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Lunar Impact Flash Locations
From NASA's Lunar Impact Monitoring Program

D.E. Moser
Jacobs ESSSA Group, Marshall Space Flight Center, Huntsville, Alabama

R.M. Suggs
Marshall Space Flight Center, Huntsville, Alabama

L. Kupferschmidt
California State Polytechnic University, Pomona, California

J. Feldman
Colorado College, Colorado Springs, Colorado

September 2015

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National Aeronautics and
Space Administration

Marshall Space Flight Center • Huntsville, Alabama 35812

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LIST OF ACRONYMS

ALaMO	Automated Lunar and Meteor Observatory
AVI	audio video interleaved
CCD	charge coupled device
CR	cross reference
FOV	field of view
GIS	Geographic Information System
GOME	Global Ozone Monitoring Experiment
HAD	hole accumulation diode
JPL	Jet Propulsion Laboratory
LRO	Lunar Reconnaissance Orbiter
MEO	Meteoroid Environment Office
NMS	New Mexico Skies
PSF	point spread function
RCOS	RC Optical Systems
TIFF	tagged image file format
TM	Technical Memorandum
WCO	Walker County Observatory

NOMENCLATURE

F_{Earth}	flux of radiation reflected from the Earth taken from the GOME spacecraft measurements
F_{flash}	blackbody curve for the flash
f	flash coordinate
k	shear factor along x-axis
m_x	change of scale in the x direction
m_y	change of scale in the y direction
n	number of control points; index of refraction
P_i	brightness of the pixel at (x_i, y_i)
R	constant of refraction
R_{CCD}	spectral response of the video camera CCD
r_{Moon}	spectral reflectance of the Moon
S	mean background sky brightness
s	skew angle measured from the y-axis
t	rotation angle measured counterclockwise from the x-axis
z_a	apparent zenith distance
z_t	true zenith distance
ε	residual error
λ	selenographic longitude; wavelength
$\lambda_{eff\ ES}$	effective wavelength for the earthshine/camera combination
$\lambda_{eff\ \text{Flash}}$	effective wavelength for the flash/camera combination
φ	selenographic latitude

TECHNICAL MEMORANDUM

LUNAR IMPACT FLASH LOCATIONS FROM NASA'S LUNAR IMPACT MONITORING PROGRAM

1. INTRODUCTION

Meteoroids are small, natural bodies traveling through space, fragments from comets, asteroids, and impact debris from planets. Unlike the Earth, which has an atmosphere that slows, ablates, and disintegrates most meteoroids before they reach the ground, the Moon has little-to-no atmosphere to prevent meteoroids from impacting the lunar surface. Upon impact, the meteoroid's kinetic energy is partitioned into crater excavation, seismic wave production, and the generation of a debris plume. A flash of light associated with the plume is detectable by instruments on Earth.

Following the initial observation of a probable Taurid impact flash on the Moon in November 2005,[1] the NASA Meteoroid Environment Office (MEO) began a routine monitoring program to observe the Moon for meteoroid impact flashes in early 2006, resulting in the observation of over 330 impacts to date. The main objective of the MEO is to characterize the meteoroid environment for application to spacecraft engineering and operations. The Lunar Impact Monitoring Program provides information about the meteoroid flux in near-Earth space in a size range—tens of grams to a few kilograms—difficult to measure with statistical significance by other means.

A bright impact flash detected by the program in March 2013 brought into focus the importance of determining the impact flash location. Prior to this time, the location was estimated to the nearest half-degree by visually comparing the impact imagery to maps of the Moon. Better accuracy was not needed because meteoroid flux calculations did not require high-accuracy impact locations. But such a bright event was thought to have produced a fresh crater detectable from lunar orbit by the NASA spacecraft Lunar Reconnaissance Orbiter (LRO). The idea of linking the observation of an impact flash with its crater was an appealing one, as it would validate NASA photometric calculations and crater scaling laws developed from hypervelocity gun testing.

This idea was dependent upon LRO finding a fresh impact crater associated with one of the impact flashes recorded by Earth-based instruments, either the bright event of March 2013 or any other in the database of impact observations. To find the crater, LRO needed an accurate area to search. This Technical Memorandum (TM) describes the geolocation technique developed to accurately determine the impact flash location, and by association, the location of the crater, thought to lie directly beneath the brightest portion of the flash. The workflow and software tools used to geolocate the impact flashes are described in detail, along with sources of error and uncertainty and a case study applying the workflow to the bright impact flash in March 2013. Following the successful geolocation of the March 2013 flash, the technique was applied to all impact flashes detected by the MEO between November 7, 2005, and January 3, 2014.

2. OBSERVATIONS

To observe the flashes produced by meteoroids striking the lunar surface, the unilluminated (earthshine) portion of the Moon was simultaneously observed with two or more telescopes outfitted with video cameras. A description of the instrumentation and methodology follows. For more details, see reference 2.

2.1 Instrumentation

The NASA Lunar Impact Monitoring Program has been primarily conducted using two telescopes at the Automated Lunar and Meteor Observatory (ALaMO) located at NASA Marshall Space Flight Center in Huntsville, Alabama (34.66° N., 86.66° W., Minor Planet Center designation H58). From 2006 to present, various combinations of the following telescopes have been employed for lunar impact observations: 0.25-m Orion® Newtonian, 0.35-m Meade® modified Schmidt-Cassegrain, 0.35-m Celestron® Schmidt-Cassegrain, and a 0.5-m RC Optical Systems (RCOS) Ritchey-Chrétien (fig. 1), all outfitted with focal reducers to give approximately the same field of view (FOV). The 20-arcmin FOV provided by each telescope covers approximately 4×10^6 km^2, or about 10% of the lunar surface on either the leading or trailing edge of the Moon.

Figure 1. The 0.5-m RCOS Ritchey-Chrétien telescope used for lunar impact monitoring at the ALaMO. This telescope worked in conjunction with another located at the ALaMO and one at WCO.

For a short time, observations were also conducted at the Walker County Observatory (WCO) near Chickamauga, Georgia (34.85° N., 85.31° W.) and at New Mexico Skies (NMS) near Mayhill, New Mexico (32.90° N., 105.53° W.). Both sites were run remotely from the ALaMO. WCO operated from September 2007 until July 2011. The observatory at NMS was operated from October 2011 to October 2012, and November 2013 to April 2014. The observations in 2013 and 2014 took place during the science mission of LADEE (Lunar Atmosphere and Dust Environment Explorer). WCO utilized a 0.35-m Meade modified Schmidt-Cassegrain telescope, while NMS employed a 0.35-m Celestron Schmidt-Cassegrain.

Each telescope was equipped with an AstroVid StellaCamEX or Watec 902-H2 Ultimate monochrome charged coupled device (CCD) video camera. These cameras incorporate a 0.5-in format Sony EXview HAD CCD™ chip, sensitive to the 400- to 800-nm wavelength range. The interleaved, 30-fps video was digitized and recorded straight to hard drive for later flash searches and photometry calculations. A Kiwi-OSD or IOTA-VTI was used for accurate GPS time keeping.

2.2 Methodology

Observations of the unilluminated portion of the Moon were typically conducted when sunlight illuminated between 10% and 50% of the Earth-facing surface. This yielded a maximum of 10 observing nights per month, with five evening observing sessions between New Moon and First Quarter lunar phases, and five morning sessions between Last Quarter and New Moon. This schedule minimizes scattered light from the sunlit lunar disc that would mask faint flashes at illuminations greater than 50%, and maximizes the amount of time on target, a problem at illuminations of 10% and less. Figure 2 shows the lunar coverage area scanned for lunar impacts since the inception of the Lunar Impact Monitoring Program. A near 50% illuminated lunar disc is shown for illustrative purposes. No observations are made near the poles or along the line of 0° longitude.

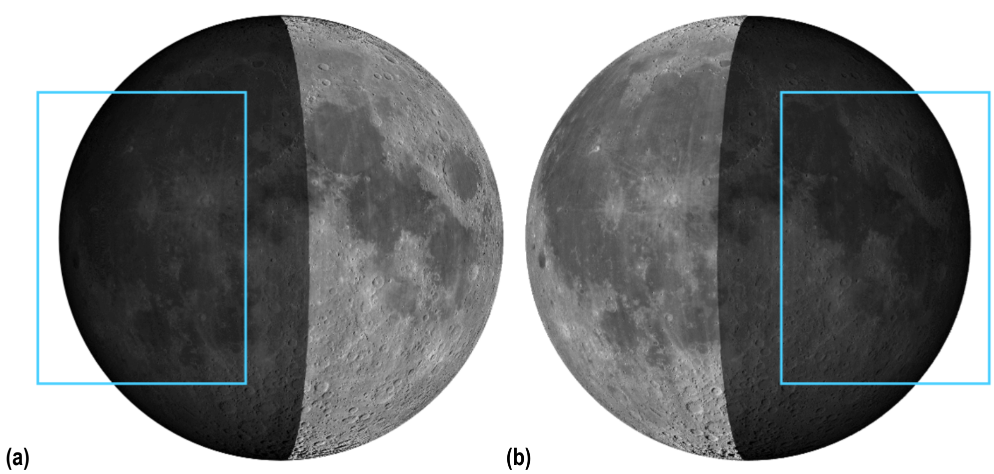


Figure 2. Observed coverage area by the NASA Lunar Impact Monitoring Program from 2006 to present on (a) the leading edge (evening observing sessions) and (b) the trailing edge (morning observing sessions) of the Moon. Note that observations are only conducted on the earthshine portion of the lunar disc, which changes depending on the lunar phase.

Impact flash detection was performed using the software LunarScan.[3] The software scans a night of video from each telescope and identifies pixels that exceed the standard deviation of the background by a selected amount. Candidate impact flashes are cross-correlated using multiple telescopes in order to eliminate false detections caused by cosmic rays or satellite glints. Figure 3 shows two different impact flashes captured by two telescopes and illustrates the camera FOV. Standard aperture photometry was applied to the impact flashes and the field and reference stars used for calibration, as described in detail in reference 2.

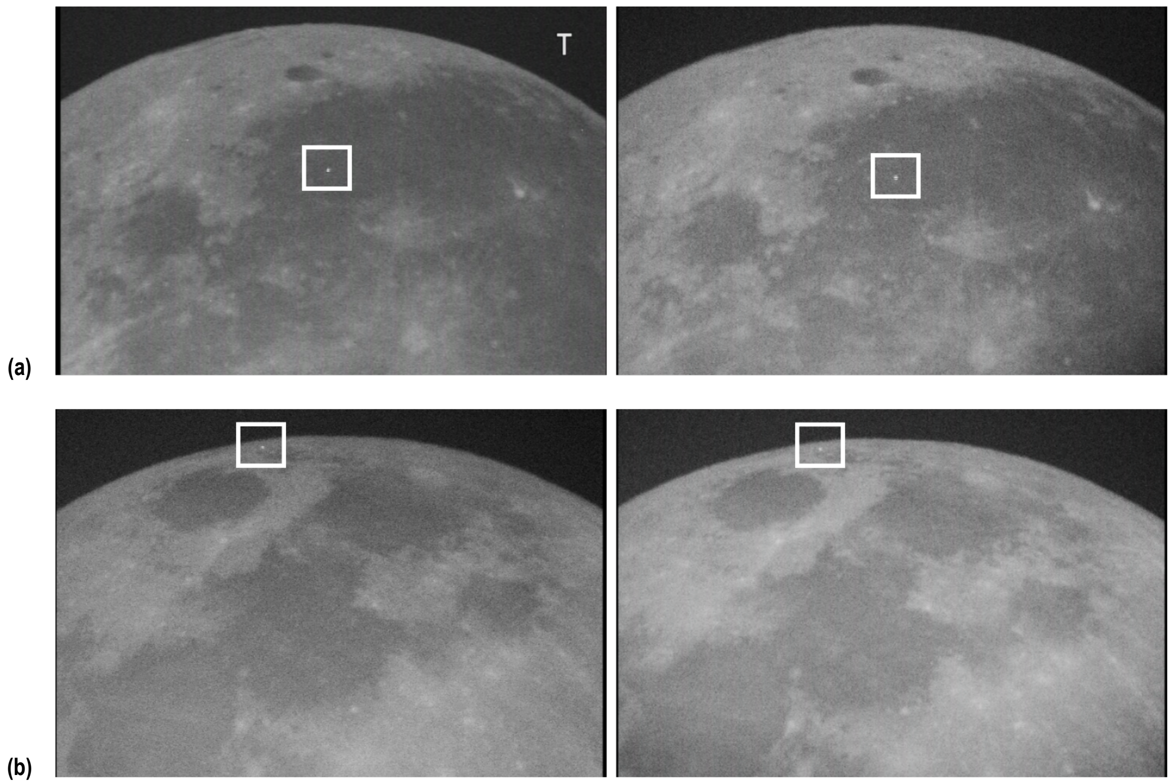


Figure 3. Impact flash examples: (a) The camera FOV during an evening observing session and an impact flash detected by two telescopes on April 8, 2011, at 01:32:17.808 UT and (b) the FOV during a morning observing session and a flash detected on November 10, 2012, at 09:55:10.243 UT by two telescopes. Impact flashes are boxed in white.

3. GEOLOCATING IMPACT FLASHES

The term ‘geolocation’ refers to the process of identifying the real-world spatial location of an object. ‘Georeferencing’ is the method used to associate an image with a map of real-world locations, and therefore geolocate an object. Applied to Moon imagery and lunar maps, these terms perhaps should be called ‘selenolocation’ and ‘selenoreferencing,’ but ‘geolocation’ and ‘georeferencing’ will be used, as this terminology is known to the Geographic Information System (GIS) community.

In broad strokes, the geolocation technique employed here takes video frames from the recordings of impact events and fits them to a map of the Moon using lunar features seen in earthshine. This allows the location of the impact flash, and therefore its associated crater, to be determined on the lunar surface.

The workflow used for the geolocation of impact flashes combines commercially available software and custom programs. An overview of the workflow and software tools used for this technique is seen in figure 4 and described in the following sections.

