Vicarious calibration of GOES Imager visible channel using the Moon

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ABSTRACT: The feasibility of vicarious calibration of the GOES Imager visible channel using its measurements of the Moon is investigated and confirmed. A total of 26 lunar images were found from GOES-10 archive between July 1998 and December 2005. In addition, monthly observation of the Moon by GOES has been scheduled since November 2005. These measurements were compared against the USGS lunar model to estimate the GOES-10 Imager visible channel degradation. Several methods of computing lunar irradiance from GOES measurements were studied; the one using the selected mean to determine space count and masking the Moon to identify lunar pixels appears superior. The resulting degradation rates of 4.5% to 5.0% per year are consistent with those using other vicarious calibration methods. Preliminary estimate of lunar calibration precision as applied to GOES-10 is 3.5%.

INTRODUCTION

The National Environmental Satellite, Data, and Information Service (NESDIS) of the National Oceanic and Atmospheric Administration (NOAA) is responsible for the operational calibration of the Geostationary Operational Environmental Satellite (GOES). The visible channel of the GOES Imager does not have an onboard calibration device. The prelaunch calibration of this channel is out of date shortly after launch, unless vicarious calibration is carried out regularly.

Calibration is the process of quantifying sensor responses to known signals. Typically, the signals are known because their sources are well understood and carefully controlled. In the case of vicarious calibration, however, the source is rarely controlled and knowledge of the source is available only to certain extent. The most common assumption is that the signal is unknown but stable, which enables relative calibration or trending of sensor degradation. Occasionally, the signal is known in radiometric terms, which enables absolute calibration of the sensor.

Several methods have been developed for vicarious calibration of the GOES Imager visible channel. These include methods based on the sensor's measurements of stars[1,2] or desert[3], the method using co-located measurements by the Moderate Resolution Imaging Spectroradiometer (MODIS)[4], and the method based on analysis of the empirical distribution function of Earth targets[5].

In this paper, the feasibility of using the Moon for vicarious calibration of the GOES Imager visible channel is investigated. The principle of this method has been previously demonstrated[6]. To further explore the utility of this technique, it is imperative to know how many data are and can be available, what is the proper way to derive lunar irradiance from GOES measurements, and how does the lunar calibration results compare with those by other vicarious calibration results.

COLLECTION OF GOES LUNAR DATA

Unscheduled Collection

From a geostationary orbit above the equator, GOES views the Moon in a way similar to that on Earth's equator, towards the local zenith, and through a square about 19° wide that is blocked by an inscribed circle, the Earth disk (Fig. 1). A gibbous Moon appears in one of the corners approximately two to four times a month.

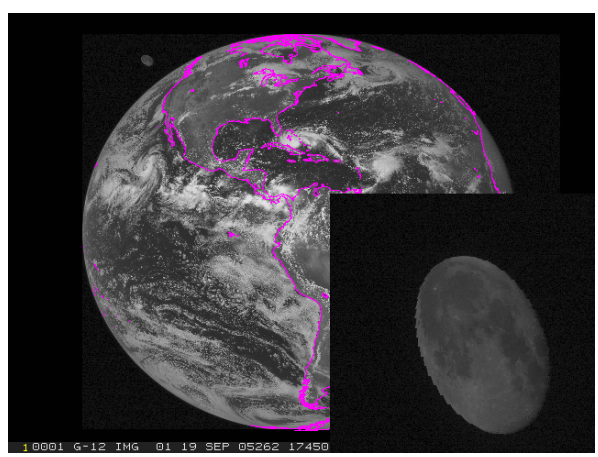

Figure 1: GOES-12 Full Disk image around 17:45 UTC on September 19, 2005. The Moon appears in the upper left corner, and is shown enlarged in the insert.

Most of these opportunities of observation, however, have been missed because GOES is operated on complicated and variable schedules. At the request by its users, sometimes on short notice, GOES images various sectors (Fig. 2) within its field of regard (FOR) at different frequency. The Full Disk sector, which offers the most capability of capturing a lunar image by chance, is imaged only every three hours. Other sectors, which are imaged more frequently but less regularly, have less or zero capability of capturing a lunar image by chance.

