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Algorithms for Lunar Flash Video Search, Measurement, and Archiving

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Abstract Lunar meteoroid impact flashes provide a method to estimate the flux of the large meteoroid flux and thus their hazard to spacecraft. Although meteoroid impacts on the Moon have been detected using video methods for over a decade, the difficulty of manually searching hours of video for the rare, extremely brief impact flashes has discouraged the technique's systematic implementation. A prototype has been developed for the purpose of automatically searching lunar video records for impact flashes, eliminating false detections, editing the returned possible flashes, and archiving and documenting the results. The theory and organization of the program is discussed with emphasis on the filtering out of several classes of false detections and retaining the brief portions of the raw video necessary for in depth analysis of the flashes detected. Several utilities for measurement, analysis, and location of the flashes on the moon included in the program are demonstrated. Application of the program to a year's worth of lunar observations is discussed along with examples of impact flashes as well as several classes of false impact flashes.

1 Introduction

NASA's Meteoroid Environment Office (MEO) has monitored the Moon for meteoroid impacts on a systematic basis since an initial detection [Cooke, 2006] in November, 2005. These observations of the lunar earthshine for many as ten nights per month have yielded an immense quantity of video data and information on over 50 impacts. The task of finding and measuring these impacts has resulted in the evolution of algorithms for the detection, measurement, calibration and evaluation of these flashes.

2 Lunar Flash Video Search Method

The pioneering work in lunar flash search by Ortiz *et al*, [1999] and Bellot Rubio *et al.* [2000a, 2000b] was superseded by Gural whose LunarScan program [Cudnick, 2003] applied terrestrial video meteor techniques to the detection of Leonid lunar impacts. These methods are based on the detection of spatially and statistically significant differences between successive frames resulting from the sudden onset of the lunar impact flash. False detections from cosmic rays, satellites, noise, atmospheric meteors and other sources are removed by a combination of software and the judgment of a human operator. Further development was done by Swift to produce the program LunaCon, based on the atmospheric meteor analysis program Meteor44 [Swift, 2004, 2007]. LunaCon added photometric analysis and improved false flash rejection to detection techniques similar to those used in LunarScan. LunaCon was used for the detection of over 40 lunar impacts at the NASA Marshall Space Flight Center from November, 2005 until the Spring of 2007 [Suggs, 2007] and is currently used for the analysis and qualification of detected flashes. Recent improvements in speed, sensitivity, and operability [Gural, 2007a,b] have resulted in LunarScan being the software of choice for lunar flash detection. Contact the MEO to obtain LunarScan. After the qualification of the detected flashes, photometric analysis can be performed as described below with LunaCon or with the aid of other astronomical photometric packages.

3 Lunar Flash Video Measurement

The lunar flash measurement goal is to evaluate the sequence of lunar video images used for impact flash surveys to estimate the mass flux of the impacting meteoroids. The flashes are optically unresolved so only intensity and duration information is available. Spectroscopy, even of the simplest sort, is limited by the dim nature of the flashes: there are few photons and one never knows when and where each flash will occur against the textured lunar background. This sparse, random nature of the events makes more elaborate analysis techniques difficult. Thus one is left with flash photometry of each video image, the time between the flashes and the area surveyed as the primary information sources.

3.1 Surveyed Lunar Area

The Moon is a very large target and as such provides an excellent sensor for those large mass, extremely small flux meteoroids which cause the observable flashes. Lunar impact observations are made of the earthshine portion of the moon to avoid the sunlit portions which blind our sensors. Since the earthshine portion of the moon varies with phase and drifts in position during the observations due to tracking errors, the total area observed must be accumulated from frame to frame and adjustments made for clouds, atmospheric effects, and the "limiting magnitude". The result is the number of effective square kilometer – hours of observations, optionally binned by "limiting magnitude", which is compared with the number of observed flashes, *N*, binned by magnitude as well. Since the time interval between detected flashes is several hours, the observed area-time product (km^2-hr) of null observations is an important part of the flux estimate.

$$Flux_{magnitude} = \frac{N_{magnitude}}{\sum_{obs} (Area \times Time)_{magnitude}} \quad (1)$$

