Absolute Calibration of Landsat Instruments Using the Moon

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ABSTRACT: A lunar observation by Landsat could provide improved radiometric and geometric calibration of both the Thematic Mapper and the Multispectral Scanner in terms of absolute radiometry, determination of the modulation transfer function, and sensitivity to scattered light. A pitch of the spacecraft would be required.

INTRODUCTION

THE MOON PRESENTS AN OBJECT whose diameter is approximately 194 pixels for the TM (Thematic Mapper) and 95 × 72 pixels for the MSS (Multispectral Scanner). It has the following unique properties: it is within the dynamic range of both instruments, it is surrounded by a black field in both reflective and thermal bands, and its surface-brightness distribution is better known than that of any other natural object at which these instruments could safely be pointed.

A single observation of the Moon by Landsat-4 or Landsat-5 could accomplish three evaluations of instrument performance that are impossible through the Earth's atmosphere: (1) radiometric calibration to the order of 2 percent; (2) determination of off-axis response (sensitivity to scattered light); and (3) measurement of the MTF (modulation transfer function) for mathematically sharp boundary.

These observations could be made in flight, after the occurrence of the uncertain changes associated with launch and initial stabilization of operation in space. Such observations would have two significant engineering impacts: temporary reorientation of the spacecraft away from nadir pointing, and assurance of the required S-band and X-band communications in this attitude.

If appropriate conventional nadir-pointing data (near-simultaneous coverage of a high-contrast scene) are available to allow cross-calibration between the Landsat instruments, either spacecraft could be used for the absolute radiometric lunar calibration; conventional scene data could be used to transfer this calibration between the two spacecraft. The MTF observation could probably be assumed to hold for both instruments. However, the off-axis response (scattered light sensitivity), which can be greatly affected by contamination of the optics, would hold only for the spacecraft used in the lunar observation.

The absolute spectral reflectivity properties of the Moon can be considered constant. The variations of its brightness with phase angle in the range near zero (significant effect) and with libration (small effect) are well known, both for the entire Moon and for individual areas on it. The brightness of the Moon relative to the Sun has been determined through the use of standard stars. The variability of the Sun as measured over the past 25 years has been less than 0.3 percent. The Moon can thus serve as an excellent standard for determination of time variations of an instrument response, for calibration between various spacecraft instruments, and as an absolute reflectance standard.

A calibration in terms of reflectivity requires only that the specific intensities of the Sun and the Moon be established in any self-consistent system; the system currently best understood is that of the standard stars. One path from this system to absolute radiometry (MKS units) is through Willstrop's calibration of the system of stellar magnitudes and colors using a standard lamp (Willstrop, 1960).

DISCUSSION

Quantitative terrestrial imaging is significant primarily for the implied values of reflectance (photometric function multiplied by normal albedo); the absolute heterochromatic specific intensity in w/(cm^2 sr) is rarely of direct significance. At present, the absolute calibrations of the TM and MSS are based on use of a standard lamp prior to launch, which involves an uncertainty of 3 to 5 percent. Reduction to reflectivity information requires the acceptance of a completely independent absolute spectral calibration of the Sun, which is of similar uncertainty. Both of these absolute calibrations can be circumvented by placing satellite imaging on the system of stellar magnitudes and colors through the acquisition of an image of the full Moon nearer to zero phase-angle than 4°. This calibration method would enable the production of images as quantitative reflectivity arrays with absolute precision of the order of 1 to 2 percent. A lunar observation can calibrate the Landsat instruments. In reducing a

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normal terrestrial scene to surface albedos, however, one must still contend with the variable atmospheric radiance.

A lunar calibration is valuable because the standard stars have luminosity constancy to a measuring threshold of about 1 percent or better; solar luminosity has been carefully measured during the past decade and varies only about 0.1 percent. In addition, the reflective properties of the Moon are stable to an even greater precision on any geologically short time-scale.

Measurements of the total solar irradiance over the last 5 years have reached levels of absolute accuracy on the order of 0.1 percent; the measurements indicate variations of this magnitude over short periods (days to weeks) and a possible gradual decrease of about 0.01 percent/year (Willson, 1984). Earth-orbiting spacecraft measurements between 1980 and 1983 indicate a decrease of 0.08 percent. Rocket and spacecraft measurements indicate constancy from 1969 to 1976 of better than 0.3 percent. Measurements from 1902 to 1964 had uncertainty greater than 1 percent and did not detect solar variability. (See the detailed review by Willson, 1984.)

There are no measurements indicating temporal variations of the bidirectional spectral reflectance of the Moon. Considering the estimated rates of impact-crater formation in the Earth-Moon system, the area of bright lunar rays, and the contrast between these bright rays and dark maria, we estimate that the Moon darkens at a rate of about 10^{-9} percent per year between large cratering events. The lunar surface is probably nearer to steady-state than indicated by this rate in terms of the micro-meteorite gardening process that influences its optical properties. Thus the time-variation of lunar reflectance is assumed to be negligible.

The Sun presents the most serious problem in the absolute calibration of albedos, regardless of method employed. Because it is almost a million times brighter than the full Moon, optical/mechanical deamplification is always necessary before transduction to the signal-form actually measured. Whereas the solar constant, integrated over all wavelengths, has been accurately measured by spacecraft-mounted, active cavity radiometers (Willson, 1984), the low-resolution spectral radiance of the Sun is best determined in comparison with standard stars and is expressed as the apparent magnitude of the Sun at a distance of 1.0 A.U. in a number of standard spectral band passes. The same standard stars are used in measurements of lunar brightness. The stability of solar luminosity and the standard stars assures that any Landsat calibration tied to the system of stellar magnitudes and colors, regardless of when they were obtained, could be revised by any future redetermination of the apparent magnitude of the Sun.