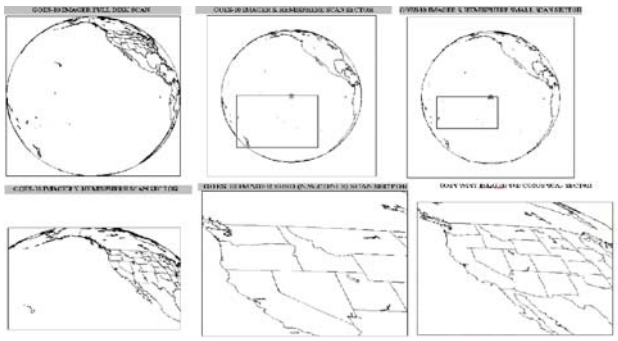

Figure 2: Scanning sectors of GOES West. Nominal and actual scan schedules are available from NOAA/NESDIS Office of Satellite Operations (e.g., http://www.oso.noaa.gov/goes/schd-sector/index.htm).

The first task, therefore, is to catalog the available lunar images. A search through the Full Disk images between July 1998 and December 2005, guided by celestial prediction of the Moon appearance within the GOES FOR during regular Full Disk imaging, yielded 18 lunar images. These, however, include ten images that were clipped by the edge of GOES FOR or by the Earth (Fig. 3). These clipped lunar images were not used for two reasons. First, computation of the irradiance from a partial lunar image requires a spatial model of the lunar radiance, which is not readily available. Second, determination of the fraction and orientation of the clipped part of the lunar image also proves to be challenging.

The first search yielded only eight usable lunar images in 7.5 years, which prompted the second search based on the possible Moon appearance within the GOES FOR, regardless of GOES operational schedule. Of the 290 images examined, most of the times GOES was not imaging the corner of interest or the lunar image was clipped, but 18 additional unclipped lunar images were recovered. Five of the total 26 images were within one hour of another image; these paired images are valuable for other purposes.

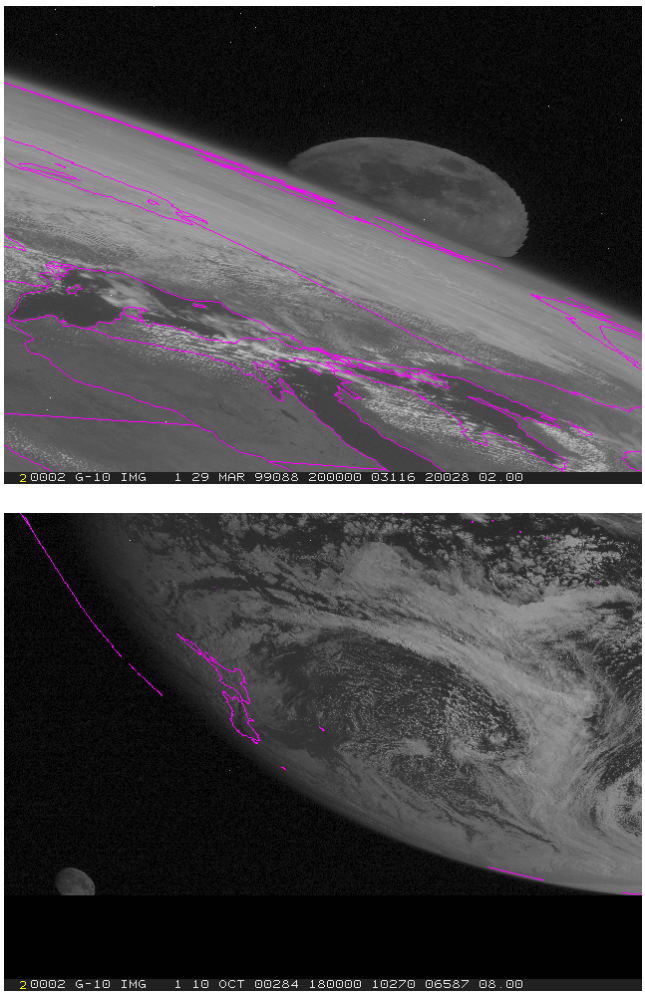

Figure 3: Examples of incomplete lunar images captured by GOES-10, in which the Moon is clipped by the Earth or by the edge of the GOES FOR.