A method has been devised for automatically detecting and evaluating the lunar area visible in each video image. As a first step, the lunar limb is located in the image, fitted to a polynomial and solved for lunar disc center, (*x0, y0*), and radius, *R*, in image pixels. The Moon is essentially spherical which implies that an image pixel near the limb covers far more lunar area than one viewed normally at the center of the disc. From the determined image radius, one can readily calculate the number of center pixels in the whole sphere and, by similarity, the lunar area, A_c, of the center pixel in km^2. Knowing (*x0,y0*) and *R*, the radial distance, *r*, for each pixel in the lunar image is determined and the area weight, *W*, the ratio of curved pixel area to center pixel area, is determined for that pixel:

$$PixelAreaWeight, W = \frac{1.0}{Cos\left(A\sin\left(r/R\right)\right)} \quad (2)$$

The total lunar area in each image is the sum over all lunar pixels of the WxA_c product. It is usually not necessary to examine every frame as long as the sampling rate is taken into account and the moon remains in approximately the same position in the field of view.

3.2 Lunar Flash Video background

The lunar mean brightness of the earthshine is significant because it forms the background from which the impact flashes must be detected. Although the exo-atmospheric brightness of earthshine can be predicted by lunar phase, it is considerably modified by atmospheric effects in the observations. The center and radius of the Moon in the image is used to mask the image so that the lunar mean intensity, *Lmi*, and the maximum and minimum intensities, [*Max, Min*] can be measured in instrument units (IU). In practice, the robust "mean median half" technique is used for *Lmi* and the 95 percentile and 5 percentile is used for *Max* and *Min* to avoid the effects of hot and dead pixels found in real images. It is useful at the same time to measure the sky mean intensity in IU, *Smi*.

The lunar mean intensity measured above, is a surface measurement while stellar calibration and flash intensities are based on total impulse intensity. The image's point spread function, *PSF*, determined by fitting a cone or Gaussian to the star or flash, allows one to compare surface and impulse intensities. From the peak and the full width half maximum (FWHM) of the fitted cone or the sigma (σ) of the Gaussian one can determine the effective area of the PSF, *Apsf,* such that $I_{Total} = Apsf*I_{peak}$. *Apsf* is approximately $(\pi/4)FWHM^2$ or $2.178\sigma^2$. This allows one to use the mean lunar surface intensity as a calibration transfer standard. The product of *Apsf* and *Lmi* yields the apparent lunar PSF intensity in IU, *Lpsfi*, a useful measure of the lunar background. The instrument sensitivity, *sen0*, is defined in terms of IU for a zero magnitude star. The effective lunar *PSF* magnitude, *Lpsfm,* for the image conditions is determined as follows:

$$Lpsfm_{image} = -2.5Log_{10}\left(\frac{Lpsfi}{sen0}\right) - 5Log_{10}\left(\frac{\text{Apsf}_{image}}{\text{Apsf}_{star}}\right) \qquad (3)$$

As an example, if the *PSF* has a sigma of 1 pixel then its area is 2.18 pixels. If *Lmi* = *75* IU and *sen0* = *2e6* IU then *Lpsfi* = *164* IU and *Lpsfm* = *+9.8.*

The next lunar image measure we wish to evaluate is contrast. Contrast has much to say about image quality, the range of values within the image, and the detectability of events within the image. Having defined the intensity range of the lunar image as [*Max, Min*], lunar contrast is defined as follows:

$$Contrast, C \equiv \frac{Max - Min}{Max + Min} \qquad (4)$$

Contrast, a dimensionless number scaled [0,1], can be used to recover the intensity range of the image given the mean intensity: *range* = *mean* $(1 \pm C)$. One can also define an exoatmospheric contrast, C^*, as contrast with the sky mean intensity removed: $C^* = C \times [Lmi\ /\ Lmi + Smi)]$. Since C^* is normally constant for an image, the variation of C can be used to estimate *Smi*. To adapt the contrast range to astronomical magnitude, note that:

$$\text{Log(mean } (1 \pm C)) = \text{Log(mean)} + [\text{Log}(1+C), \text{Log}(1-C)] \quad (5)$$

Adding sen0 to form the appropriate ratios and Astronomical scaling gives the lunar *PSF* magnitude range, *Range* $_{Lpsfm}$:

$$\text{Range}_{\text{Lpsfm}} = -2.5Log_{10}\left(\frac{Lpsfi}{sen0}\right) + \left[-2.5Log_{10}\left(1+C^*\right), -2.5Log_{10}\left(1-C^*\right)\right] \quad (6)$$

Range $_{Lpsfm}$ is a very useful pair of numbers since they approximate the mare and highland intensities covering a spot the same size as the *PSF* of a lunar impact flash providing an estimate the bounds on what is observable.

