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Radiometric stability monitoring of the MODIS reflective solar bands using the Moon

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Abstract
Because of its stable surface reflectance and its stable irradiance in the visible (VIS) and near-infrared (NIR) spectral regions, the Moon can be used as a reference source for monitoring the response stability of Earth-orbiting sensors. MODerate Resolution Imaging Spectroradiometer (MODIS) Protoflight Model (PFM), launched on-board the NASA Terra spacecraft on 18 December 1999, has been in operation for more than two years. Its reflective solar bands (RSB) are calibrated on-orbit by a solar diffuser (SD). In addition, MODIS on-orbit lunar views are used to characterize the stability of the RSB radiometric calibration and the response change at an angle of incidence (AOI) different from that of the SD. In this report, we describe an approach that properly selects the viewing conditions to minimize the effects that need to be corrected and its application to the MODIS lunar observations. Results, derived from MODIS lunar views, are reported and compared with the on-board SD observations.

1. Introduction

The Moon is an excellent radiometric reference because of its stable surface reflectance and its stable irradiance in the visible (VIS) and near-infrared (NIR) spectral regions [1–3]. It can be used on-orbit by Earth-orbiting sensors for monitoring their response stability. Lunar observations have played an important role in the calibration and characterization of the NASA Earth observing system (EOS) MODerate Resolution Imaging Spectroradiometer (MODIS), which was launched on-board the Terra spacecraft on 18 December 1999. References [4, 5] have provided detailed descriptions of the MODIS instrument and its pre-launch calibration and on-orbit performance.

MODIS has 36 spectral bands located on four focal plane assemblies (FPAs), covering wavelengths from 412 nm to 14 200 nm and providing spatial resolutions of 0.25 km (B1–2), 0.5 km (B3–7) and 1 km (B8–36) at nadir. MODIS on-orbit calibration is performed using its on-board calibrators: a solar diffuser (SD) for radiometric calibration of the 20 reflective solar bands (RSB), a blackbody (BB) for radiometric calibration of the 16 thermal emissive bands (TEB), and a spectroradiometric calibration assembly (SRCA) for the sensor's spatial and spectral calibration. The detectors' dark response, including thermal background, is provided by a deep space view through its space view (SV) port. A two-sided scan mirror samples the SD, BB, SV and the Earth scene continuously with a scan period of 1.478 s.

During MODIS on-orbit operation, the Moon is viewed through its SV port approximately monthly. The sensors' response to the lunar view depends strongly on the viewing conditions. By careful control of the MODIS lunar view geometry we can minimize the corrections and simplify the correction algorithms. The selected observations are used for the study of sensor's RSB calibration stability. In addition, lunar views through the SV port complement the RSB calibrations using the SD by providing information at a different angle of incidence (AOI) of the scan mirror.

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In this report, we provide a description of how to select the lunar views such that the effects due to viewing conditions are minimized and discuss algorithms used to correct various effects. A quantity that is proportional to the normalized lunar irradiance is defined. With all the corrections applied, this quantity is independent of the view conditions and can be used to monitor the MODIS RSB radiometric stability. The results, derived from MODIS on-orbit lunar observations, are reported and compared with the on-board SD calibration.

2. Radiometric stability monitoring using the Moon

The lunar irradiance strongly depends on the lunar view conditions such as the distance between the Sun and the Moon, r_{SM}, the distance between the Moon and the spacecraft, r_{MS}, the Sun–Moon–MODIS phase angle, φ, the spacecraft roll manoeuver angle, η, and the lunar latitude and longitude of the Sun and the MODIS, α_{Sun}, β_{Sun}, α_{Sat}, β_{Sat}, respectively. Assume θ, ϕ are the spherical angles of a point on the lunar surface and $\rho(\theta, \phi, \alpha_{Sun}, \beta_{Sun}, \alpha_{Sat}, \beta_{Sat})$ is the corresponding bidirectional reflection distribution function. Then the lunar irradiance $I(\lambda)$ observed by a detector of a band with centre wavelength at λ can be expressed as

$$I(\lambda) \sim \frac{f_{os}(\eta)\Theta(\alpha_{Sun}, \beta_{Sun}, \alpha_{Sat}, \beta_{Sat}, \lambda)}{r_{SM}^2 r_{MS}^2} \tag{1}$$

where $f_{os}(\lambda)$ is an oversampling factor defined as the number of times that the lunar surface is viewed by the detector, and

$$\Theta(\alpha_{Sun}, \beta_{Sun}, \alpha_{Sat}, \beta_{Sat}, \lambda) = \int_0^{\pi}\int_0^{2\pi} d\theta\, d\phi \sin\theta \times \cos(\theta_{Sun})\rho(\theta, \phi, \alpha_{Sun}, \beta_{Sun}, \alpha_{Sat}, \beta_{Sat}, \lambda). \tag{2}$$

θ_{Sun} in (2) is the angle at which sunlight is incident angle on the lunar surface.