While the current study focuses on GOES-10 because of its long record, similar effort was made to collect lunar images by GOES-12 data between April 2003 and June 2006, which recovered ten unclipped Moon images. GOES-12 is less likely to view the Moon by chance because it is more often to be operated in the Rapid Scan mode. Also unlike GOES-10, five of the 10 captured Moon images appear in the Full Disk scan, and five are clipped by the Earth or the FOR.

Scheduled Collection

Since "observation by opportunity" can not reliably provide sufficient frequency of lunar images, NOAA has scheduled monthly collection of lunar image beginning in November 2005. Each month and for each satellite, satellite operators, informed well in advance, replace approximately one minute of scheduled star views with a lunar view. So far this has been done

interactively, including the prediction of suitable Moon appearances and the change of schedule. Although the work involved may be reduced if the procedure is automated, satellite operations have been able to manage the extra burden. Also, satellite operations (navigation in particular) have not been adversely affected by the loss of a small part of the star view data. This indicates that scheduled collection of GOES lunar images is not only necessary but also feasible and sustainable in current GOES operation.

The scheduled data collection went well for the first six months. In May 2006, however, the scheduled GOES-12 lunar observation was overridden due to a weather situation that required the GOES-12 be in the Rapid Scan mode. The scheduled GOES-12 lunar observation in June was affected by an East-West maneuver. GOES-10 stopped collecting lunar images in May 2006, as it was replaced by GOES-11. Data collection is expected to return to normal soon. Experience with GOES-12 is representative of scheduled data collection. The success rate, while not 100% due to weather situations or satellite station-keeping, is adequate.

ANALYSIS OF GOES LUNAR DATA

Theory

By definition, the lunar irradiance E can be computed from GOES measurements by

$$E = \sum_i R_i \omega_i$$

where R_i is the radiance from a pixel i on the Moon, and ω_i is the solid angle subtended by that lunar pixel. Note that

$$\omega_i = const, \qquad R_i = S\left(C_R^i - C_S\right)$$

leads to

$$E = \omega S \sum_i \left(C_R^i - C_S\right) \tag{1}$$

where S is a calibration coefficient commonly referred to as "slope" (reciprocal of the instrument gain), C^i_R is the raw count for pixel i (instrument response to the radiance from pixel i), and C_S is the space count (instrument response to zero radiance). In Eq. 1, the calibration coefficient S is the parameter we will eventually determine, for that we must know precisely the solid angle ω and space count C_S.

Solid Angle

The solid angle is directly related to the sensor's instantaneous geometric field of view (IGFOV) and scanning characteristics. According to the GOES I-M DataBook (Space System/Loral, 1996, DRL 101-08, Revision 1, 196 pp)[7], the IGFOV of the visible channel of the GOES Imager is 28 microradians (μrad). There is neither over-sampling nor under-sampling between the scanning lines (north-south direction). However, the GOES Imager scans at a rate of 20°/sec while sampling at a rate of 21817 samples/sec, thus it over-samples along the scanning line (east-west direction) at a rate of 1.75. Assuming the IGFOV is a rectangular of 28 μrad by 28/1.75 = 16 μrad, the solid angle subtended by one pixel of GOES Imager visible channel is (28 μrad) × (16 μrad) = 4.48×10^{-10} sr.

Note that the values quoted above are nominal numbers subject to further revision. Partly because of this uncertainty, the focus of current study is on relative calibration.

Space Count – Baseline Algorithm

After a designated space view, the GOES Imager averages all the measurements and sets the instrument response to that average to a prescribed value. For the visible channel the value is 29. This procedure, performed onboard the satellite and referred to as "space clamp", ensures that the instrument response to space is constant over the mission life even the sensor responsivity may experience short term fluctuation or long term degradation.