3.3 Lunar Flash Video Photometry

It often seems that to evaluate the intensity of the lunar impact flash just found one must break every rule of astronomical photometry. In the first place, one has no choice of sky condition and cannot wait for a better night. Next, one cannot just search about for a standard calibration star since the sky part of the field of view is so small. This sometimes means that the only poor dim star seen in the half million images that night must be used to estimate the intensity of a lunar impact flash several hours displaced in time, in a different part of the sky, and contaminated with cirrus. It is proposed to use the lunar surface brightness as a transfer standard for sensitivity determination and extinction compensation to mitigate these problems.

As a first step, a calibration star is located in the video stream and its image isolated with a bit of sky background. The total intensity of the star is measured in IU using the usual circular aperture methods. The magnitude of the star corrected for camera spectral sensitivity (usually R band) is used along with the measured intensity in IU to estimate the response the camera would have to a zero magnitude (Vega) star. This is the sensitivity, $Sen0_0$, of the camera / telescope / atmosphere system for the image containing the calibration star in IU.

The next step involves determining the lunar mean intensity, *Lmi*, and the sky mean intensity, *Smi*, in IU as above. From this a lunar sensitivity factor, *Lsf*, for the dataset is determined and the sensitivity for each frame, $Sen0_k$, is found.

$$Lsf = \frac{Sen0_0}{Apsf_0\left(Lmi_0 - Smi_0\right)} \Rightarrow Sen0_k = Lsf \times Apsf_0 \times \left(Lmi_k - Smi_k\right) \qquad (7)$$

The sensitivity for frame *k*, $Sen0_k$, includes the atmospheric extinction for that frame and is insensitive to changes in *PSF* and light scattered into the lunar disc. This sensitivity is used in the normal manner to establish the exo-atmospheric magnitude of the flash. Furthermore, since the lunar altitude and thus the image air mass is known for each image the relative atmospheric extinction can be found as well.

4 Lunar Flash Characterization from Video

Examination of the brighter observed lunar flashes shows the light curve to be well represented by an exponential decay curve. It is currently accepted that the impact flashes observed to date are due to the hypervelocity impact of kilogram class meteoroids into lunar regolith. Unlike similar impacts onto solid targets, most of the initial plasma event is obscured and the plasma quenched by the regolith dust [Gault, 1963; Yanagisawa, 2002]. This implies that our video cameras observe the thermal emissions from the hot dust cloud and perhaps the evolving crater. Hypervelocity impact tests into simulated regolith at the NASA Ames Vertical Gun Facility [Ernst, 2004; Edwards, 2007] with these same cameras produce similar light curves from the extremely bright images of hot ejecta dust [Suggs, 2007]. The goal is to get as much information as possible from the more commonly observed lunar impact flashes which last, at most, several frames and to be able to compare flashes.

4.1 Flash Characterization Method

A simple thermal decay can be represented by a time constant, α, and an initial peak value, I_0. The most reliable, measurable quantities observed in a lunar flash consist of the peak intensity, I_a, and the total intensity, I_T, of the flash in instrument units (IU). The peak intensity, I_a, depends on the camera exposure time and, to a lesser extent, on when the flash began in the exposure. The total intensity, I_T, is particularly significant due to its assumed direct relationship to the total energy of the event. One notes that I_T is mathematically the integral over all time of the decay exponential which is simply the product of I_0 and α. For the case where the flash peak is the first exposure of period a,

$$I_a = \int_0^a i_0 e^{-\left(\frac{t}{\alpha}\right)} dt = i_0 \alpha \left[1 - e^{-\left(\frac{a}{\alpha}\right)}\right] \Rightarrow \frac{I_a}{I_T} = 1 - e^{-\left(\frac{a}{\alpha}\right)} \qquad (8)$$

Which yields an estimate of I_0 and α given the peak intensity, exposure time and the total intensity.

$$\alpha = \frac{a}{\ln\left(\frac{I_T}{I_T - I_a}\right)} \Rightarrow Initial\_Intensity, I_0 = {}^{I_T}\!/_{\alpha} \qquad (9)$$

From the above, it is apparent that, although undefined for the single flash case, it is useful to let $\alpha \equiv 1$ when $I_a = I_T$ so that $I_0 = I_T$. For the lunar impact thermal decay observed by earthbound video, the decay time constant, α, is of the order of milliseconds so a value of $\alpha \equiv 1$ should be taken as a special case.

