of the USGS lunar irradiance specification is an extensive database of radiance images acquired by the ground-based RObotic Lunar Observatory (ROLO[∗]), located at the USGS Science Center in Flagstaff, AZ. ROLO observed the Moon on clear nights between First Quarter and Last Quarter lunar phases for over 6 years. Twin telescopes on a common mount cover the Visible and Near-infrared (VNIR) range (350-950 nm) in 23 bands, and the shortwave infrared (SWIR - 950-2350 nm) in 9 bands. Substantial observing time was dedicated to imaging stars, for the purpose of determining atmospheric extinction corrections. Calibration to radiance is based on measurements of the star Vega, although efforts to tie the ROLO data to the SI radiometric scale are ongoing, involving the radiometry group at NIST. The ROLO database contains over 85,000 individual lunar images, and several hundred thousand star images.

Operational Lunar Model

Modeling emphasis has been on the disk-integrated lunar irradiance. A spatially resolved radiance model has been developed, but the irradiance quantity has been found preferable for spacecraft calibration work due to the higher accuracy and precision achievable. The USGS lunar irradiance model was developed from fitting ROLO observational data that have been calibrated to exoatmospheric radiance and spatially integrated over the entire lunar disk, regardless of the illuminated fraction. The model analytic form was determined empirically through study of the fit residuals, with the goal of reducing correlations seen in the residuals. Further details of the irradiance model development, the model form, and the data fitting procedure are under the Lunar Modeling link.

The lunar irradiance model fits the ROLO observational data with an average residual over all bands of just under 1%. This value constitutes a measure of the model precision with which the model can predict the variations in lunar irradiance due to view geometry, including phase, libration, and the lunar photometric function, over the useful range of the geometric variables. These range in phase from 90 degrees (before and after Full Moon) to near-eclipse (~1.5 degrees), and virtually all libration angles viewable from the Earth's surface.

Spacecraft Instrument Team Interaction

The procedures for spacecraft instrument teams to participate in lunar calibration have been largely formalized; an overview of the information exchange between a Spacecraft Calibration Team (SCT) and the USGS Lunar Calibration Team (LCT) can be found at the Spacecraft Calibration link. At present, lunar calibration results are reported as the fractional discrepancy between the irradiance measured by an instrument that has viewed the Moon and the model prediction for the ephemeris, view geometry, and band wavelength of the spacecraft observation. Although the LCT has provided assistance to some instrument teams with lunar image processing, generally the SCT is expected to provide their observations calibrated to irradiance.

Utility

The USGS model can specify the lunar irradiance with relative precision ~1%, based on the fit residuals and data error analysis. The absolute scale of the ROLO data and lunar model has an uncertainty currently estimated ~5-10%, based on comparisons of a number of spacecraft instrument calibrations. A dedicated effort is underway to reduce the absolute uncertainty and tie the ROLO scale to SI units; the program uncertainty goals are 1% (VNIR) to 2% (SWIR) absolute. However, a number of important instrument characterizations can be achieved independent of the absolute scale, such as tracking of instrument degradation over time, and intercomparison among instruments that have viewed the Moon, regardless of the proximity in time and location of the observations.

Given a time series of lunar views taken by a spacecraft instrument, smooth sensor degradation curves can be fitted to the irradiance model comparisons, resulting in relative response trending with sub-percent precision over the series. This capability has been demonstrated for SeaWiFS[1], and represents attainment of the stability requirement for measuring global climate change from space for solar-band instruments (NISTIR 7047).

Lunar Modeling

There are significant complications to using the Moon as a radiometric standard source, primarily resulting from the variegation of the surface albedo, the constantly changing lunar phase and librations, and the strong dependence of the surface reflectance function on phase angle. However, the lunar surface reflectance properties are extremely stable, and therefore knowable to high precision. The practical considerations of using the Moon for instrument calibration call for the use of a model, which can predict the lunar brightness for the precise geometry of illumination and viewing of the instrument. Such a model, once established, is valid for any observation of the Moon within the geometry range, including those made in the past.

Radiance Model

A spatially resolved lunar radiance model is under development at USGS. The model source data are the ROLO lunar images, co-registered in the ALEX projection and calibrated to exoatmospheric radiance. To accommodate limitations of computer memory and to facilitate individual pixel I/O, the radiance image dataset has been re-sampled and transposed, forming ALEX bricks. Data selection has drawn on the irradiance model criteria, with additional quality checks built into the fitting algorithm. This model also operates in reflectance, with individual pixels converted by:

$$L_k = \frac{A_k \cdot E_k}{\pi}$$

where Lk is the radiance of a pixel and Ek is the solar irradiance in band k, both at the standard Sun-Moon distance of 1 AU. Additionally, ephemeris information for each ROLO image is used to compute the incidence and emission angles and phase angle for each point on the (hemispheric) Moon.

Model coefficients are generated by fitting a user-defined photometric function to individual data pixels using linear least squares and SVD. The linear restriction was imposed for runtime considerations, and places limitations on the ability to fully model the lunar photometric behavior, e.g. the opposition effect. Even using a 3-parameter fit, given the ~200,000 pixels in 32 bands there are about 20 million coefficients to be found.

Additional Info for Spacecraft Teams

Suggested Observing Strategy

Many spacecraft teams have chosen to observe the Moon at near 7 degrees phase, both before and after Full Moon. This geometry provides good S/N while avoiding the “opposition effect” enhanced backscatter at low phase angles. However, there is no requirement to restrict observations to a narrow range of phase angles -- the lunar irradiance model is valid for any phase angle between eclipse and 90 degrees, with precision on the order of 1% over the entire range. The radiance of the Full Moon is comparable to that of clear land viewed from space.

A typical lunar observing sequence for a nadir-viewing spacecraft involves an attitude pitch maneuver, starting approximately when the spacecraft enters the Earth's shadow. The spacecraft is rotated to the Moon, then scans the Moon at a constant rate such that the image acquired is oversampled in the down-track direction. The spacecraft is then pitched back toward Earth, regaining its normal nadir-viewing attitude before passing out of the shadow. This adds (or subtracts) one complete revolution to the normal nadir-locked pitch rate. The scanning past the Moon should be at a constant rate, typically 4 to 8 times slower than a normal nadir scene, and should extend at least one degree past the edge of the Moon to allow adequate sampling of the space level beyond the extended point-spread function in all bands.

Lunar Maximum Radiance Prediction

To assist spacecraft instrument teams with planning lunar views, the USGS Lunar Calibration Team has developed a tool that can predict the maximum radiance expected for a given lunar observation geometry, for a particular instrument band spectral response and spatial resolution.

Considerations for Geostationary Instruments

The visible channels of geostationary meteorological imagers typically lack on-board calibration hardware, relying instead on vicarious and cross-calibration techniques. The Moon appears regularly in the margins of full-disk operational images acquired by GEO instruments with rectangular field of regard. The USGS Lunar Calibration Team has developed a tool to predict the appearance of the Moon in a GEO image based on the satellite Two-Line Element (TLE) orbital parameters. This can be used to find images of the Moon in a data archive, or to determine future Moon capture opportunities. A time series of lunar images can be used to develop calibration histories for these instruments, regardless of their current operational status.

[∗] The acronym ROLO was created by Bob Wildey, and is used in his memory

[1] Applied Optics 43, 5838-5854 (2004)