The GOES Imager visible channel has eight detectors. Normally, the clamp noise, measured as the root-mean-square (RMS) of the space clamp values for an individual detector over a period of time, is less than one count. The clamp variability, measured as the difference in space clamp among the eight detectors at any time, is also on the order of one count. Occasionally, however, the clamp noise for a single detector may increase substantially, creating large clamp variability and hence striping in the images. For this reason, "relativization" was implemented in spring of 1996 as part of the ground system processing to ensure that the eight space clamp values have mean of 29 and variability of one count[8].

The GOES instrument measurements are occasionally contaminated by cosmic rays. Relatively rare and random, these high energy particles cause sudden and isolated increases in pixel values. Typically, a contaminated single pixel value is several times the normal value, resulting in a bright spot in the image. Sometimes the value is so high that it causes an overflow or roll-over of the down linked 10-bit data, resulting in a dark spot in the image. These are collectively referred to as "pepper and salt", whose characteristics are related to the space environment in

which the instrument is operating. (Depending on the quality of reproduction, "pepper and salt" might be discerned in Fig. 3.) Experience indicates that the maximum count values from lunar pixels is about 230, so pixels with count value more than 250 are eliminated from further analysis. Similarly, pixels with count value less than 15 are also eliminated. This is because the standard deviation of space counts, by instrument specification, should be less than 2.8 counts (often 2.5 or less). Pixels with count value of 14 or less, even if they are legitimate space pixels, are extremely rare and practically negligible as they are more than five standard deviations from the expected space value.

Space Count – Alternative Algorithm

The baseline algorithm of using a constant as space count may be inadequate for two reasons. First, the sensor's response to space may drift between space clamps. While the space clamp is executed frequently (every 2 to 36 seconds, depending on scanning mode), it is still desirable to use the actual space count value near the time when the Moon is imaged. Second, the space count can be truncated due to digitization. Typical raw count values of lunar pixels (C_R in Eq. 1) range from 70 to 150, depending on the phase of the Moon. The δ-count, or $C_R - C_S$ in Eq. 1 that directly corresponds to pixel radiance, is therefore 40-120. For these values, a one-half count uncertainty in the space count leads to 0.4-1.2% relative uncertainty in the computed lunar irradiance. For these reasons, considerable effort has been devoted to improving the estimate of the space count.

Average and mode are often used as representative value of a collection of samples. Compared to average, mode is more resistant to the outliers if present, so one alternative is to use mode instead of constant for space count.

On the other hand, mode is more affected by digital quantization, which is significant in this particular case. Another alternative, therefore, is to use the average from a sample that is free of outliers. It is straightforward to avoid outliers on the low value side, in fact the minimum acceptable value of 15, adopted to avoid "pepper and salt", has largely prevented low value outliers from entering the analysis. The situation is more complicated on the high value side of the space count distribution. Fig. 4 suggests the existence of a transition zone outside of the edge of the Moon where it is uncertain whether a pixel is truly space. Consequently, the space count histogram approaches to zero more gradually on the high value side than on the low value side (Fig. 5).