Although the full Moon is over ten thousand times brighter than the brightest star, the direct specific-intensity measurements as admitted through a small diaphragm covering but a tiny fraction of its surface are within the spread of apparent magnitudes of calibration stars. These measurements, all of which are obtained in the linear range of telescope-assisted photomultipliers, constitute the data set directly tied to the system of stellar magnitudes and colors. In addition, through an effort that integrates point-sequential photoelectric photometry, electronography, and photography, many photometric images have been obtained of the Moon within a few degrees of zero phase-angle. This work has enabled determination of normal albedo distribution over the lunar nearside with a selenographic precision exceeding the angular resolution of the TM by a factor of 3, along with a well-determined photometric function for this angular range (Wildey, 1976, 1977).

The spectral reflectivity of several locations on the Moon has been measured from 0.3 to 2.5 μm with 0.03 μm resolution. These spectra show a basic similarity. Normalized to 1.0 at 0.56 μm, they increase nearly linearly from 0.5 at 0.3 μm to 1.4 at 1.1 μm (McCord *et al.*, 1972). Spectral ratios of different terrain types typically show variations less than 10 percent and are known to 1 percent. Much of the lunar nearside has been mapped with silicon-vidicon imaging systems from 0.38 to 1.05 μm (Johnson *et al.*, 1977; McCord *et al.*, 1979). The Moon exhibits a significant variation in reflectivity with phase angle (Lane and Irvine, 1973); this variation is well known for times near full Moon (Wildey, 1976) which correspond also to the phase of the spectral mapping.

Lunar spectral reflectivities on a relative scale at wavelengths from 0.65 to 2.5 μm have been obtained recently (McCord *et al.*, 1981) and are tied to laboratory measurements of the spectral reflectivity of Apollo 16 soil samples. Beyond about 2.0 μm, a small correction for lunar thermal emission must be applied.

Approximately one-tenth of the lunar nearside is more than 50 percent brighter than the average of the nearside, and can be relied upon for higher DN (digital quantization level) tie points. The DN levels expected for an area 1.5 times brighter than the average near-full Moon for the TM (255 DN Max) and MSS (127 DN Max) bands are:

TM		MSS	
Band	DN	Band	DN
1	155	1	40
2	75	2	47
3	111	3	42
4	86	4	38
5	232		
7	182		

Owing to the large number of samples on the Moon and also to the presence of approximately 1 DN noise, the instrument response could be determined to the order of 0.1 DN, which is more than adequate to support the radiometric absolute accuracy at these response levels.

If the Landsat instruments were to obtain a lunar image close to full Moon, maps of lunar reflectivity (the product of normal albedo and photometric function) for the wavelength passbands used by the TM and MSS could be computed for the time of the Landsat observations. Thus the absolute radiance calibration in terms of reflectivity could be obtained directly.

The mid-infrared brightness temperature of the center of the full Moon is near 400° K; the radiance within TM band 6 would be about 2.3 times that at the TM saturation temperature of 320° K. Only areas near the lunar east limb would be within the dynamic range of the TM, but even these could not be used for a reliable radiometric calibration owing to the strong lateral temperature gradients.

Near full phase, the Moon represents a circular source one-half degree in diameter. At the nominal slew rate, each detector of the TM or MSS would cut more than 10 parallel chords across the Moon. Reconstruction of the lunar limb in this image would allow location of the limb relative to the sampling pattern to a precision better than 0.1 pixel. A large set of samples could be selected that represents apparent offsets of the limb by increments less than 0.2 pixel (MSS) or 0.1 pixel (TM). The relation between response and limb offset for such pixels would yield the near-field response to a knife-edge source from which the MTF could be determined.

The off-axis response could be determined with one-half degree angular resolution by transforming the full-scene image of the Moon in annular elements to construct a radial response function. Although the ideal response (if all the optic elements have remained clean) to the off-axis Moon would be less than 1 DN, thousands of samples could be averaged within the one-half degree resolution element. Here, the existence of instrument noise is an advantage. Without noise, the response over most of the image would be constant at the nominal dark level. However, where the instrument noise level is one-half degree DN or more, valid statistical averages could be obtained that would be virtually unaffected by the discreet digitization levels.

For the TM thermal band, which is approximately defraction limited, these results can be compared with a Fraunhofer diffraction response for a finite circular detector in a Cassagrain optical system of the appropriate dimensions. (See Chase *et al.*, 1978, especially Figure 6).

A time window for carrying out this calibration occurs once a month, and minimum uneclipsed phase (optimum) occurs twice a year. The slew past the Moon should be in pitch, and the spacecraft should pass the Moon at a rate of 33°/min (9.6 mrad/sec) in order to create a conventional image; any rate from 1/30 to twice this rate is adequate for calibration purposes. For the absolute radiometric calibration, the time of year must be taken into account, as the eccentricity of the Earth's orbit contributes a ±3.4 percent variation in solar irradiance; the orbit of the Moon around the Earth corresponds to only one-half percent variation in irradiance.

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