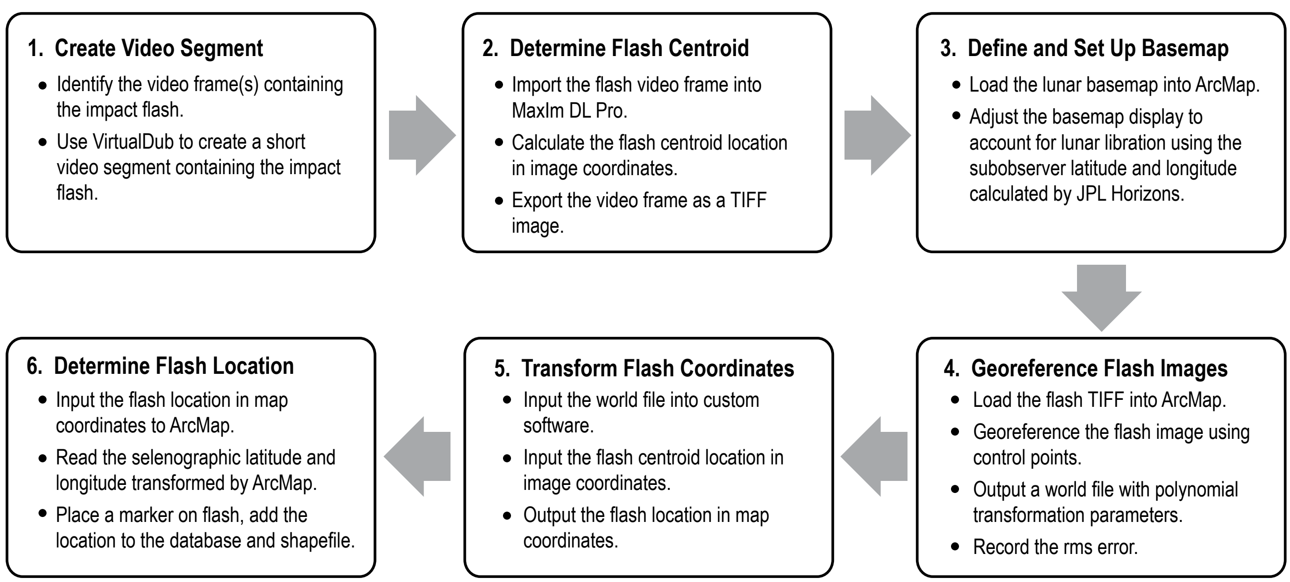


Figure 4. Workflow for geolocating impact flashes on the Moon.

3.1 Create Video Segment

The freely available program, VirtualDub (<www.virtualdub.org>), was used to create short video segments of each of the impact flashes in audio video interleaved (AVI) format. This reduced the amount of computer storage space needed to analyze all of the flashes and also made the dataset easier to manage for the analyst. The video segments were stepped through frame-by-frame. A video frame containing the impact flash was saved for analysis.

3.2 Determine Flash Centroid

The video frame containing the impact flash was selected for inspection in MaxIm DL Pro, commercially available software (<www.cyanogen.com>). It was assumed that the crater associated with the impact lies directly beneath the brightest part of the flash. The flash centroid was calculated in MaxIm by weighting each pixel along the x- and y-axes by the amount of light produced by the impact:

$$\bar{x} = \frac{\sum x_i \left(P_i - S\right)}{\sum \left(P_i - S\right)}$$

and

$$\bar{y} = \frac{\sum y_i \left(P_i - S\right)}{\sum \left(P_i - S\right)} \quad , \tag{1}$$

where P_i is the brightness of the pixel at (x_i, y_i) and S is the mean background sky brightness.[4] See figure 5. The flash centroid at ($\bar{x}_f$, $\bar{y}_f$) in image coordinates was recorded to a fraction of a pixel. Once the centroid coordinates were obtained, the video frame containing the flash was saved as a tagged image file format (TIFF), a raster graphics format. Raster datasets are essentially arrays of numbers with array indices determining the coordinates. This file format is ideal for georeferencing and is a format accepted by GIS mapping software, ArcMap.

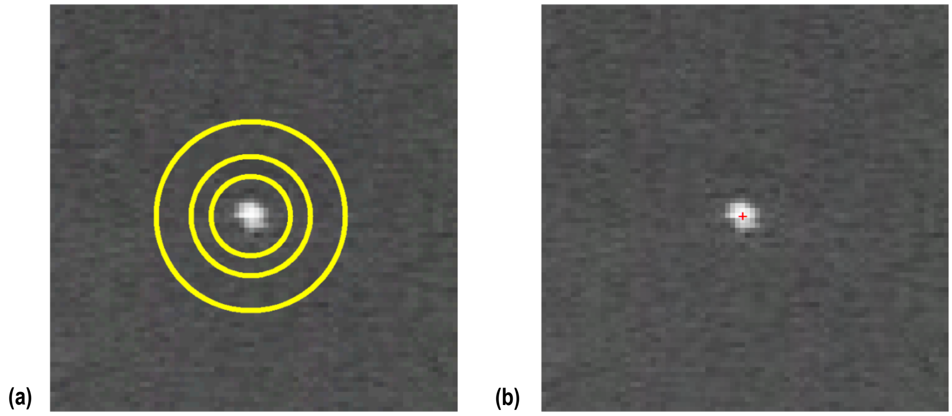


Figure 5. Determining the flash centroid using MaxIm DL Pro: (a) The intensity-weighted centroid is determined using all of the light in the inner circle. The outer annulus is used by MaxIm to determine the background sky brightness. (b) The centroid is marked with a red '+'.

3.3 Define and Set Up Basemap

Georeferencing was performed with the commercially available program ArcMap, part of the ArcGIS software suite (<www.arcgis.com>). To begin the process, a reference basemap and coordinate system were set up. A basemap is a map layer that serves as the foundation for mapping and visualizing geographic information. In this case, selenographic information was needed for locating lunar impacts. A recent, LRO-created orthographic projection of the lunar surface with a resolution of 32 pixels per degree and center at 0° N., 0° E. was downloaded and installed as the basemap (<http://wms.lroc.asu.edu/lroc/view_rdr/WAC_GLOBAL>). It was assigned the standard lunar latitude and longitude coordinate system.

The Moon exhibits a slight north-south nodding and east-west wobbling known as lunar libration. Librations in latitude (north-south) are caused by the tilt of the Moon's orbital plane with respect to the ecliptic. Librations in longitude (east-west) are caused by variations in orbital velocity due to the Moon's elliptical orbit. To account for lunar libration, adjusted map center coordinates for displaying the basemap were calculated using the apparent subobserver latitude and longitude output from JPL Horizons (<http://ssd.jpl.nasa.gov/horizons.cgi>) and input into the basemap projection controls for each impact flash. Figure 6 shows the LRO basemap with two different map centers.

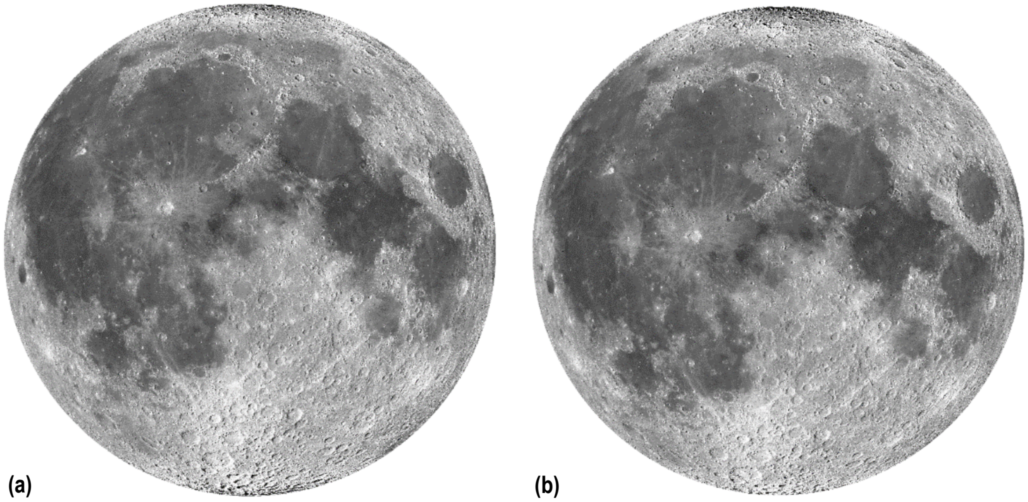


Figure 6. The LRO basemap centered at (a) 0° N., 0° E. and (b) 7.269° N., 0.275° E. To account for lunar libration, the map center must be adjusted for each impact flash before the flash imagery can be georeferenced.

3.4 Georeference Flash Images

ArcMap was utilized to georeference the flash imagery, mapping the flash images to real-world spatial locations. Generally, the steps for georeferencing an image are as follows: (1) Add the raster data that needs to be aligned to the basemap, (2) link known raster positions in the image (x, y) to known positions in map coordinates (x', y') using 'control points,' (3) save the transformation used to align the images ('register' the alignment), and (4) record the fit error estimate for use in the uncertainty determination.

Following the steps outlined above, the video frame TIFF image containing the flash was imported into ArcMap and overlaid on the LRO basemap after the map display had been adjusted for lunar libration. The image's brightness and contrast were adjusted to emphasize the Moon's prominent features. ArcMap's 'Georeferencing toolbar' was used to assign control points to prominent features one at a time in both the basemap (where coordinates were known) and the flash image (where coordinates were unknown). Noticeable features like small, high-albedo craters (e.g., Byrgius A, Mersenius C, Dionysius, and Alfraganus), transitions between mare and highland (e.g., between Oceanus Procellarum and Grimaldi), or where a ray crosses into mare/highland (e.g., Tycho and Mare Nubium) were typically chosen as control points. Note that because the lunar terrain is illuminated by earthshine, there are no shadows to make craters or mountains distinct. Only albedo features are visible. The flash image was automatically resized and repositioned by ArcMap to match the basemap after each control point was added; control points were chosen until the flash image was aligned with the basemap. Figure 7 illustrates this process. Evenly distributing a number of control points across the image was necessary for obtaining good image alignment.

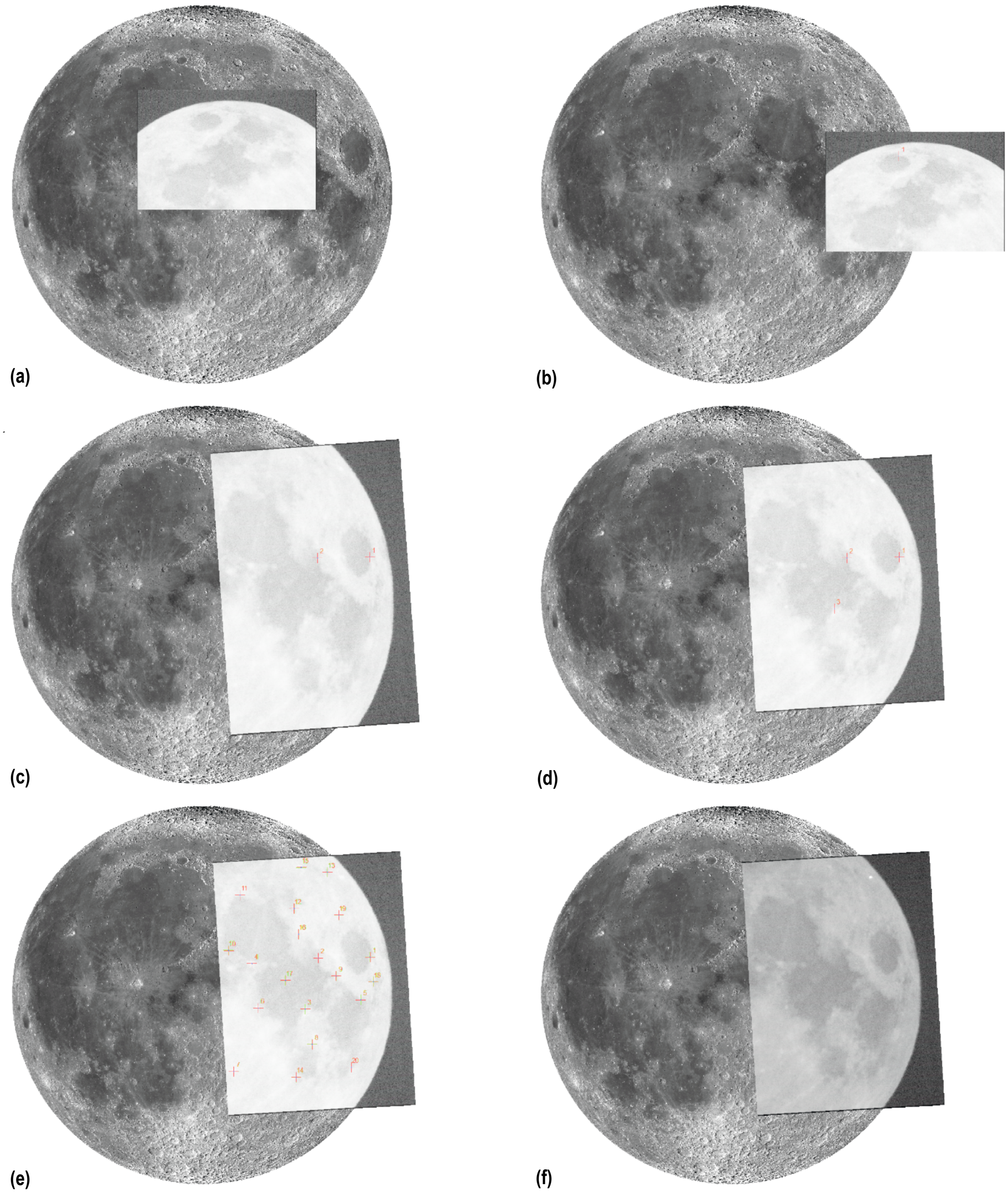


Figure 7. Georeferencing lunar impact flash imagery. (a) The video frame containing the flash is overlaid on the LRO basemap with libration adjustment. (b) One control point ('+') is added, linking unknown (red) feature coordinates in the image to known coordinates (green) on the basemap. The first control point translates the image so that control point No. 1 on the flash image and basemap are aligned. (c) A second control point is added. This rotates and stretches the flash imagery to better align it with the basemap. (d) Control point No. 3 is added, further stretching the image to align it to the basemap. (e) Twenty control points have been added to georeference the flash image. (f) The final georeferenced lunar impact flash image.

ArcMap uses the control points and a least-squares fitting algorithm to create a first-order polynomial transformation,

$$x' = Ax + By + C$$

and

$$y' = Dx + Ey + F \quad , \qquad (2)$$

that transforms the flash image coordinates (x, y) in pixels to the basemap coordinates (x', y') in meters, shifting the displayed flash image to the spatially correct location on the basemap in the process. Map coordinates (x', y') are an orthographic projection of the three-dimensional Moon onto a two-dimensional plane. Parameters A, B, C, D, E, and F are determined by the control points; they scale, shear/skew, rotate, and translate all coordinates in the image to map coordinates. The parameters are determined by

$$\begin{aligned}
A &= m_x \cos t \\
B &= m_y (k \cos t - \sin t) \\
C &= \text{translation in } x \text{ direction} \\
D &= m_x \sin t \\
E &= m_y (k \sin t + \cos t) \\
F &= \text{translation in } y \text{ direction,}
\end{aligned} \qquad (3)$$

where m_x is the change of scale in the x direction, m_y is the change of scale in the y direction, $k = \tan(s)$ is the shear factor along the x-axis, s is the skew angle measured from the y-axis, and t is the rotation angle measured counterclockwise from the x-axis (<http://help.arcgis.com/en/arcgis-desktop/10.0/help/>). The parameters used to define the transformation were saved in a 'world file' (.tfwx file extension) when the image was registered, so named because it describes the image-to-world (or image-to-map) transformation.