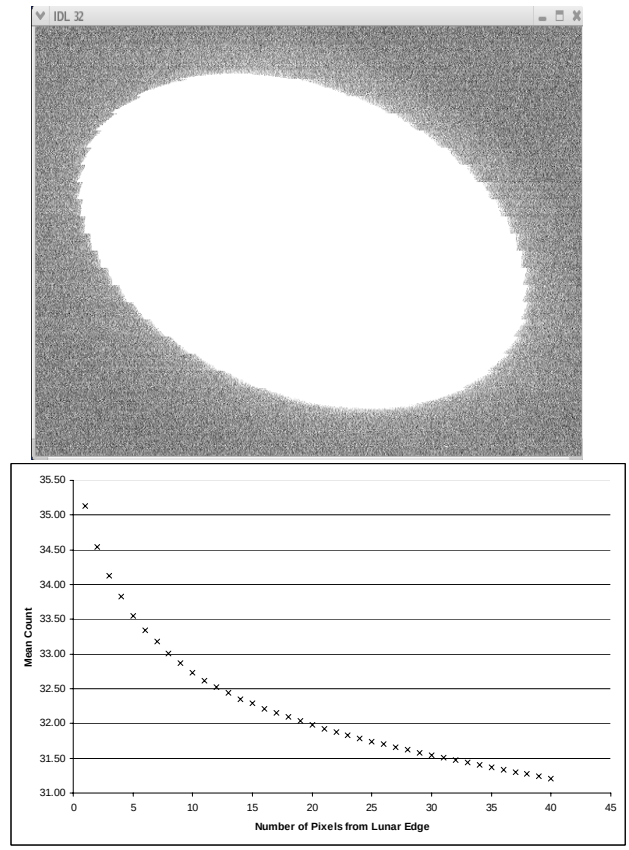

Figure 4: Top: Image in the vicinity of the Moon on Day 307 of 1998, where a stretch has been applied to show count values between 15 and 45. Bottom: Mean raw count values plotted as a function of number of pixels away from the edge of the Moon image.

Insight into identifying the space views that are possibly contaminated by stray light may be gained by studying the second derivative of the histogram of an image that contains both the Moon and space:

$$\begin{aligned} D_t &= S_{t+1} - S_t \\ &= \left(N_{t+1} - N_t\right) - \left(N_t - N_{t-1}\right), \qquad 30 \le t \le 45 \\ &= N_{t+1} + N_{t-1} - 2N_t \end{aligned}$$

where N is the frequency of occurrence for a raw count value of t, S is the first derivative (slope), and D is the second derivative. Fig. 5 is an example for the case of Day 307 of 1998. The second derivative D reaches a maximum at raw count value t, as indicated by the "*" symbol in Fig. 5, which means that there is relatively little change in number of occurrence beyond t. This value t is chosen as the high end cut off.

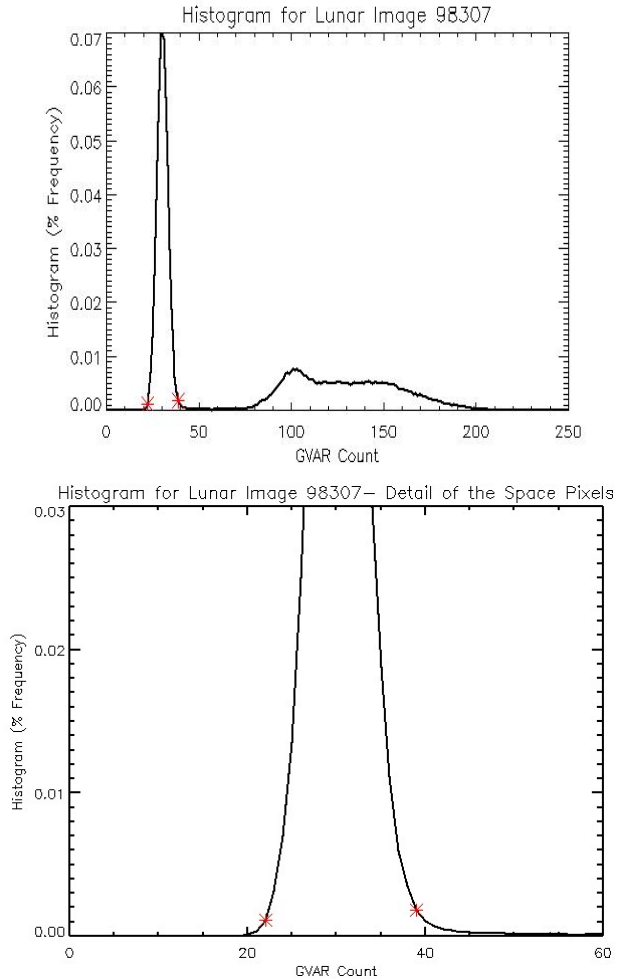

Figure 5: Histogram, or the frequency of occurrence for each raw count value, for the case of Day 307 of 1998. In the upper panel, the narrow mode at 30 corresponds to the space count. The broad mode between 100 and 150 corresponds to the Moon. The "*" symbols indicate the position of maximum second derivative of the histogram. A close-up to this portion is presented in the lower panel.