The oversampling factor can be evaluated from

$$f_{os}(\eta) = \frac{P_{Moon}}{t_{scan} v_{track}} \tag{3}$$

where P_{Moon} is the pixel size of the detector on the lunar surface, t_{scan} is the time of one scan, and v_{track} is the projection of the velocity of the detector's view on the lunar surface along the track direction. The oversampling factor is a function of the roll angle η since v_{track} depends on the roll angle.

Since the angle between the orbital planes of the Sun and the Moon around the Earth is about 1°32′, the solar latitude varies in a very small region around zero. Thus, $\Theta(\alpha_{Sun}, \beta_{Sun}, \alpha_{Sat}, \beta_{Sat}, \lambda)$ can be written approximately as $\Theta(\varphi, \alpha_{Sat}, \beta_{Sat}, \lambda)$, in which β_{Sun} is replaced by the phase angle φ. Since the Moon always exhibits approximately the same face to the Earth due to the synchronism between rotation and revolution, the effect of the librations is relatively small and can then be expressed as a first-order Taylor series:

$$\Theta(\varphi, \alpha_{Sat}, \beta_{Sat}, \lambda) = \Gamma(\varphi, \lambda)[1 + L(\varphi, \alpha_{Sat}, \beta_{Sat}, \lambda)] \tag{4}$$

where

$$\Gamma(\varphi, \lambda) = \Theta(\varphi, 0, 0, \lambda). \tag{5}$$

Using a function $p(\varphi, \lambda)$ describing the phase angle effect [6], $\Gamma(\varphi, \lambda)$ can be expressed as

$$\Gamma(\varphi, \lambda) = 10^{-p(\varphi, \lambda_B)/2.5}. \tag{6}$$

Extensive work has been done by both theoreticians and experimentalists to obtain this function, $p(\varphi, \lambda)$. The analytical expression of Hapke [7] and his coworkers and the measured curves of Lane and Irvine [6] are frequently cited. In our analysis, $p(\varphi, \lambda)$ is constructed by interpolating the data of Lane and Irvine. The constructed function is shown in figure 1.

Kieffer and coworkers [8] have measured the variation of the lunar irradiance with the librations at $\varphi = 62.5°$ and $67.5°$. With exactly the same approach used for $p(\varphi, \lambda)$, we can construct two functions, $\Lambda_{62.5}(\alpha, \beta)$ and $\Lambda_{67.5}(\alpha, \beta)$, in the region of $\alpha \in [-7.5°, 7.5°]$ and $\beta \in [-7.5°, 7.5°]$ from the data provided by Kieffer. By assuming that $\Lambda(\varphi, \alpha, \beta)$ is a linear function of φ, we can write

$$\Lambda(\varphi, \alpha, \beta) = \Lambda_{62.5}(\alpha, \beta) - \frac{(\varphi - 62.5)[\Lambda_{67.5}(\alpha, \beta) - \Lambda_{62.5}(\alpha, \beta)]}{5}. \tag{7}$$

Figure 2 is the surface of the function $\Lambda(\varphi, \alpha, \beta)$ for $\varphi = 55.5°$.

With all the corrections considered, a normalized lunar irradiance can be defined as

$$L(\lambda) = \frac{I(\lambda) r_{SM}^2 r_{MS}^2}{f_{os}(\eta)\Gamma(\varphi, \lambda)[1 + \Lambda(\varphi, \alpha_{Sat}, \beta_{Sat}, \lambda)] r_{0,SM}^2 r_{0,MS}^2} \tag{8}$$

where $r_{0,SM}$ and $r_{0,MS}$ are the average distance between the Sun and the Moon and that between the Moon and the spacecraft. The normalized lunar irradiance is independent of the lunar viewing conditions and can thus be used to monitor the radiometric stability of RSB sensors.

4. Conclusions

The Moon has been viewed by the MODIS approximately monthly on-orbit. The lunar irradiance observed by the MODIS through its SV port depends on viewing conditions such as distance between Sun and Moon, Sun–Moon–MODIS phase angle, lunar librations, roll angle and distance between the Moon and MODIS. The influences of these factors on the observed lunar irradiance have been studied and expressions (or algorithms) for evaluating them quantitatively have been discussed. A normalized lunar irradiance is defined. It is independent of the viewing conditions and can be used to monitor the long-term stability of the MODIS RSBs.

From the lunar views, averaged RSB calibration coefficients have been calculated. The result shows that the normalized lunar irradiance can provide a reliable monitoring of the long-term radiometric stability. It also indicates that the degradation of the MODIS scan mirror is strongly AOI dependent, especially for bands 8, 9 and 10 in the visible spectral region. The results from the lunar observations and other on-board calibrators have been used to derive look-up tables for time-dependent response versus scan angle used in the MODIS calibration algorithm.