Applying the transformation to each control point in turn yields a residual error ε that is the difference between the actual control point location in basemap coordinates and the transformed location. The rms error is calculated using

$$\text{rms error} = \sqrt{\frac{\sum_{i=1}^{n} \varepsilon_i^2}{n}} \quad , \qquad (4)$$

where n is the number of control points. The rms error is a measure of how consistent the transformation is between different control points. It was recorded for each impact flash. An emphasis was placed on choosing multiple control points of good quality and minimizing the rms error, though low rms error does not necessarily indicate that the impact flash image was accurately georeferenced. Application of these errors to the uncertainty in the flash location is discussed in section 4.4.

3.5 Transform Flash Coordinates

ArcMap calculates a first-order polynomial transformation to transform image coordinates (x, y) to orthographically projected basemap coordinates (x', y'). The same transformation can be used to transform the impact flash centroid in image coordinates, ($\overline{x}_f$, $\overline{y}_f$) to map coordinates ($\overline{x}_f{}'$, $\overline{y}_f{}'$). As per equation (2):

$$\overline{x}_f{}' = A\overline{x}_f + B\overline{y}_f + C$$

and

$$\overline{y}_f{}' = D\overline{x}_f + E\overline{y}_f + F \quad . \tag{5}$$

Custom Python code read in the world file containing the transformation parameters and the impact flash centroid in pixels, and performed the transformation. The output was the flash location in the coordinates of the basemap in meters.

3.6 Determine Flash Location

The selenographic longitude and latitude (λ, φ) of the impact flash are determined by entering the mapped flash coordinates, ($\overline{x}_f{}'$, $\overline{y}_f{}'$) in ArcMap using the 'Go to XY' dialog. A marker placed at this location to denote the position of the flash, as in figure 8, was used to display basemap coordinates and (λ, φ). A quick spot check compared the location of the marker and the flash. If georeferencing was successfully executed, the marker laid directly on top of the flash.

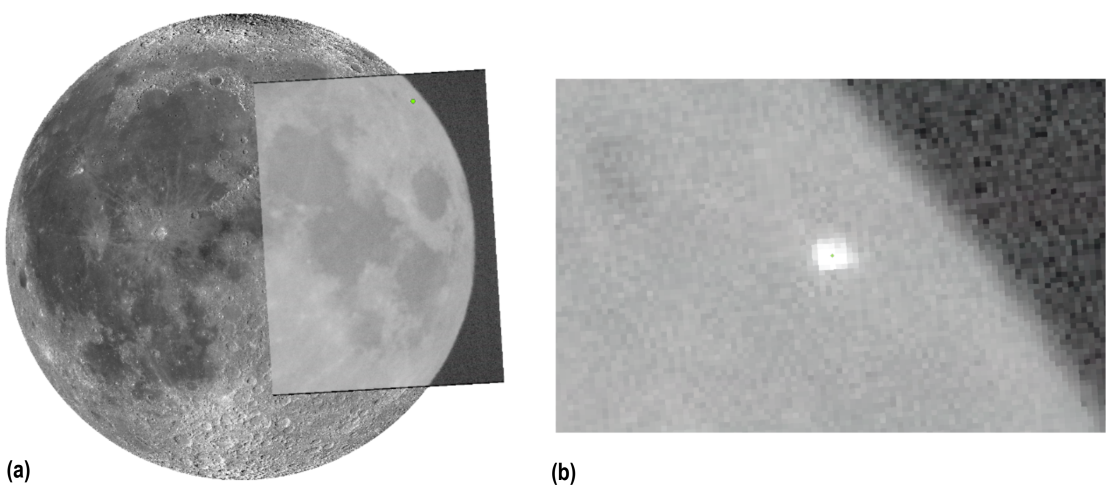


Figure 8. The impact flash is geolocated: (a) A green marker is placed on the impact flash location after transforming the impact flash centroid in image coordinates to map coordinates and (b) zooming in on the impact flash, the green marker lies directly on top of the flash centroid.

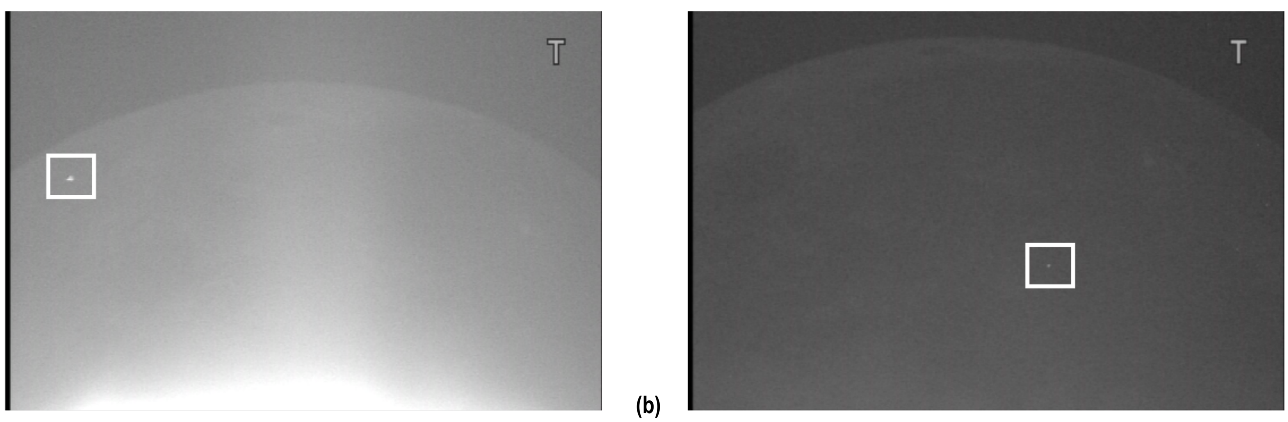
The successfully georeferenced point was added to an ArcMap shapefile, a vector data storage format that stores attributes of geographic features. A database of attributes was compiled for the impact flash dataset. It can be exported to multiple different relational database management systems.

4. SOURCES OF ERROR AND UNCERTAINTY

The strategy outlined in section 3 is capable of producing high-accuracy location estimates for impact craters, though there are several potential sources of error. Issues that contribute to the uncertainty in the crater position are discussed in the following sections.

4.1 Image Quality

Poor image quality makes georeferencing flash imagery difficult and sometimes unfeasible. The lunar phase, lunar altitude, cloud cover, and glare from the sunlit portion of the Moon affect the amount of earthshine visible in the flash imagery. This can make the identification of lunar surface features problematic and thus affect the assignment of control points, and by extension, the whole geolocation process. Two examples of poor images are shown in figure 9. In images with few visible surface features, control points were preferentially chosen in the vicinity of the flash.



(a) (b)

Figure 9. Impact flashes with poor image quality: (a) Glare from the sunlit portion of the Moon on December 13, 2010, and (b) low lunar altitude on August 26, 2009, make these two impact flashes, boxed in white, difficult to georeference because not many features on the lunar surface are recognizable.

Image resolution also has an effect on the assignment of control points. Impact flash image resolution is much poorer than that of the basemap. Choosing the point where mare transitions to highland, for example, can be done with more accuracy on the basemap than in the flash imagery.

4.2 Astronomical Seeing

The atmosphere is not a transparent, homogenous layer. Turbulent air conditions cause variations in the refractive index of the atmosphere. This produces image blurring and instability in telescopic observations. The phenomenon, referred to as atmospheric seeing, can cause the impact flash location to shift relative to the control points. This adds uncertainty to the flash location.

4.3 Flash Duration and Brightness

The characteristics of the impact flash influence the determination of the flash centroid. Short flashes and extremely bright flashes may have more uncertainty associated with their position. An interlaced video frame (1/30 s) combines two fields (1/60 s exposure each) captured at different moments in time. An impact flash may exhibit interlacing effects when only one field captures the flash in a single frame. In this case, the light from the flash is seen only on every other line of the video. An example of this artifact, referred to as 'combing' or 'venetian blinding,' is seen in figure 10. For short flashes (1/60 s in duration) only one frame is available for analysis, and the centroid results are less reliable.

Figure 10. An example of 'combing' in an impact flash. Light appears on every other line of the video.

Bright flashes can exceed the dynamic range of the detector. This not only causes problems with determining the magnitude of the flash, but also affects the determination of the flash centroid. The characteristic 'flat top' of a saturated flash point spread function (PSF) is shown in figure 11 next to an unsaturated PSF. Saturated flashes do not accurately represent the true brightness of the flash and, as a result, the centroid calculation cannot properly weight the true pixel intensities. Where possible, saturated images were not used; a later, fainter frame was analyzed instead.

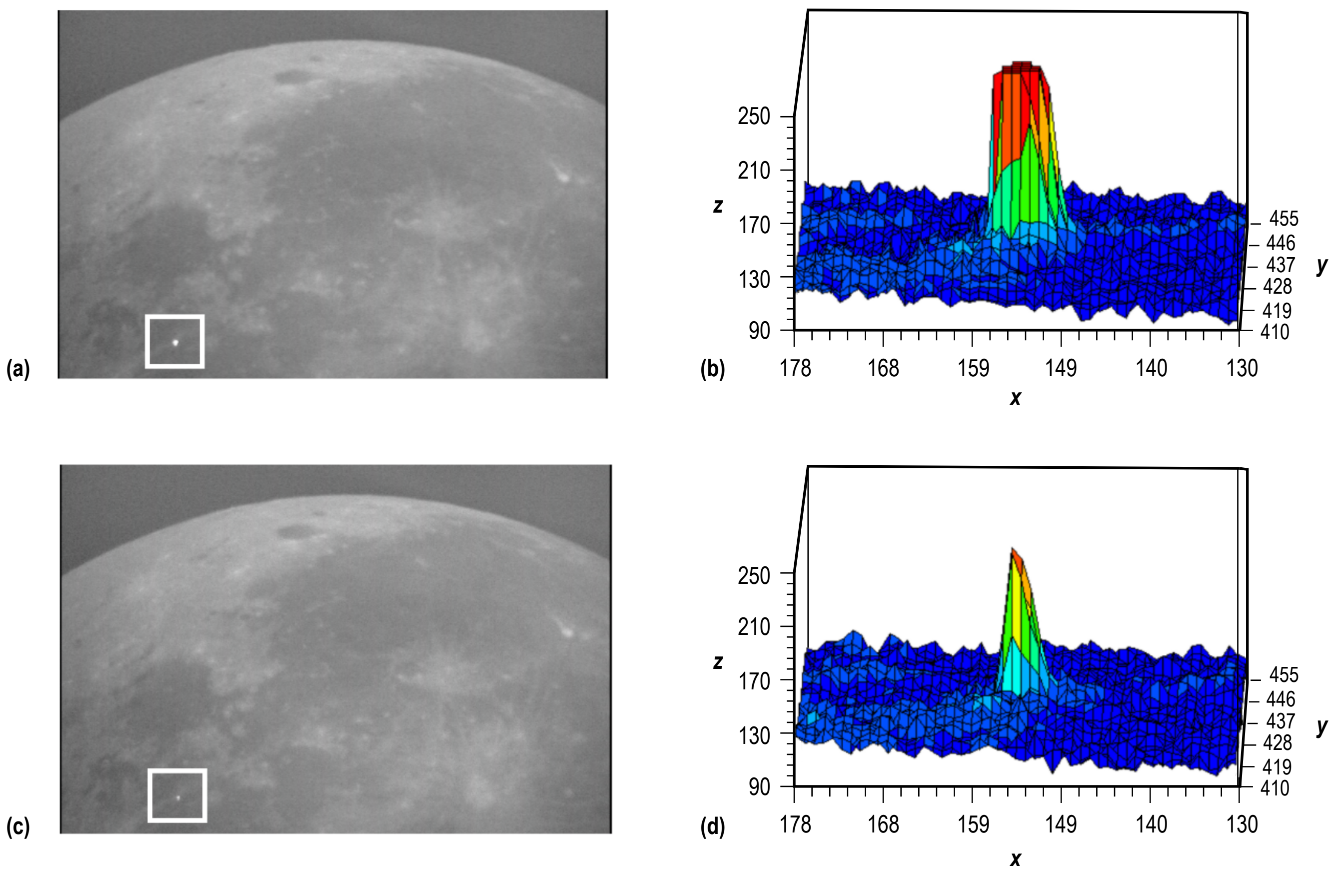


Figure 11. An example of a saturated impact flash compared to an unsaturated detection observed on March 12, 2008. Panels (a) and (c) show the impact flash saturated at 00:40:42.442 UT and unsaturated two frames (1/15 s) later, respectively. Panels (b) and (d) show corresponding graphs of the flash intensity on the *z*-axis (pixel values) versus image coordinates in the *x*-*y* plane (pixels). The flat top of the PSF (b) is indicative of a saturated signal. The spiked PSF (d) looks like a typical unsaturated flash.

4.4 Human Analyst

By far, the largest source of error in lunar impact flash geolocation may be attributed to the human analyst. The control points must be identified by eye, and a cursor has to be placed on them by hand. The quality of the control points selected during the georeferencing process varies from person-to-person. Two people were responsible for geolocating the impact flashes presented in this TM. To quantify the difference between the two analysts, five impact flashes analyzed by both people were compared. The result with the worst standard deviation was chosen to represent the conservative location error bars. Table 1 shows the different results for the impact on October 9, 2012, at 06:46:16.550 UT in selenographic longitude and latitude coordinates (λ, φ) and orthographically projected map coordinates ($\bar{x}_f{}'$, $\bar{y}_f{}'$). The standard deviation in projected map coordinates in the x' and y' directions was about 5,997.950 m and 1,699.572 m, respectively. The root sum of the squares of the standard deviation in x' and y' is 6,234.096 m, which is the value used as the human error contribution.

Table 1. Impact flash geolocation results from two analysts for the flash detected on October 9, 2012, at 06:46:16.550 UT. Negative latitude coordinates indicate southern latitudes.

Analyst	λ (deg)	φ (deg)	$\bar{x}_f'$ (m)	$\bar{y}_f'$ (m)
1	50.0890	–12.3457	1,395,696.818030060	–473,475.52735959200
2	50.6385	–12.4784	1,404,179.200895170	–475,879.0852216600
stdev	–	–	5,997.950444540	1,699.572063243

In addition to this estimate of human error determined by comparing two different analysts, ArcMap displays an rms error describing the fit of the control points as discussed in section 3.4. This is an estimate of how well the system of control points represents the transformation between image and map coordinates. Although this error is certainly not independent of the human error, the two values were combined as a root sum of the squares to give the final uncertainty in the latitude and longitude. The resulting error thus includes both the variations between different analysts (and thus the expected level of human error) and the quality of the fit to the control points for the measurements of each flash. A Python program utilizing the Basemap package (<http://matplotlib.org/basemap/>) was used to perform the coordinate transformations between an orthographic projection of the Moon as seen from the ALaMO (x'-y' plane) and the selenographic spherical coordinates (λ, φ). The subobserver selenographic latitude and longitude calculated using JPL Horizons were used in the transformation to account for lunar libration, as described in section 3.3. After the measured flash location ($\bar{x}_f$, $\bar{y}_f$) was converted to ($\bar{x}_f{}'$, $\bar{y}_f{}'$) in the orthographically projected plane of the map, the uncertainty was added and subtracted in x' and y' from the refraction-corrected flash location (see sec. 4.5), and extremes of longitude and latitude were calculated by projecting those locations back onto the Moon.