Computation of GOES Lunar Irradiance

The last issue regarding Eq. 1 is the range of summation, or determining which pixels will be counted. The Moon has been framed as images of 400 scanning lines by 700 pixels on each line. The baseline algorithm is to use all the pixels, assuming the space pixels do not contribute to the computed irradiance on average.

Alternatively, one can distinguish lunar pixels from space pixels and compute the sum of only the lunar pixels. This requires a geometric model of the Moon with the location of its center and semi-major and semi-minor axes known. Originally, the model was obtained by first reconstructing an elliptical lunar image. The raw lunar image has a "saw tooth" pattern along the edge that is eight scanning lines wide, as seen in Fig. 1, because the Moon moves relative to the Earth (and GOES) while being imaged. When the image is close to a corner and as the GOES Imager scans back and forth horizontally, two 8-line bands are scanned closely in time whereas they are far apart for the previous and the next two 8-line bands, creating a broader saw tooth of 16-lines wide. This is the case in Fig. 1. It is then possible to sequentially adjust each 8-line band to reconstruct a nearly smooth edge. Once the elliptical lunar image is available, one can select a number of pixels (typically 30) that are well distributed along the edge and use their coordinates as input to find the parameters for the geometric model of the Moon through least squares fitting. Lately, the procedure of obtaining the geometric model of the Moon is mostly automated and, in particular, the manual reconstruction of smooth lunar edge and manual selection of samples along the edge is no longer necessary.

The geometric model of the elliptical lunar image can be used in two ways. One approach, used by Stone et al (2005)[6], starts with an ellipse about 20 pixels inside of the edge and compute the lunar irradiance repeatedly while enlarging the lunar image one pixel at a time. The "growth" of the Moon stops when increase of ellipse results in insignificant change (<0.01%) of lunar irradiance. Alternatively, one can assume that the lunar image is a similar but slightly larger (10 pixels) ellipse than as modeled.

MODELED LUNAR IRRADIANCES

The capability for predicting the lunar irradiance has been developed at the U.S. Geological Survey (USGS) in Flagstaff, Arizona, as a NASA-sponsored effort for on-orbit calibration of the imaging instruments on the Earth Observing System (EOS) research satellites. This work has shown that a practical approach to using the Moon as a radiometric standard requires a model that accommodates the geometry of illumination and viewing corresponding to satellite lunar views without restriction. The USGS lunar calibration program has produced an operational model for the lunar spectral irradiance[9], covering phase angles from eclipse to 90° (First Quarter to Last Quarter lunar phase) and all lunar librations observable from Flagstaff, Arizona.

The USGS lunar irradiance model was developed from fitting thousands of lunar measurements acquired by a dedicated ground-based facility called the RObotic Lunar Observatory (ROLO), located on-site at the USGS Flagstaff Science Center. ROLO operated for more than 6 years, acquiring over 85,000 individual

lunar images in 32 wavelength bands from 350 nm to 2450 nm. Images of stars were collected each observing night, for use in computing atmospheric extinction corrections for the lunar radiance measurements. For model development, the ROLO at-telescope data are calibrated to exoatmospheric radiance, and then summed spatially to irradiance in a similar fashion as Eq. 1. Because this quantity follows the "one-over-R-squared" law for distances, the individual irradiance values are corrected to standard distances of 1 AU for Sun-Moon and 384,400 km for Moon-observer (the mean Earth-Moon distance).

Development of the model analytic equation and fit coefficients is done in dimensionless reflectance, converted from irradiance E by:

$$E = A \ \Omega_M \ E_S / \pi$$

where A is the disk-equivalent lunar reflectance (albedo), Ω_M is the solid angle of the Moon at standard distance, and E_S is the solar spectral irradiance for a wavelength band of moonlight. The disk reflectance model has the form, for wavelength band k:

$$\ln A_k = \sum_{i=0}^{3} a_{ik} g^i + \sum_{j=1}^{3} b_{jk} \Phi^{2j-1} + c_1\theta + c_2\phi + c_3\Phi\theta + c_4\Phi\phi + d_{1k} e^{-g/p_1} + d_{2k} e^{-g/p_2} + d_{3k} \cos((g - p_3)/p_4)$$

where g is the absolute phase angle, θ and φ are the selenographic latitude and longitude of the observer, and Φ is the selenographic longitude of the Sun. In a multi-step fitting process, ~1200 data points are fitted for each of the 32 ROLO bands. The band-averaged absolute residual of the fit is ~1%; this value represents a measure of the model's capability to predict the variations in the lunar irradiance with geometry over the full range of the geometric variables g, θ, φ, and Φ.