The initial flash intensity, I_0, can be used to find the exo-atmospheric initial flash magnitude, m_f,. m_f, together with the time constant, α, comprise a better measure of lunar flash properties than the magnitude of the peak value, I_a which depends to a large extent on the camera properties. Indeed, if the light curve of the flash is plotted as stellar magnitude by the usual methods, the exponential decay is linear and the time constant, α , and initial flash magnitude, Im_f, are readily determined by point slope methods. From Im_f and α the total intensity and expected peak intensity for any given exposure time can be found with no knowledge of the properties of the camera that recorded the data.

4.2 Flash Characterization Example

The flash observed on May 1, 2006 at 2:34:40.05UT is presented as an example of the characterization of an exceptionally intense lunar impact. The intensity data in Figure 2, (left plot) shows a reasonable fit to the log decay curve for an initial intensity of 6500 instrument units (IU) with a time constant of 0.040 seconds. When the intensities as compared to a known star are plotted by magnitude, Figure 2, (right plot) the linear fit to the magnitude decay is quite evident and the time constant readily determined from the slope. The initial flash magnitude is the intercept of the linear magnitude decay line with the initial time.

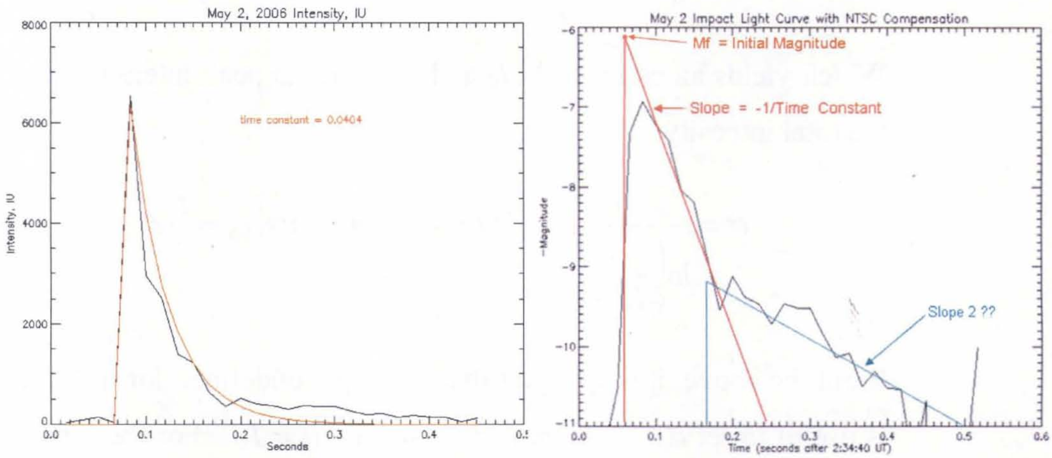

Figure 1. May 1, 2006 Impact Intensity plot, left, and (-)Magnitude Plot, right. Time constant, α = 0.04 seconds, initial intensity, I_0 = 6500 IU, Initial Magnitude, m_f = 6.1. Note the second, dim portion of the curve with a slower decay possibly of crater surface origin.

5 Lunar Flash Archiving

Original recordings of lunar flash data are sparse but immense. Continuous video observations of up to six hours duration make the long term storage of complete data difficult and collaboration at a distance almost impossible. To overcome this, a system of "condensed" data files has evolved which leaves out the dead time between events. Each condensed dataset is comprised of an AVI file assembled from the flash and stellar calibration segments padded with a dozen frames before and after plus an auxiliary file containing metadata describing each frame as well as site, lunar area, flash photometry, and calibration data. Using GPS time tags, the UT of each frame is known to a thirtieth of a second. The NASA/MSFC observing program has detected and characterized nearly 60 flashes to date as described in Suggs *et al.* [2007].

6 Summary

Ground based lunar flash monitoring has evolved as a result of the regular observation program undertaken by the Meteoroid Environment Office of the NASA Marshall Space Flight Center. Methods have been developed for semi-automated lunar impact flash detection and software for this purpose is being made available for amateur observation. In order to evaluate the meteoroid flux from the observed impact rate, methods have been developed for finding lunar survey area which accounts for the spherical surface. The problems of intensity calibration of the observed flashes are partially resolved by a technique using the lunar intensity over the observed point spread function as a stellar calibration transfer standard which includes atmospheric effects within the image. A system for the characterization of impact flashes developed independent of instrumentation is described which works with the sparse data available in most observed flashes. Nearly 60 flashes have been archived to date.

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