Impact flashes that occur near the Moon's limb have larger uncertainties in position compared to flashes that are located closer to the center of the lunar disc. The transformation from orthographic back to the spherical Moon stretches the error bars near the limb, as seen in figure 12. The measured flash location is marked with a yellow '+,' the refraction-corrected position is marked with a white '+,' and the positional uncertainties are marked with red '+'s. Similar stretching of latitude uncertainties would occur near the poles if the FOV covered the high-latitude regions. While only one of the flashes was so close to the limb that the coordinate transformation failed (MEO flash No. 16 on December 14, 2006, at 08:56:43.008 UT), several others were close enough that the limbward longitude error bar was off the Moon so that the worst-case longitude was indeterminate.

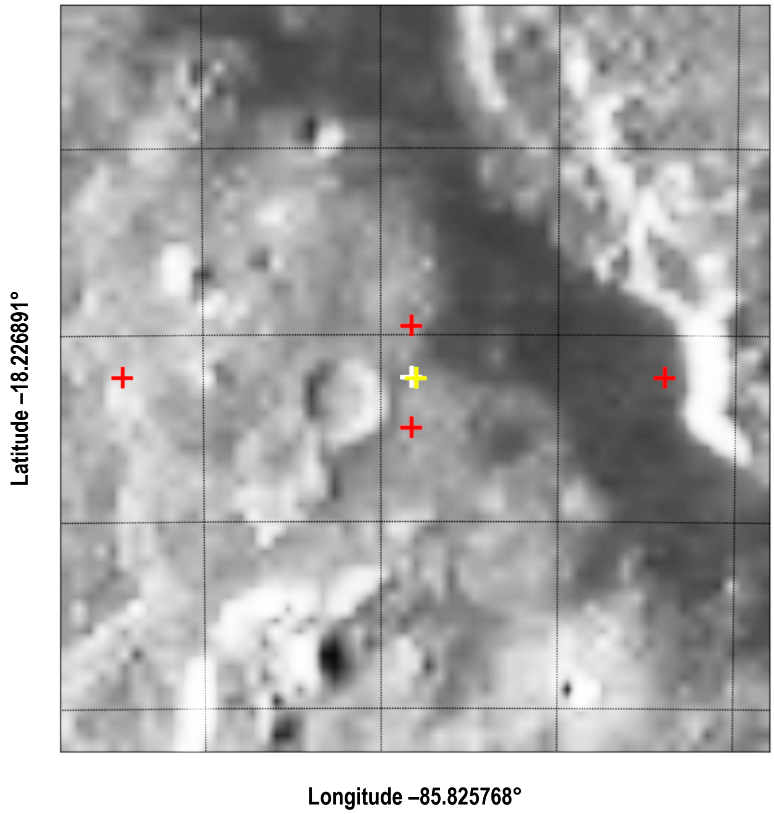


Figure 12. Example of the large uncertainty in longitudinal position for an impact flash located near the limb. The original georeferenced flash location (yellow '+') is shown alongside the refraction-corrected flash location (white '+'; see sec. 4.5) and extremes in latitude and longitude (red '+'), denoting the uncertainty. The graphic is centered at the latitude (vertical) and longitude (horizontal) location indicated and gridded every 1°. This impact flash was detected on December 18, 2007, at 01:32:19.277 UT.

4.5 Differential Atmospheric Refraction

The low elevation and high air mass (large zenith distance) of some of the flash observations leads to an apparent shift between the location of the lunar features used as control points, which are illuminated by blue-green earthshine and the deep red impact flash that is a blackbody with a temperature of approximately 2,800 K.[5] The redder impact flash is shifted towards the zenith less than the bluer earthshine. The magnitude of this shift depends on the atmospheric conditions for the night, the zenith distance of the observed flash, and the effective wavelengths of the earthshine and impact flash.

The calculation of the refractive index of the atmosphere and differential refraction is taken from reference 6. A standard pressure of 1,013.24 mbar corrected to the ALaMO's altitude and an average nighttime low temperature at the observatory for each month were used in the calculations. The effective wavelength for the impact flash was found by convolving a blackbody for 2,800 K with the spectral response for the Sony EXview HAD CCD chip used in the video cameras which recorded the data:[7]

$$\lambda_{eff\ \mathrm{Flash}} = \frac{\int \lambda F_{\mathrm{flash}}(\lambda) R_{\mathrm{CCD}}(\lambda) d\lambda}{\int F_{\mathrm{flash}}(\lambda) R_{\mathrm{CCD}}(\lambda) d\lambda} \quad , \tag{6}$$

where $\lambda_{eff\ \mathrm{Flash}}$ is the effective wavelength for the flash/camera combination, F_{flash} is the blackbody curve for the flash, and R_{CCD} is the spectral response of the video camera CCD.

A similar expression is used for the earthshine effective wavelength, but the spectrum of the earthshine is more complicated as it consists of sunlight reflected from clouds, ocean, and land masses and must also take into account the spectral reflectivity of the lunar surface. The earth-reflected spectrum was taken from plots of clear sky and cloudy sky measurements acquired by the Global Ozone Monitoring Experiment (GOME) mission.[8] These were convolved with the lunar surface reflectivity measured by reference 9:

$$\lambda_{eff\ ES} = \frac{\int \lambda F_{\mathrm{Earth}}(\lambda) r_{\mathrm{Moon}}(\lambda) R_{\mathrm{CCD}}(\lambda) d\lambda}{\int F_{\mathrm{Earth}}(\lambda) r_{\mathrm{Moon}}(\lambda) R_{\mathrm{CCD}}(\lambda) d\lambda} \quad , \tag{7}$$

where $\lambda_{eff\ ES}$ is the effective wavelength for the earthshine/camera combination, F_{Earth} is the flux of radiation reflected from the Earth taken from the GOME spacecraft measurements, r_{Moon} is the spectral reflectance of the Moon, and the other parameters are as in equation (6). The convolution of F_{Earth} and r_{Moon} was compared with the earthshine measurements of reference 10, which covered a narrower wavelength range. This showed that a combination of the GOME measurements for a clear sky and cloudy sky was necessary for the profiles to match (fig. 13, magenta and black curves). Using a combination of 33% cloudy plus 67% clear gave the best fit of the Rayleigh scattering dominated blue wavelengths while matching the redder wavelengths dominated by ocean, land, clouds, and molecular absorption bands.

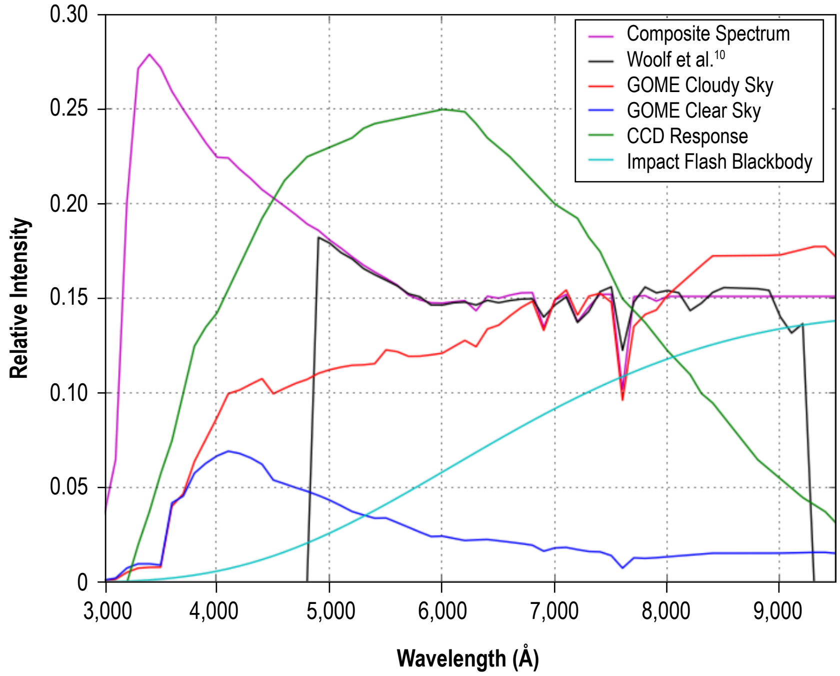


Figure 13. Earthshine spectrum from reference 10 (black curve) and GOME Earth reflectivity spectrum[8] with 33% cloudy and 67% clear sky convolved with lunar spectral reflectance from reference 9 (magneta curve). The red and blue curves are the cloudy sky and clear sky earthshine, respectively, convolved with the lunar reflectivity. Green is the relative response of the CCD and cyan is the flash blackbody curve. The vertical axis is arbitrary units.

The image shift due to differential refraction is greatest at large zenith distances (low elevation angles). Air temperature also affects the amount of refraction. Figure 14 shows these effects. The effective wavelengths and resulting indices and constants of refraction are given in table 2 for an air temperature of 0 °C and atmospheric pressure of 1,000 mbar. The constant of refraction *R* in arcsec is given by

$$R = 206{,}265\frac{n^2-1}{2n^2} \quad , \tag{8}$$

where *n* is the index of refraction. The difference between the true and apparent zenith distances (z_t and z_a, respectively), is calculated using

$$z_t - z_a = R \tan z_t \quad . \tag{9}$$

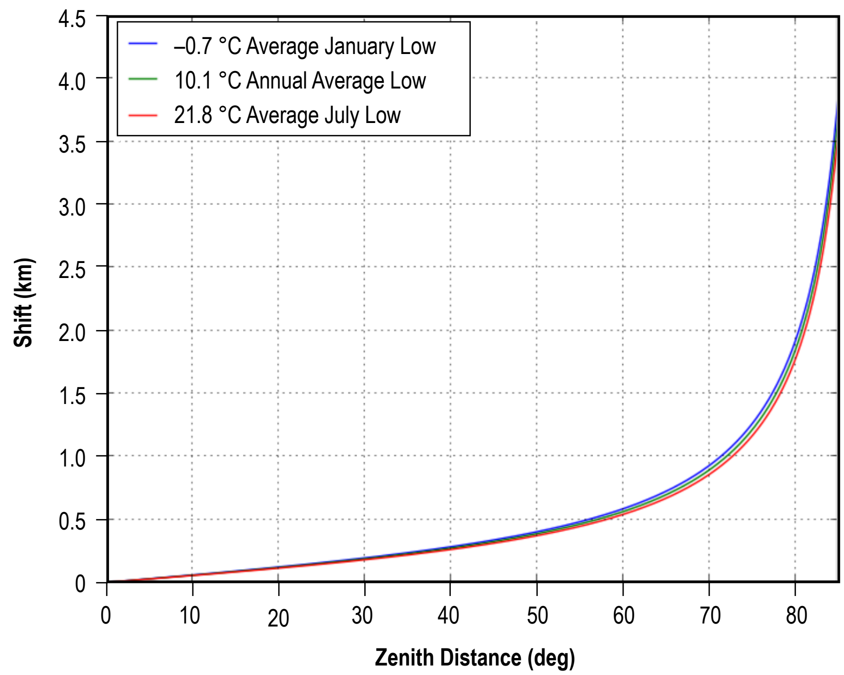


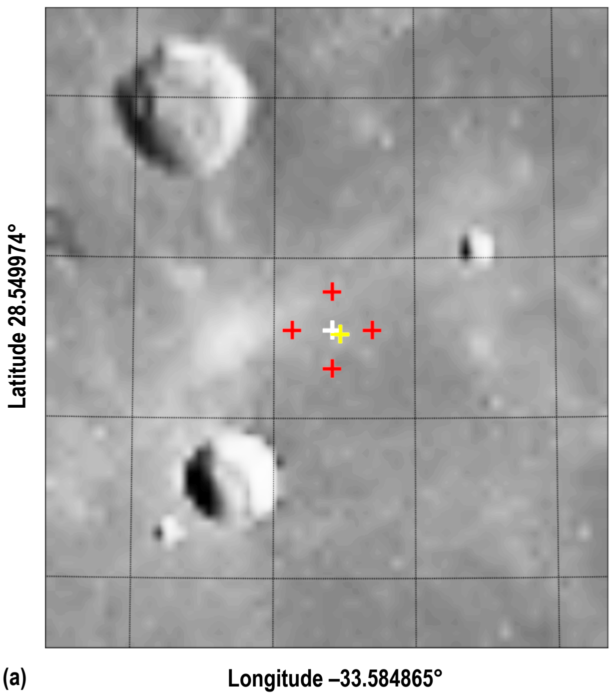
Figure 14. Flash shift on the orthographically projected surface of the Moon due to differential refraction as a function of zenith distance for three average nighttime low air temperatures at the ALaMO and average lunar distance.

Table 2. Effective wavelength, index of refraction, and constant of refraction for a 2,800 K impact flash and three combinations of sunlight reflected by Earth and then reflected by the Moon.

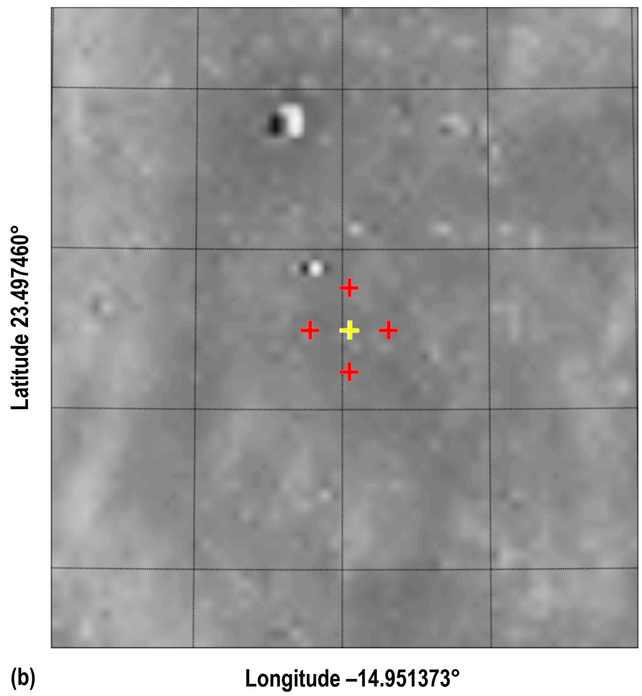
Source	Effective Wavelength (Å)	Index of Refraction	Constant of Refraction (arcsec)
Impact flash	7,093.3	1.000291005	59.9979
33% cloudy + 67% clear Earth and Moon	6,303.5	1.000291897	60.1818
100% cloudy Earth and Moon	6,438.5	1.000291720	60.1454
100% clear Earth and Moon	5,474.5	1.000293297	60.4703

Since refraction causes a shift toward the zenith, it was necessary to determine the direction in which the correction should be applied to the lunar coordinates. This required calculating the direction to the zenith on the orthographically projected Moon. JPL Horizons was used to determine the position angle of the lunar pole relative to celestial north, the right ascension and declination of the Moon, and the local sidereal time at the time of the flash. Spherical trigonometry was used to find the angle between the zenith and celestial north at the position of the Moon, and this angle was added to the position angle of the pole of the Moon to determine the angle to the zenith in the orthographic x'-y' plane. The flash location measured using the geolocation workflow (in sec. 3) was then shifted toward the zenith by the appropriate distance in meters corresponding to the shift in arcsec (eq. (9)) at the distance to the Moon calculated by JPL Horizons. This shifted position was then converted to longitude and latitude using the Python Basemap package.