Spacecraft instrument teams access the lunar model through a set of data exchanges; a description of this process can be found at the website: www.moon-cal.org → Spacecraft Calibration. For each lunar observation, the instrument team supplies to USGS the location of the satellite and the time of the observation, a measure of the oversampling rate (usually the down-track size of the Moon in the image), and the measured irradiance computed with the usual instrument calibration coefficients. At USGS, an ephemeris is computed to find the phase and orientation of the Moon, thus the librations, for the observation time and location. The lunar model is queried at the corresponding geometry, and then interpolated along a smooth lunar reflectance spectrum to the instrument's wavelength band. For wide-band instruments such as GOES, a weighted sum of ROLO bands is used. The model results are reported to the instrument team as the discrepancy in irradiance between the instrument measurement (corrected to standard distances) and the model. The lunar ephemeris calculations are also supplied.

RESULTS AND ANALYSIS

Every time the GOES-10 captures a Moon image, the lunar irradiance can be computed with the USGS lunar model, E_{model}, and derived from the GOES measurement, E_{GOES}. Using E_{model} as reference, the ratio R of these two quantities, in particular the change of R in time, indicates sensor performance and degradation:

$$R(t) = \frac{E_{GOES}}{E_{model}}$$

where t stands for time but the notion is omitted in the E terms for clarity. Using Eq. 1, we have

$$R(t) = \frac{\omega S \sum_i \left(C_R^i - C_S\right)}{E_{model}} = \frac{\omega S \left(\sum_{i=1}^{N} C_R^i - N C_S \right)}{E_{model}} \qquad (2)$$

There are a total of nine sets of $R(t)$, derived from three choices of C_S (Constant, Mode, and Selected Mean), each with three choices of N (All, Growth, Mask). The data are summarized in the Appendix, from which $R(t)$ can be calculated. Fig. 6 is a scatter plot for one case (all pixels) with three choices of space count, as well as exponential fits of those data.

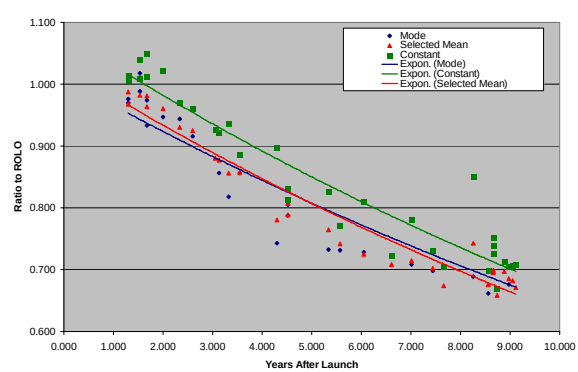

Figure 6: Scatter plot of *R(t)* in Eq. 2 as a function of time for the case of using all pixels, with three choices of space count. Also plotted are exponential fits to the three *R(t)*.

The results of regression analyses are summarized in Table 1. Judging by the standard error of estimates, it seems that using the selected mean to represent the space count is superior to using a constant or the mode. Also, using the Moon mask improves the estimate. The rest of the analysis will focus on the method using Masking Moon and Selected Mean.

Eight of the nine resulting degradation rates (β) are rather consistent, ranging from 4.5%/year to 5.0%/year. This agrees broadly with degradation rate obtained for GOES-10 Imager visible channel based on other methods. For example, 5.5%/year between June 1999 to October 2003 by the Empirical Distribution Function (EDF) method; 4.9%/year between December 1999 to December 2004 by the desert method; 5.1%/year between March 1998 and April 2006 by the star method; and 3.9%/year between January 2001 and April 2006 by the star method. In particular, an analysis of the data between 2000/01/01 to 2005/05/30, using Masking Moon and Selected Mean, yields $a=0.8711$ and $\beta = 0.045$, or a degradation rate of 4.5%/year. This compares very well with the 4.4%/year degradation rate produced by the vicarious calibration over the same period using MODIS.