Examples of the differential refraction correction applied to two impact flashes can be seen in figure 15. The location of the flash on the Moon can be determined by the latitude (vertical) and longitude (horizontal) axis labels. The yellow '+' is the original flash location as determined by the geolocation workflow. The white '+' is the location corrected for differential refraction. Red '+'s show the latitude and longitude extremes determined from the georeferencing rms errors and the human analyst error described in section 4.4.



(a)



(b)

Figure 15. Examples of the differential refraction correction applied to the location of an impact flash. The original georeferenced flash location (yellow '+') is shown alongside the refraction-corrected flash location (white '+') and extremes in latitude and longitude (red '+') determined from the uncertainties. The graphic is centered at the latitude (vertical) and longitude (horizontal) location indicated and gridded every 1°. (a) The impact flash detected on November 26, 2006, at 01:30:29.030 UT has a significant correction due to the fact that it was observed at a large zenith distance of 76.3° and (b) the impact flash detected on March 25, 2007, at 00:59:10.176 UT was observed at a small zenith distance of 23.2° and therefore has only a very slight correction applied.

5. GEOLOCATION CASE STUDY

The workflow for geolocating impact flashes on the Moon was developed following the observation of an unusually bright impact flash. On March 17, 2013, at 03:50:53.981 UT, the NASA Lunar Impact Monitoring Program observed the largest impact flash recorded since the program began, as seen in figure 16. Such a bright event was thought to have produced a crater large enough to be detected by the LRO, a NASA spacecraft mapping the Moon from lunar orbit. Accurately determining the impact location from observations of the flash became a priority, as LRO would need to know where to search for the crater.

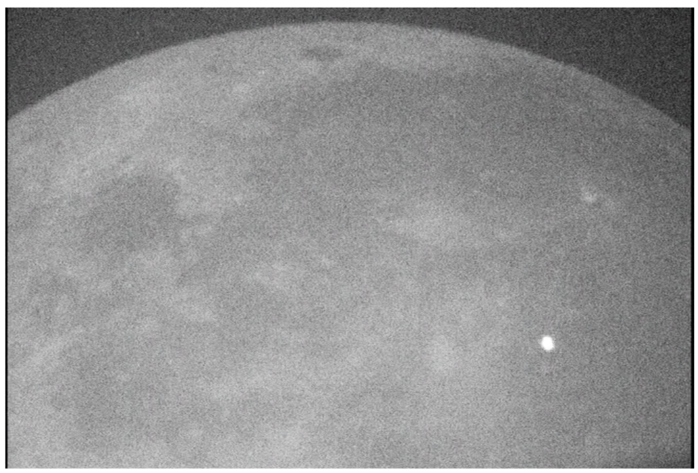


Figure 16. Bright impact flash observed on March 17, 2013, at 03:50:53.981 UT.

The March 17 lunar impact imagery was first georeferenced following a rough version of the workflow described in sections 3.3 and 3.4, but using the following: (1) Clementine imagery for the basemap instead of LRO imagery, (2) 'late impact' flash imagery (captured 10 frames (333 ms) after peak brightness) instead of the image at or close to peak brightness, and (3) the geometric center of the flash instead of the intensity-weighted centroid. The late-impact image was georeferenced three times and averaged to yield a crater location at 23.922 ± 0.304° W., 20.599 ± 0.172° N., as in reference 11. The uncertainties listed were determined by taking the standard deviation of the three attempts; they most certainly underestimated the uncertainty of the crater location.

These coordinates were submitted to LRO. On December 14, 2013, the spacecraft reported finding and imaging the fresh impact crater associated with the March 17 impact flash. Its final confirmed location was 24.3302° W., 20.7135° N.[12] Comparing the actual crater location to the nominal location determined by geolocating the impact flash using the rough workflow gives a difference of 0.39875°, corresponding to 12.096 km on the lunar surface. The actual crater is located northwest of the original estimated location.

A refined geolocation workflow, as described in section 3, was developed in early 2014. Reprocessing the March 17 impact flash using the refined workflow yielded an impact location at 24.1566° W., 20.6644° N., a distance of 5.1469 km from the observed crater. Applying the correction for differential refraction described in section 4.5, the impact location was found to be 24.2277° W., 20.6842° N. This is 3.0415 km from the observed location. Table 3 summarizes the nominal impact locations found by various methods. Figure 17 shows the results of the rough workflow, refined workflow, the refraction-corrected location and uncertainties, and the location of the observed crater on the lunar basemap.

Table 3. Results of geolocating the March 17 impact flash using different methods as compared to the LRO observed crater location. The radius of the Moon was taken to be 1,738.1 km.

Method	Longitude (°W.)	Latitude (°N.)	Angular Distance From Observed (deg)	Surface Distance From Observed (km)
Rough workflow	23.922	20.599	0.39875	12.096
Refined workflow	24.1566	20.6644	0.169665	5.1469
Refined, with refraction correction	24.2277	20.6842	0.100261	3.0415
Observed	24.3302	20.7135	–	–

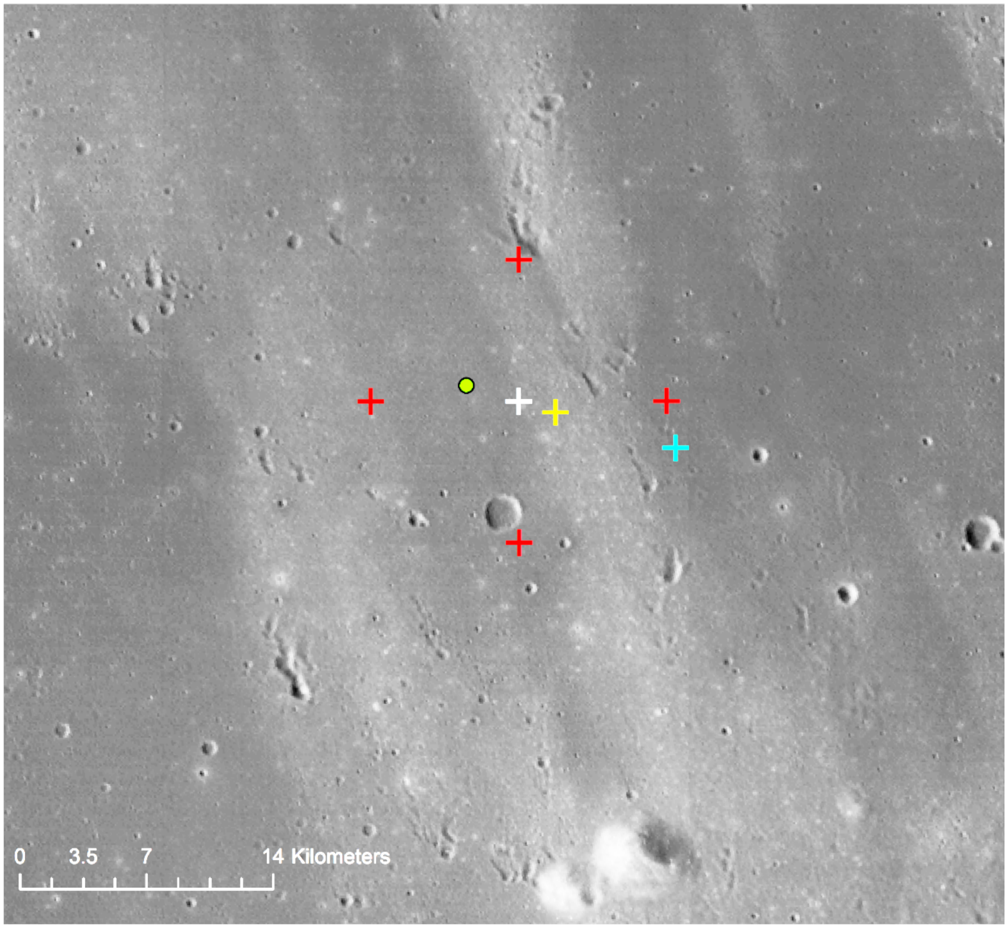


Figure 17. The location of the impact flash observed on March 17, 2013, at 03:50:53.981 UT. The georeferenced flash location using the rough work flow (blue '+') and the refined workflow (yellow '+') are shown alongside the refraction-corrected flash location as applied to the refined workflow solution (white '+') and extremes in latitude and longitude (red '+') that represent the uncertainties in the final location. The location of the fresh crater observed by LRO is marked in green.

6. RESULTS

Following the successful geolocation of the March 17 impact flash, the workflow was put into production on the full set of impact flashes recorded by the NASA Lunar Impact Monitoring Program, observed between November 2005 and January 2014. A total of 300 flashes were geolocated following the process detailed in section 3 and corrected for differential atmospheric refraction following the discussion in section 4.5. A map of the impact flash locations, after application of the differential refraction correction, is found in figure 18.

Table 4 lists the details for each flash, including the location determined using the geolocation workflow and the refraction-corrected location. In column 1, the flashes are numbered with a MEO number in order of discovery, matching that on the NASA lunar impact web page (<http://www.nasa.gov/centers/marshall/news/lunar/index.html>); in column 2, cross reference (CR) numbers have also been added for flashes analyzed in reference 2. For each flash, the UT date and time of observation is given in columns 3 and 4, as well the zenith distance of the Moon in degrees at the time of observation in column 5. The measured flash location determined by the geolocation workflow detailed in section 3 is listed in columns 6 and 7 in selenographic longitude and latitude coordinates. Negative longitude coordinates indicate west longitudes; negative latitude coordinates indicate south latitudes. Columns 9 and 10 list the refraction-corrected position of the impact flash in selenographic coordinates, as described in section 4.5, with the amount of shift given as the refraction correction in meters in projected map coordinates in column 8. The total uncertainty in this location is given in column 11, also in projected map coordinates. This uncertainty is translated into selenographic longitude (columns 12 and 13) and latitude (columns 14 and 15) extremes for each flash.

The following flashes could not be geolocated due the scarcity of lunar features visible in the image: MEO flash No. 1 on November 7, 2005, at 23:40:53.040 UT; MEO flash No. 3 on June 4, 2006, at 04:48:35.338 UT; MEO flash No. 108 on August 3, 2006, at 03:17:10.234 UT; MEO flash Nos. 8 and 9 on August 4, 2006, at 02:24:57.024 UT and 02:50:14.035 UT, respectively; and MEO flash No. 176 on August 26, 2009, at 01:58:15.082 UT.

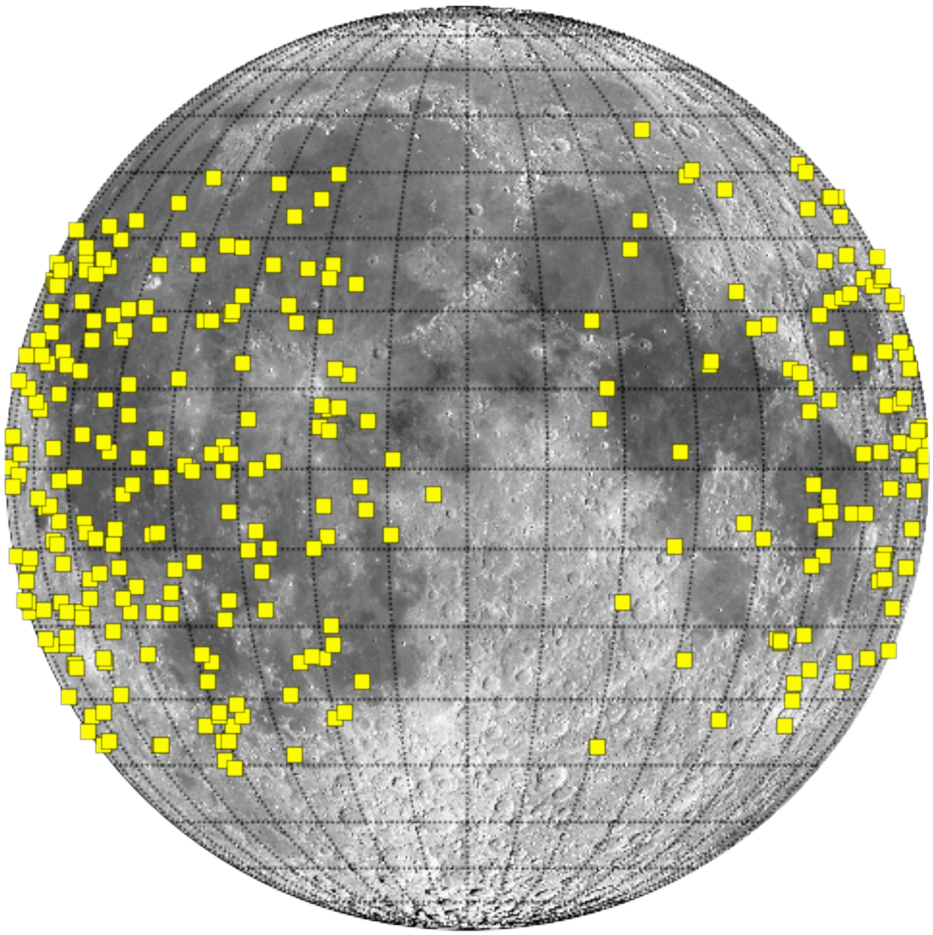


Figure 18. Three hundred lunar impacts detected by the NASA Lunar Impact Monitoring Program from November 2005 to January 2014. The flash locations have been corrected for differential refraction. No observations are made near the poles or along the line of 0° longitude. The map is gridded at intervals of 10°.

Table 4. Three hundred lunar impact flashes observed from November 2005 to January 2014 by the NASA Lunar Impact Monitoring Program. See the text for a description of the columns.

MEO Flash No.	CR No.	Date (UT)	Time (UT)	Zen. Dist. (deg)	Measured Location		Refraction Correction (m)	Refraction-Corrected Location		Total Uncertainty (m)	Longitude Extremes		Latitude Extremes	
					Long. (deg)	Lat. (deg)		Long. (deg)	Lat. (deg)		(°E.)	(°W.)	(°N.)	(°S.)
2		2006-May-02	02:34:39.014	63.5	–19.7249	–24.3252	636.9	–19.7446	–24.3135	6,844.8	–19.4743	–20.0154	–24.0775	–24.5497
105		2006-Jun-21	08:35:45.024	74.4	27.7945	1.8406	1,079.8	27.8196	1.8687	6,988.1	28.0716	27.5681	2.1000	1.6375
4		2006-Jun-21	08:57:16.963	70.1	61.4345	13.3620	832.5	61.4770	13.3858	7,082.7	61.9325	61.0273	13.6324	13.1395
5		2006-Jul-19	10:14:43.987	38.1	57.9721	21.1627	235.4	57.9850	21.1697	7,513.8	58.4370	57.5381	21.4510	20.8891
6		2006-Aug-03	01:43:19.114	61.8	–40.5000	26.1709	589.0	–40.5105	26.1909	6,654.0	–40.2219	–40.8000	26.4223	25.9599
7		2006-Aug-03	01:46:11.222	62.1	–80.7600	31.1595	595.9	–80.8104	31.1768	7,273.7	–79.9812	–81.6742	31.4040	30.9484
106		2006-Aug-03	02:20:32.986	65.8	–49.7555	35.0167	703.5	–49.7818	35.0409	6,566.7	–49.4366	–50.1287	35.2822	34.8000
107		2006-Aug-03	02:40:31.613	68.3	–43.6223	–8.3828	794.8	–43.6305	–8.3579	12,808.8	–43.0954	–44.1695	–7.9205	–8.7962
10	1	2006-Sep-16	09:52:53.040	45.1	56.1549	–34.0444	319.4	56.1698	–34.0399	6,821.1	56.5568	55.7852	–33.7943	–34.2858
109		2006-Sep-17	10:16:11.251	51.8	26.5905	32.4743	410.0	26.6081	32.4791	6,850.9	26.8946	26.3221	32.7675	32.1920
110	2	2006-Sep-28	00:42:56.966	76.6	–31.6960	2.6346	1,349.4	–31.7206	2.6724	6,618.0	–31.4806	–31.9610	2.8910	2.4536
58	3	2006-Oct-29	01:18:43.056	68.4	–45.3619	1.1559	799.2	–45.3832	1.1751	6,580.7	–45.1062	–45.6613	1.3928	0.9573
59		2006-Oct-29	02:00:15.264	73.2	–17.7451	–8.5598	1,045.6	–17.7698	–8.5355	6,724.1	–17.5415	–17.9984	–8.3061	–8.7651
111		2006-Oct-30	00:13:47.971	57.5	–52.4174	8.3858	488.0	–52.4269	8.4005	6,788.9	–52.1034	–52.7523	8.6231	8.1779
13		2006-Oct-30	00:24:26.986	57.6	–39.3824	–27.6442	491.1	–39.3838	–27.6263	6,856.3	–39.0731	–39.6958	–27.3536	–27.8999
21		2006-Nov-13	11:03:14.026	28.1	87.6441	–23.3890	179.7	87.6703	–23.3843	6,891.2	89.5447	86.1366	–23.1673	–23.5988
22		2006-Nov-14	08:26:38.976	67.7	20.5936	–16.9367	833.4	20.6221	–16.9300	6,944.9	20.8714	20.3732	–16.6926	–17.1676
12	4	2006-Nov-17	10:46:27.034	73.8	72.5844	41.1625	1,175.1	72.7691	41.1702	6,935.0	73.6925	71.8847	41.4351	40.9047
11	5	2006-Nov-17	10:56:33.994	71.9	76.5387	35.9282	1,048.7	76.7278	35.9333	6,904.8	77.8299	75.6972	36.1757	35.6896
23	6	2006-Nov-17	11:02:27.974	70.9	85.7237	5.2281	986.4	86.1413	5.2185	6,937.6	***	83.6870	5.4329	5.0024
24	7	2006-Nov-17	11:09:11.030	69.7	67.4500	–10.7657	923.6	67.5221	–10.7580	7,063.5	68.1646	66.8971	–10.5147	–11.0016
25		2006-Nov-24	23:24:03.974	70.0	–88.2474	3.7616	890.6	–88.3971	3.7678	6,480.0	–86.9124	–90.2603	3.9706	3.5643
26	8	2006-Nov-24	23:58:13.037	74.0	–28.3247	–38.6004	1,130.3	–28.3488	–38.5642	7,122.4	–28.0184	–28.6802	–38.2304	–38.9000
27	9	2006-Nov-25	00:55:53.962	81.9	–81.2463	0.1044	2,292.1	–81.4898	0.1241	6,991.2	–80.5803	–82.4609	0.3555	–0.1078
28	10	2006-Nov-26	00:59:15.965	71.9	–21.1474	39.6349	982.4	–21.1869	39.6587	7,107.7	–20.8725	–21.5017	39.9419	39.3765
29	11	2006-Nov-26	01:28:43.018	76.0	–32.5836	19.4386	1,291.8	–32.6295	19.4618	7,028.4	–32.3556	–32.9041	19.6999	19.2240
30	12	2006-Nov-26	01:30:29.030	76.3	–33.5315	28.5253	1,317.2	–33.5849	28.5500	6,733.1	–33.3020	–33.8683	28.7901	28.3102
14		2006-Dec-14	08:12:40.032	78.0	34.2288	47.3130	1,638.5	34.3343	47.3315	6,965.4	34.7357	33.9345	47.6531	47.0117
117		2006-Dec-14	08:16:46.358	77.2	51.8758	–21.2977	1,535.7	51.9532	–21.2851	6,986.4	52.3577	51.5524	–21.0310	–21.5398
118		2006-Dec-14	08:32:06.605	74.4	70.3604	3.2327	1,241.9	70.4753	3.2400	7,093.9	71.1641	69.8082	3.4727	3.0072

*** Calculation not possible due to proximity to lunar limb.

Table 4. Three hundred lunar impact flashes observed from November 2005 to January 2014 by the NASA Lunar Impact Monitoring Program. See the text for a description of the columns (Continued).

MEO Flash No.	CR No.	Date (UT)	Time (UT)	Zen. Dist. (deg)	Measured Location		Refraction Correction (m)	Refraction-Corrected Location		Total Uncertainty (m)	Longitude Extremes		Latitude Extremes	
					Long. (deg)	Lat. (deg)		Long. (deg)	Lat. (deg)		(°E.)	(°W.)	(°N.)	(°S.)
119		2006-Dec-14	08:32:51.965	74.2	66.9735	7.6474	1,230.2	67.0738	7.6554	6,998.1	67.6573	66.5035	7.8849	7.4259
120		2006-Dec-14	08:39:57.139	72.9	73.2242	–24.5153	1,130.0	73.3448	–24.5079	6,900.8	74.2739	72.4659	–24.2397	–24.7774
121	13	2006-Dec-14	08:46:01.920	71.8	80.0028	14.2648	1,055.8	80.1949	14.2675	6,991.2	81.5222	79.0097	14.4911	14.0436
15	14	2006-Dec-14	08:50:36.067	70.9	45.9820	12.3780	1,005.9	46.0300	12.3872	7,065.4	46.3688	45.6931	12.6227	12.1519
122	15	2006-Dec-14	08:51:20.563	70.8	52.0530	–10.9310	998.2	52.1019	–10.9219	7,019.4	52.4861	51.7210	–10.6828	–11.1613
16	16	2006-Dec-14	08:56:43.008	69.8	89.0577	–9.3321	***	***	***	7,040.6	***	***	***	***
17	17	2006-Dec-14	09:00:22.118	69.2	38.0236	39.2611	912.8	38.0768	39.2723	7,076.8	38.4516	37.7038	39.5609	38.9846
18	18	2006-Dec-14	09:03:32.976	68.6	61.3004	21.7482	885.9	61.3668	21.7561	6,990.3	61.8662	60.8747	21.9957	21.5168
123		2006-Dec-14	10:11:07.296	57.2	40.8178	–8.7861	537.0	40.8376	–8.7783	6,708.8	41.1339	40.5426	–8.5522	–9.0046
124		2006-Dec-14	10:28:51.139	54.5	83.8211	36.0700	485.4	83.9885	36.0721	7,034.2	86.3035	82.1873	36.2816	35.8500
19		2006-Dec-14	10:56:41.770	50.7	71.5493	7.9455	422.3	71.5877	7.9519	6,624.2	72.2789	70.9199	8.1680	7.7358
125		2006-Dec-14	11:21:22.666	47.8	49.4234	–5.9715	380.6	49.4370	–5.9637	7,268.0	49.8101	49.0668	–5.7206	–6.2069
20		2006-Dec-14	11:28:08.400	47.1	27.2649	–9.7265	371.2	27.2744	–9.7182	7,312.4	27.5504	26.9992	–9.4711	–9.9656
31	19	2006-Dec-15	09:15:14.026	77.3	77.5672	35.9722	1,543.0	77.8691	35.9734	6,625.2	79.0263	76.7973	36.1885	35.7556
32	20	2006-Dec-15	09:17:39.005	76.9	60.4691	26.5243	1,490.2	60.5873	26.5358	7,019.5	61.1041	60.0781	26.7781	26.2937
33		2006-Dec-15	09:53:28.032	70.7	67.5345	–14.1482	986.4	67.6130	–14.1398	6,822.5	68.2836	66.9629	–13.8961	–14.3841
35		2006-Dec-24	00:27:41.990	75.0	–61.3048	–18.2278	1,203.6	–61.3627	–18.2102	6,835.3	–60.9117	–61.8198	–17.9615	–18.4594
36		2007-Feb-23	00:11:35.952	26.7	–9.5699	–8.3232	158.2	–9.5749	–8.3213	6,905.2	–9.3385	–9.8116	–8.0936	–8.5491
37	21	2007-Feb-23	00:47:44.506	33.5	–12.5701	–5.1382	208.4	–12.5770	–5.1362	6,768.2	–12.3436	–12.8107	–4.9132	–5.3592
38	22	2007-Feb-23	04:02:43.584	71.8	–32.3722	19.7908	966.9	–32.4158	19.8026	7,127.9	–32.1020	–32.7311	20.0659	19.5400
39		2007-Mar-25	00:59:10.176	23.2	–14.9461	23.4955	135.4	–14.9514	23.4975	6,802.3	–14.6865	–15.2168	23.7580	23.2376
40		2007-Apr-13	10:38:03.926	72.8	76.3191	–17.7100	992.3	76.3704	–17.6819	6,642.0	78.8509	74.5994	–17.4203	–17.9478
41		2007-Apr-20	01:40:03.763	70.9	–77.5868	23.9237	874.4	–77.9623	23.9756	6,826.4	–75.6934	***	24.3885	23.6054
42	23	2007-Apr-22	01:15:05.069	40.9	–19.7664	–32.7637	268.8	–19.7759	–32.7594	6,629.8	–19.4900	–20.0624	–32.5168	–33.0025
43	24	2007-Apr-22	01:15:43.862	41.0	–19.7228	–10.1146	270.0	–19.7318	–10.1107	6,849.8	–19.4770	–19.9871	–9.8849	–10.3366
44	25	2007-Apr-22	01:38:33.821	45.5	–18.8769	26.2504	316.9	–18.8900	26.2559	6,855.3	–18.6080	–19.1728	26.5252	25.9875
45	26	2007-Apr-22	03:12:24.336	63.8	–19.0115	24.3525	636.0	–19.0366	24.3653	6,542.4	–18.7718	–19.3021	24.6164	24.1147
46	27	2007-Apr-22	03:52:36.970	71.4	–18.1009	–4.7268	929.5	–18.1290	–4.7095	6,786.2	–17.8826	–18.3759	–4.4859	–4.9330
47	28	2007-Apr-22	04:22:27.091	76.8	–43.5925	29.5091	1,339.0	–43.6831	29.5461	6,703.0	–43.2654	–44.1052	29.8266	29.2667
48		2007-Apr-22	04:42:59.587	80.4	–41.2182	–1.1477	1,867.9	–41.2914	–1.1059	6,687.9	–40.9643	–41.6206	–0.8849	–1.3268

*** Calculation not possible due to proximity to lunar limb.

Table 4. Three hundred lunar impact flashes observed from November 2005 to January 2014 by the NASA Lunar Impact Monitoring Program. See the text for a description of the columns (Continued).

MEO Flash No.	CR No.	Date (UT)	Time (UT)	Zen. Dist. (deg)	Measured Location		Refraction Correction (m)	Refraction-Corrected Location		Total Uncertainty (m)	Longitude Extremes		Latitude Extremes	
					Long. (deg)	Lat. (deg)		Long. (deg)	Lat. (deg)		(°E.)	(°W.)	(°N.)	(°S.)
49	29	2007-Apr-23	01:15:54.576	29.9	–47.3941	6.5733	181.5	–47.4036	6.5772	6,740.0	–47.0143	–47.7968	6.8062	6.3484
50	30	2007-Apr-23	02:23:21.379	43.5	–18.6038	5.0743	299.9	–18.6135	5.0798	6,950.4	–18.3581	–18.8695	5.3130	4.8468
51	31	2007-Apr-23	03:01:10.330	51.0	–69.3098	–25.0868	391.9	–69.3415	–25.0766	6,985.6	–68.4425	–70.2919	–24.8595	–25.2927
52	32	2007-Apr-23	04:08:48.797	64.3	–27.8500	26.2401	661.8	–27.8797	26.2562	6,669.4	–27.5764	–28.1844	26.5163	25.9969
193	33	2007-Apr-23	04:38:21.984	70.0	–39.2745	11.1943	875.0	–39.3126	11.2147	6,782.2	–38.9798	–39.6476	11.4495	10.9803
194	34	2007-Apr-23	04:40:44.976	70.4	–37.1493	–11.7618	897.1	–37.1788	–11.7419	6,908.7	–36.8595	–37.4997	–11.5142	–11.9698
53	35	2007-Apr-23	04:42:34.790	70.8	–28.6587	–10.2080	914.7	–28.6861	–10.1882	6,828.5	–28.4070	–28.9661	–9.9630	–10.4135
54	36	2007-Apr-23	04:59:57.638	74.0	–59.1411	29.5201	1,116.6	–59.2706	29.5575	7,062.5	–58.5440	–60.0229	29.8639	29.2532
55	37	2007-May-21	02:50:53.002	65.1	–27.0536	–0.2803	669.3	–27.0742	–0.2656	6,703.3	–26.8093	–27.3399	–0.0441	–0.4870
56	38	2007-May-21	03:10:06.960	68.8	–68.4045	7.2266	803.4	–68.4946	7.2500	6,838.3	–67.6125	–69.4333	7.4864	7.0141
57		2007-May-22	03:10:25.018	60.6	–44.7750	39.0613	561.1	–44.8216	39.0802	6,871.8	–44.3371	–45.3121	39.3940	38.7681
60		2007-Aug-08	08:03:09.965	71.9	70.3576	24.1231	916.1	70.4527	24.1524	7,346.7	71.1884	69.7412	24.4559	23.8507
61		2007-Aug-08	09:01:16.982	60.9	61.0311	13.2143	537.8	61.0637	13.2270	6,849.3	61.5013	60.6316	13.4719	12.9827
62		2007-Aug-08	09:44:16.714	52.6	81.1979	4.5416	390.1	81.2510	4.5536	7,333.9	82.4006	80.1967	4.8076	4.3003
63	39	2007-Aug-09	09:10:49.814	70.6	48.4994	10.0048	856.1	48.5365	10.0216	7,175.3	48.8710	48.2040	10.2691	9.7744
64		2007-Aug-21	02:52:44.803	77.0	–81.2476	–37.1585	1,402.5	–81.1436	–37.0918	7,321.9	–78.9598	–84.6349	–36.5572	–37.7299
65		2007-Sep-19	02:36:10.166	80.7	–50.5845	1.8868	1,985.1	–50.6408	1.9348	7,288.0	–50.3026	–50.9811	2.1756	1.6938
66	40	2007-Oct-06	08:42:52.013	75.4	74.3383	23.2915	1,248.5	74.4633	23.3073	7,167.0	75.1455	73.8004	23.5743	23.0410
67		2007-Oct-20	01:16:35.011	58.8	–70.8023	8.1080	528.1	–70.8238	8.1223	7,686.0	–70.2737	–71.3841	8.3731	7.8714
68		2007-Oct-20	04:28:17.443	80.1	–62.3709	–6.5946	1,848.3	–62.4568	–6.5677	8,100.6	–61.9955	–62.9234	–6.2950	–6.8408
69		2007-Nov-05	09:20:47.875	77.7	48.7948	–2.0660	1,554.1	48.8620	–2.0558	7,239.1	49.1870	48.5387	–1.8164	–2.2953
70	41	2007-Nov-16	00:11:21.178	63.9	–56.6582	–37.1216	677.6	–56.6636	–37.0985	6,683.6	–56.2178	–57.1142	–36.7961	–37.4026
71	42	2007-Nov-16	00:27:08.899	65.5	–57.8193	32.4618	727.4	–57.8625	32.4807	7,038.6	–57.4486	–58.2797	32.7377	32.2241
72		2007-Nov-17	02:06:01.210	67.9	–76.1195	23.4815	807.4	–76.1974	23.4953	7,063.5	–75.5512	–76.8612	23.7363	23.2545
73		2007-Nov-17	03:11:38.458	78.0	–33.4769	–19.2585	1,539.4	–33.5255	–19.2340	7,126.9	–33.2494	–33.8023	–18.9809	–19.4877
74		2007-Nov-17	03:53:16.022	85.0	–37.6250	–34.0865	3,762.9	–37.7604	–34.0281	7,741.4	–37.4039	–38.1184	–33.7100	–34.3475
75		2007-Dec-16	23:47:03.437	38.4	–22.4391	25.6287	255.6	–22.4450	25.6370	7,134.8	–22.1738	–22.7167	25.9019	25.3727
76		2007-Dec-17	00:43:08.890	42.1	–50.8587	–9.6017	291.1	–50.8673	–9.5948	7,023.7	–50.5424	–51.1941	–9.3616	–9.8281
77		2007-Dec-17	04:04:46.099	74.2	–51.1817	16.4031	1,149.4	–51.2381	16.4151	6,869.9	–50.9080	–51.5702	16.6552	16.1754
78		2007-Dec-18	00:32:08.880	31.8	–42.7331	–39.4408	196.7	–42.7343	–39.4338	7,299.1	–42.3541	–43.1161	–39.1390	–39.7297