Table 1: Summary of exponential fits to the nine *R(t)*. SE is the standard error of fit.

$y = a * e^{\beta}$		Constant	Mode	Selected Mean
All Pixels	a	1.081	1.010	1.029
	β	-0.048	-0.045	-0.049
	SE	0.038	0.042	0.030
Growing Moon	a	1.064	1.030	1.038
	β	-0.048	-0.046	-0.048
	SE	0.033	0.033	0.030
Masking Moon	a	1.049	1.026	1.031
	β	-0.050	-0.048	-0.049
	SE	0.029	0.030	0.029

As pointed out earlier, lunar irradiance can be used for absolute calibration of the GOES Imager visible channel. Using the results over the period when MODIS data are available, lunar calibration suggests that GOES-10 Imager visible calibration needs a correction of 1.47 by the end of May 2005 to compensate for the degradation at that time. The MODIS-based calibration indicates a correction of 1.55 is needed; the relative difference between the two is about 5% and is within the standard error of both estimates.

Standard error is a measure of the difference between the estimated and predicted values. To assess the relative difference, we computed (estimated/predicted-1) for each case and found the standard deviation of these values is 0.035. This value of 3.5% indicates the current precision of lunar calibration for GOES.

While both the accuracy and precision of lunar calibration seem to be excellent, it must be emphasized that current results are preliminary and must be subject to further scrutiny as well as peer review before a solid conclusion can be drawn.

SUMMARY

Perched on geostationary orbit, the GOES Imager visible channel views the Moon with ease as compared with sensors on a polar orbit. In that regard, it would be a waste of opportunity not to use the Moon for calibration of visible and near infrared sensors on GOES. Even without any special schedule, three Moon images have been found on average each year from a GOES by chance. With reasonable effort, lunar images are now collected monthly for each GOES. Such scheduled collection is necessary to increase the number and regularity of lunar views; it also proves feasible and sustainable for satellite operations. Future GOES such as GOES-R may not view the space surrounding the Earth disk as generously, thus it may not be possible to capture a Moon image by chance. Still, it is much easier to schedule and execute a Moon view on GOES than on POES.

Space clamp circuitry in the current GOES Imager presents a significant challenge to applying lunar calibration. A total of nine methods of determining the space count and identifying lunar pixels were considered; the best method seems to be masking the Moon and using the mean of selected space pixels. It was discovered that there may exist a rather wide transition zone outside of the edge of the Moon where the probability is high to encounter a space pixel whose count value is substantially higher than expected. It remains to be verified whether sampling the space pixels on the same scanning lines of the lunar image but farther away from the Moon's edge may help. It is also crucial to improve the estimate of the pixel's effective solid angle, both the instantaneous geometric field of view and the rate of over-sampling.

Nearly eight years of GOES-10 data were examined that yielded 33 usable lunar images, including seven since November 2005 from scheduled collection. It was found that the degradation rates derived from these are

consistent with most other methods and agree well with past experience. Compared with the vicarious calibration results based on MODIS over the period January 2000 to May 2005, the degradation rate from the Moon-based calibration (4.5%/year) agrees very well with the MODIS-based calibration (4.4%/year)[11], confirming the capability of lunar calibration for relative calibration. The Moon- and MODIS-based calibrations indicate a correction of 1.47 and 1.55, respectively, by the end of May 2005. The difference between the two, about 5%, is also very encouraging for absolute calibration based on the Moon. Finally, one estimate of lunar calibration precision as applied to GOES is 3.5%.

Because the Moon is a very stable reflectance surface and the USGS lunar model is precise to predict the lunar irradiance, the GOES lunar observations can find many other applications in sensor characterization and performance monitoring. Lunar calibration, together with other techniques (especially onboard calibration for the visible channel imagers), can further improve sensor performance to meet meteorology and climatology requirements[10].

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