*** Calculation not possible due to proximity to lunar limb.

Table 4. Three hundred lunar impact flashes observed from November 2005 to January 2014 by the NASA Lunar Impact Monitoring Program. See the text for a description of the columns (Continued).

MEO Flash No.	CR No.	Date (UT)	Time (UT)	Zen. Dist. (deg)	Measured Location		Refraction Correction (m)	Refraction-Corrected Location		Total Uncertainty (m)	Longitude Extremes		Latitude Extremes	
					Long. (deg)	Lat. (deg)		Long. (deg)	Lat. (deg)		(°E.)	(°W.)	(°N.)	(°S.)
79		2007-Dec-18	01:08:41.712	34.0	–47.7625	26.0794	214.5	–47.7725	26.0856	7,152.8	–47.4165	–48.1306	26.3590	25.8129
80		2007-Dec-18	01:32:19.277	36.4	–85.8021	–18.2333	234.6	–85.8258	–18.2269	8,674.6	–84.3976	–87.4553	–17.9533	–18.4993
81		2007-Dec-18	01:56:40.733	39.5	–59.5060	–29.6252	262.3	–59.5157	–29.6195	7,713.9	–59.0457	–59.9903	–29.3421	–29.8975
82		2008-Jan-01	07:43:38.986	80.6	80.2435	23.9875	2,101.8	80.5318	23.9834	7,102.7	81.4647	79.6473	24.2014	23.7646
83		2008-Jan-02	08:33:12.960	82.4	40.6979	–33.2960	2,620.1	40.8041	–33.2648	7,774.6	41.2070	40.4040	–32.9260	–33.6055
84	43	2008-Jan-03	10:25:37.776	74.4	88.1622	27.1359	1,251.3	88.5942	27.1078	6,954.4	91.3994	86.6606	27.2132	26.9777
85	44	2008-Jan-04	10:58:26.227	78.9	39.5390	40.0765	1,791.7	39.6438	40.1092	6,769.0	40.0030	39.2860	40.3680	39.8509
86	45	2008-Jan-04	11:42:38.707	72.9	73.3868	39.8632	1,133.9	73.5477	39.8753	7,277.4	74.3784	72.7436	40.1042	39.6443
87	46	2008-Jan-04	11:48:36.403	72.1	63.1589	34.1562	1,083.0	63.2530	34.1738	7,052.7	63.7971	62.7167	34.4116	33.9359
88	47	2008-Jan-14	00:22:26.026	45.0	–49.2487	–23.9644	323.5	–49.2605	–23.9585	6,875.6	–48.9226	–49.6001	–23.7185	–24.1989
89		2008-Jan-15	02:19:55.574	52.9	–37.6010	0.2140	424.1	–37.6170	0.2184	7,063.6	–37.3406	–37.8943	0.4521	–0.0153
90		2008-Jan-15	02:57:06.509	60.0	–74.2986	–32.7042	557.8	–74.3448	–32.6958	7,035.1	–73.6598	–75.0486	–32.4553	–32.9361
91		2008-Jan-15	04:05:07.872	73.4	–65.1140	–9.0509	1,082.6	–65.1817	–9.0387	7,880.9	–64.6668	–65.7046	–8.7816	–9.2959
92	48	2008-Feb-11	01:09:26.899	64.0	–27.2512	–17.8677	652.5	–27.2744	–17.8620	7,114.1	–27.0075	–27.5417	–17.6215	–18.1027
93	49	2008-Feb-12	00:24:44.438	42.2	–76.5604	–11.9646	286.8	–76.5894	–11.9592	6,871.0	–75.8332	–77.3787	–11.7422	–12.1759
94		2008-Feb-14	03:15:30.528	49.1	–82.8011	–29.7220	364.7	–82.8600	–29.7125	7,014.1	–81.6162	–84.2487	–29.5286	–29.8909
95		2008-Feb-14	05:15:03.110	72.3	–74.3655	25.6123	997.9	–74.4844	25.6097	7,588.1	–73.6671	–75.3354	25.8431	25.3754
96	50	2008-Mar-12	00:40:42.442	44.0	–23.2726	–24.8109	297.1	–23.2836	–24.8084	6,821.5	–23.0167	–23.5510	–24.5728	–25.0443
97	51	2008-Mar-12	01:13:31.930	50.5	–50.2569	–7.5184	374.0	–50.2753	–7.5144	7,008.8	–49.9183	–50.6348	–7.2852	–7.7436
98	52	2008-Mar-12	02:03:07.027	60.3	–56.6364	–6.9684	541.4	–56.6669	–6.9617	7,032.3	–56.2541	–57.0842	–6.7324	–7.1910
99	53	2008-Mar-13	01:38:48.509	42.1	–48.3136	–3.1965	279.4	–48.3273	–3.1933	6,938.4	–47.9775	–48.6795	–2.9649	–3.4216
100	54	2008-Mar-13	02:04:22.368	47.2	–76.6599	–22.6601	334.1	–76.7011	–22.6529	6,866.2	–75.7689	–77.6941	–22.4511	–22.8534
101		2008-Mar-14	01:59:33.878	33.2	–28.3724	6.1855	203.4	–28.3801	6.1878	7,436.9	–28.0923	–28.6688	6.4394	5.9366
102	55	2008-Apr-09	02:16:38.496	75.4	–32.5215	–16.6076	1,156.4	–32.5636	–16.5925	6,982.8	–32.2800	–32.8480	–16.3601	–16.8251
103	56	2008-Apr-10	01:15:24.682	50.4	–66.1913	–4.9903	365.4	–66.2217	–4.9839	6,829.2	–65.6221	–66.8374	–4.7622	–5.2054
104		2008-May-09	02:57:02.448	71.6	–18.1955	–32.0231	897.6	–18.2222	–32.0040	7,074.9	–17.9264	–18.5185	–31.7411	–32.2676
112	57	2008-Jun-07	02:27:24.768	71.7	–74.2952	23.2816	899.2	–74.4975	23.3084	6,858.0	–73.0809	–76.1717	23.5718	23.0468
113	58	2008-Jun-07	03:31:31.469	83.9	–12.3614	5.7469	2,803.8	–12.4308	5.8150	7,084.6	–12.1840	–12.6780	6.0504	5.5797
114		2008-Jun-09	03:21:01.008	67.7	–40.9444	–36.4537	748.7	–40.9522	–36.4291	7,135.1	–40.5094	–41.3990	–36.1264	–36.7332
115	59	2008-Jun-27	09:31:24.470	45.9	81.0547	2.8845	308.4	81.1762	2.9041	8,574.8	***	77.4698	3.2215	2.5942

*** Calculation not possible due to proximity to lunar limb.

Table 4. Three hundred lunar impact flashes observed from November 2005 to January 2014 by the NASA Lunar Impact Monitoring Program. See the text for a description of the columns (Continued).

MEO Flash No.	CR No.	Date (UT)	Time (UT)	Zen. Dist. (deg)	Measured Location		Refraction Correction (m)	Refraction-Corrected Location		Total Uncertainty (m)	Longitude Extremes		Latitude Extremes	
					Long. (deg)	Lat. (deg)		Long. (deg)	Lat. (deg)		(°E.)	(°W.)	(°N.)	(°S.)
126		2008-Jul-28	07:22:09.552	80.0	56.7389	16.2895	1,672.8	56.8401	16.3382	10,803.0	57.5736	56.1227	16.7335	15.9445
127	60	2008-Jul-28	08:35:36.989	67.5	73.4348	0.3932	707.4	73.5037	0.4142	6,273.2	74.2931	72.7517	0.6228	0.2060
128	61	2008-Jul-28	08:47:07.411	65.4	23.7794	28.2291	636.9	23.8044	28.2454	6,554.5	24.0776	23.5318	28.5079	27.9836
129	62	2008-Jul-28	09:05:16.397	61.9	70.6938	3.2600	546.1	70.7427	3.2753	6,529.5	71.4508	70.0607	3.4963	3.0548
130	63	2008-Jul-29	09:43:10.790	66.6	64.2613	22.2550	673.2	64.3217	22.2723	7,329.3	64.9572	63.7018	22.5578	21.9881
131		2008-Jul-29	10:11:45.485	61.2	31.3359	–24.6336	528.4	31.3527	–24.6239	6,328.1	31.6165	31.0895	–24.4039	–24.8441
132	64	2008-Sep-23	10:14:32.669	35.3	76.4189	2.9779	212.6	76.4420	2.9815	6,346.5	77.1747	75.7388	3.1935	2.7696
133	65	2008-Sep-24	08:46:40.714	65.7	64.9698	–25.0410	671.7	65.0096	–25.0323	7,596.1	65.5624	64.4656	–24.7637	–25.3013
134		2008-Oct-06	01:35:21.840	75.1	–44.2735	18.1062	1,266.8	–44.3171	18.1409	8,573.8	–43.9222	–44.7143	18.4273	17.8548
135	66	2008-Oct-22	07:25:10.214	69.7	69.2979	–14.0310	844.0	69.3542	–14.0223	7,753.8	69.9401	68.7797	–13.7600	–14.2850
136	67	2008-Oct-22	07:51:31.075	64.5	89.3885	21.0025	654.5	89.6023	21.0103	6,673.1	92.1937	87.7791	21.2518	20.7700
137	68	2008-Oct-22	10:03:13.910	38.6	75.2453	33.0561	247.6	75.2770	33.0595	6,344.0	75.9989	74.5786	33.3116	32.8082
138	69	2008-Oct-22	10:30:20.995	33.5	79.5006	4.5726	205.2	79.5235	4.5753	7,938.3	80.4795	78.6187	4.8382	4.3125
139	70	2008-Nov-02	23:48:39.946	70.8	–83.2454	–11.0408	986.3	–83.3331	–11.0200	6,553.7	–81.9051	–85.0740	–10.7746	–11.2672
140	71	2008-Nov-03	00:11:05.971	73.4	–68.5358	13.1764	1,155.6	–68.6070	13.2023	6,568.8	–68.0835	–69.1409	13.4153	12.9894
141		2008-Nov-03	00:16:34.118	74.1	–30.8719	38.0483	1,208.2	–30.9222	38.0846	6,515.7	–30.6171	–31.2281	38.3399	37.8299
142		2008-Nov-03	00:33:37.526	76.3	–41.5473	–15.8357	1,414.8	–41.5792	–15.7995	6,339.9	–41.2968	–41.8629	–15.5751	–16.0244
143	72	2008-Nov-03	23:59:24.490	65.1	–65.1890	–4.8527	736.1	–65.2120	–4.8330	7,947.0	–64.6619	–65.7722	–4.5667	–5.0995
144	73	2008-Nov-04	00:04:06.067	65.5	–54.2127	19.2467	750.8	–54.2431	19.2673	6,314.3	–53.9046	–54.5838	19.4809	19.0538
145	74	2008-Nov-04	01:10:01.286	73.0	–21.4228	–24.2840	1,118.5	–21.4478	–24.2543	6,409.6	–21.2044	–21.6915	–24.0155	–24.4936
146	75	2008-Nov-04	01:39:03.802	77.8	–62.0201	–1.5506	1,584.1	–62.0927	–1.5197	6,657.0	–61.6799	–62.5104	–1.2992	–1.7403
147		2008-Nov-04	23:32:35.894	57.6	–42.6377	–8.1577	534.7	–42.6438	–8.1411	6,891.8	–42.3533	–42.9355	–7.9098	–8.3726
148	76	2008-Nov-05	00:38:37.939	61.4	–66.5803	–16.9589	623.0	–66.5959	–16.9416	7,222.8	–66.0691	–67.1322	–16.6864	–17.1973
149	77	2008-Nov-05	00:53:58.013	63.5	–18.0913	–22.4720	678.8	–18.1049	–22.4529	6,312.9	–17.8738	–18.3363	–22.2240	–22.6821
150	78	2008-Nov-05	02:05:07.901	72.3	–64.8482	31.4765	1,061.9	–64.9347	31.4996	6,446.4	–64.4616	–65.4141	31.7389	31.2608
151	79	2008-Nov-05	02:09:44.726	72.9	–42.9997	–33.9707	1,105.8	–43.0288	–33.9434	7,570.7	–42.6458	–43.4140	–33.6336	–34.2544
152	80	2008-Nov-05	02:32:47.213	76.3	–31.8851	–0.4600	1,399.8	–31.9270	–0.4339	7,481.6	–31.6519	–32.2028	–0.1870	–0.6807
153	81	2008-Nov-20	11:03:05.818	32.0	52.4082	–5.4838	199.6	52.4148	–5.4796	6,510.9	52.7216	52.1097	–5.2623	–5.6971
154	82	2008-Nov-22	09:41:24.518	67.9	82.5904	1.2993	814.6	82.6901	1.2988	6,654.8	83.5679	81.8605	1.5172	1.0800
155		2008-Nov-22	11:44:44.938	48.1	84.8695	21.8677	366.2	84.9240	21.8701	6,768.1	85.9249	83.9865	22.0745	21.6648

*** Calculation not possible due to proximity to lunar limb.

Table 4. Three hundred lunar impact flashes observed from November 2005 to January 2014 by the NASA Lunar Impact Monitoring Program. See the text for a description of the columns (Continued).

MEO Flash No.	CR No.	Date (UT)	Time (UT)	Zen. Dist. (deg)	Measured Location		Refraction Correction (m)	Refraction-Corrected Location		Total Uncertainty (m)	Longitude Extremes		Latitude Extremes	
					Long. (deg)	Lat. (deg)		Long. (deg)	Lat. (deg)		(°E.)	(°W.)	(°N.)	(°S.)
156	83	2008-Nov-23	10:48:24.278	67.5	85.5574	–0.4728	807.4	85.6837	–0.4760	6,665.7	86.8833	84.6009	–0.2543	–0.6983
157	84	2008-Nov-23	11:15:53.222	62.1	46.3506	–21.7942	630.7	46.3738	–21.7855	6,764.4	46.6936	46.0557	–21.5300	–22.0418
158	85	2008-Dec-03	00:30:57.600	67.0	–61.6797	–18.9981	814.6	–61.7099	–18.9804	7,698.6	–61.2300	–62.1960	–18.7098	–19.2515
159	86	2008-Dec-03	02:09:03.514	82.4	–68.5329	–3.7541	2,593.4	–68.6947	–3.7170	6,272.1	–68.2452	–69.1512	–3.5095	–3.9246
160		2008-Dec-05	00:23:13.373	47.5	–80.0427	3.8137	367.0	–80.0713	3.8238	6,575.6	–79.3586	–80.8135	4.0429	3.6048
161		2008-Dec-05	01:29:40.387	55.0	–75.2829	1.6536	481.9	–75.3178	1.6638	6,695.7	–74.7458	–75.9039	1.8855	1.4423
162	87	2009-Feb-01	01:40:30.979	56.2	–65.7988	–18.2442	489.2	–65.8272	–18.2381	7,012.0	–65.3862	–66.2734	–18.0090	–18.4672
163	88	2009-Feb-01	02:04:52.262	61.0	–50.4120	–12.5127	591.1	–50.4376	–12.5070	6,945.5	–50.1223	–50.7544	–12.2786	–12.7354
169	89	2009-Feb-02	02:45:43.085	56.6	–55.1457	–20.8567	491.4	–55.1691	–20.8517	6,982.9	–54.8145	–55.5259	–20.6192	–21.0844
164	90	2009-Mar-03	02:51:42.509	56.4	–35.1588	–32.7188	474.1	–35.1780	–32.7140	7,636.3	–34.8384	–35.5186	–32.4359	–32.9927
165	91	2009-Mar-03	04:02:49.286	70.1	–83.1480	26.4728	875.8	–83.3850	26.5068	6,407.8	–81.9130	–85.1834	26.8372	26.1874
166	92	2009-Mar-03	04:27:48.672	74.8	–74.6077	10.0338	1,168.5	–74.7273	10.0577	7,724.8	–73.9533	–75.5334	10.3332	9.7829
167	93	2009-Mar-30	01:43:10.906	68.0	–67.3116	26.6645	778.3	–67.3882	26.6792	7,270.1	–66.7343	–68.0605	26.9867	26.3735
168		2009-Apr-02	02:59:16.368	45.9	–37.6133	–24.9902	315.5	–37.6244	–24.9850	6,345.1	–37.3399	–37.9099	–24.7610	–25.2093
170		2009-Apr-28	01:45:26.035	68.4	–79.6184	–21.8041	770.5	–79.7074	–21.7871	6,539.2	–78.7649	–80.7173	–21.5840	–21.9894
171		2009-May-19	08:58:32.390	71.1	52.1566	–3.4821	931.6	52.1841	–3.4539	7,666.8	52.6711	51.7037	–3.2022	–3.7056
172		2009-May-21	09:47:53.664	72.8	32.8352	12.9017	997.6	32.8657	12.9319	6,547.5	33.1552	32.5776	13.1614	12.7028
173	94	2009-May-30	03:52:11.309	69.6	–15.0717	11.7099	814.9	–15.0914	11.7307	7,167.2	–14.8359	–15.3473	11.9694	11.4923
174	95	2009-Jun-19	09:00:07.085	72.2	54.8708	–30.4491	934.3	54.8882	–30.4208	7,307.9	55.4180	54.3657	–30.1714	–30.6704
175	96	2009-Jun-26	02:04:06.730	72.5	–57.6176	15.9796	929.4	–57.6725	16.0011	6,325.8	–57.2304	–58.1207	16.2117	15.7907
177	97	2009-Oct-24	23:57:35.712	59.5	–81.0867	10.8866	567.6	–81.1628	10.9027	8,031.2	–79.3893	–83.4724	11.1640	10.6410
178	98	2009-Oct-25	00:14:24.000	60.5	–64.9302	14.6549	592.2	–64.9621	14.6725	6,524.8	–64.4248	–65.5108	14.8919	14.4531
179	99	2009-Oct-25	01:19:59.606	66.7	–59.8728	–24.9686	777.1	–59.8908	–24.9468	7,064.2	–59.3616	–60.4292	–24.6855	–25.2087
180	100	2009-Oct-25	01:52:04.166	70.7	–70.1214	17.0768	955.9	–70.2115	17.0989	8,164.6	–69.3762	–71.0831	17.3760	16.8220
181	101	2009-Oct-25	01:55:07.334	71.1	–38.8728	–23.9113	978.2	–38.8958	–23.8863	6,556.8	–38.5881	–39.2050	–23.6477	–24.1254
182	102	2009-Oct-25	01:58:10.330	71.5	–22.5165	35.5938	1,001.8	–22.5565	35.6218	7,219.2	–22.2387	–22.8751	35.9112	35.3335
183	103	2009-Oct-25	02:37:58.166	77.2	–42.3228	3.7304	1,482.3	–42.3766	3.7607	6,992.5	–42.0616	–42.6933	3.9914	3.5300
184	104	2009-Oct-25	02:38:07.670	77.2	–56.5667	4.1941	1,485.2	–56.6406	4.2240	6,989.5	–56.2160	–57.0702	4.4546	3.9935
185	105	2009-Oct-25	02:53:59.366	79.7	–69.3756	28.4650	1,851.5	–69.5963	28.5035	6,351.7	–68.9181	–70.2970	28.7363	28.2711
186	106	2009-Nov-12	10:10:22.627	65.7	77.6267	15.8881	703.1	77.7041	15.8876	7,425.6	78.5124	76.9279	16.1193	15.6555

*** Calculation not possible due to proximity to lunar limb.

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MEO Flash No.	CR No.	Date (UT)	Time (UT)	Zen. Dist. (deg)	Measured Location		Refraction Correction (m)	Refraction-Corrected Location		Total Uncertainty (m)	Longitude Extremes		Latitude Extremes	
					Long. (deg)	Lat. (deg)		Long. (deg)	Lat. (deg)		(°E.)	(°W.)	(°N.)	(°S.)
187	107	2009-Nov-13	10:15:44.899	77.2	52.6878	8.4118	1,415.3	52.7558	8.4188	7,003.4	53.0965	52.4173	8.6479	8.1896
188		2009-Nov-13	11:44:38.803	61.8	43.6929	18.0287	597.2	43.7186	18.0354	6,655.8	44.0081	43.4301	18.2569	17.8140
189	108	2009-Dec-10	09:41:53.894	60.7	92.3356	–8.6530	579.4	92.6686	–8.6849	7,093.0	***	89.4946	–8.3655	–9.0426
190	109	2009-Dec-21	00:12:37.814	65.4	–36.1450	28.7015	761.6	–36.1800	28.7182	6,474.7	–35.8855	–36.4756	28.9699	28.4672
191	110	2009-Dec-21	00:33:45.734	68.8	–35.2711	–30.7919	897.0	–35.2999	–30.7744	7,643.3	–34.9555	–35.6455	–30.4907	–31.0588
192		2009-Dec-22	02:48:43.229	82.3	–75.7237	–0.8996	2,564.3	–75.9765	–0.8567	7,734.8	–75.1842	–76.8034	–0.6018	–1.1114
195		2010-Jan-19	00:28:45.062	69.2	–58.1578	18.4934	920.4	–58.2156	18.5083	6,609.9	–57.8164	–58.6190	18.7507	18.2664
196		2010-Jan-19	00:57:07.402	74.5	–17.4304	7.2378	1,261.1	–17.4718	7.2513	7,323.6	–17.2221	–17.7218	7.4984	7.0044
197		2010-Feb-18	01:31:42.902	72.6	–73.6386	–36.3031	1,091.0	–73.7226	–36.2866	6,510.8	–73.1462	–74.3097	–36.0660	–36.5069
198	111	2010-Feb-19	00:45:39.485	52.1	–39.8548	–36.4993	433.3	–39.8735	–36.4950	6,687.8	–39.5568	–40.1909	–36.2446	–36.7460
199	112	2010-Feb-19	01:15:10.858	57.9	–74.7335	–11.2930	539.2	–74.7763	–11.2853	6,443.4	–74.2433	–75.3209	–11.0795	–11.4909
200		2010-Mar-20	01:07:26.976	58.0	–45.3827	–18.3183	525.1	–45.4043	–18.3136	7,016.0	–45.0984	–45.7115	–18.0787	–18.5488
201	113	2010-Apr-21	02:48:02.794	46.7	–30.0039	13.2039	327.5	–30.0146	13.2103	7,282.4	–29.7412	–30.2885	13.4557	12.9652
202		2010-May-18	01:32:36.125	56.3	–22.7813	18.3935	452.6	–22.7961	18.4022	6,393.0	–22.5609	–23.0317	18.6230	18.1817
203	114	2010-May-18	01:38:30.710	57.4	–36.3483	–0.4897	473.6	–36.3636	–0.4810	6,579.7	–36.1052	–36.6228	–0.2641	–0.6980
204	115	2010-May-18	01:56:32.698	61.0	–62.6172	12.7721	546.8	–62.6507	12.7821	6,980.0	–62.1943	–63.1132	13.0161	12.5482
205	116	2010-May-18	02:31:09.494	67.9	–50.9622	17.3167	745.6	–50.9980	17.3313	7,437.3	–50.6201	–51.3786	17.5859	17.0771
206		2010-Jul-08	08:08:58.416	81.8	53.3943	–27.8524	2,124.5	53.4451	–27.7919	7,172.1	53.9466	52.9502	–27.5417	–28.0424
207	117	2010-Jul-08	08:48:55.843	74.4	20.8351	–37.2384	1,090.0	20.8591	–37.2073	6,775.8	21.1699	20.5491	–36.9420	–37.4734
208	118	2010-Sep-02	06:54:15.898	66.8	37.3337	–6.8547	724.7	37.3590	–6.8400	8,402.4	37.7465	36.9740	–6.5626	–7.1174
209		2010-Sep-13	01:10:23.578	76.6	–4.0228	–3.2649	1,288.6	–4.0418	–3.2269	7,226.3	–3.7985	–4.2854	–2.9859	–3.4680
210	119	2010-Oct-04	09:27:00.691	74.1	57.3540	–5.6795	1,060.0	57.4210	–5.6752	6,236.7	57.8427	57.0047	–5.4643	–5.8864
211		2010-Nov-13	02:49:58.310	69.7	–74.5130	–18.0765	918.4	–74.6078	–18.0540	7,263.1	–73.5719	–75.7274	–17.8254	–18.2820
212		2010-Dec-13	23:53:51.590	31.8	–47.8077	–15.0714	213.2	–47.8099	–15.0646	6,313.4	–47.5034	–48.1180	–14.8569	–15.2724
213		2010-Dec-13	23:53:56.861	31.8	–58.4498	–16.5006	213.2	–58.4519	–16.4937	6,709.8	–58.0440	–58.8640	–16.2750	–16.7125
214		2010-Dec-14	00:25:25.478	32.4	–76.3424	25.1963	218.8	–76.3792	25.2070	7,607.2	–75.1045	–77.8120	25.5618	24.8585
215		2010-Dec-14	01:16:14.621	36.6	–39.5316	–32.5716	255.9	–39.5384	–32.5652	6,385.5	–39.2316	–39.8461	–32.3353	–32.7956
216		2010-Dec-14	01:16:41.923	36.6	–27.0754	–12.9785	256.3	–27.0823	–12.9729	6,466.5	–26.8411	–27.3239	–12.7590	–13.1869
217		2010-Dec-14	01:17:08.794	36.7	–25.6041	–10.1476	256.8	–25.6111	–10.1420	7,796.2	–25.3262	–25.8965	–9.8850	–10.3991
218		2010-Dec-14	01:49:31.498	40.9	–65.7806	25.2277	298.7	–65.8109	25.2365	6,926.8	–65.1714	–66.4688	25.5275	24.9473

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					Long. (deg)	Lat. (deg)		Long. (deg)	Lat. (deg)		(°E.)	(°W.)	(°N.)	(°S.)
219		2010-Dec-14	01:55:48.029	41.8	–40.4838	–12.6282	308.5	–40.4945	–12.6225	7,135.8	–40.1891	–40.8011	–12.3876	–12.8574
220		2010-Dec-14	01:56:51.533	42.0	–64.1723	–9.6029	310.2	–64.1899	–9.5962	7,772.5	–63.6475	–64.7419	–9.3451	–9.8471
221		2010-Dec-14	02:51:00.691	50.8	–82.5960	–16.8863	424.2	–82.6596	–16.8741	6,694.1	–81.5159	–83.9345	–16.6834	–17.0632
222		2010-Dec-14	02:55:57.562	51.7	–41.5521	–40.7911	437.8	–41.5704	–40.7839	7,998.9	–41.1394	–42.0034	–40.4741	–41.0947
223		2010-Dec-14	03:25:50.880	57.2	–59.5303	25.8166	536.1	–59.5733	25.8267	6,722.7	–59.0774	–60.0774	26.1043	25.5503
224		2010-Dec-14	03:31:47.280	58.3	–62.2808	24.9071	559.7	–62.3293	24.9179	8,072.7	–61.6862	–62.9880	25.2505	24.5871
225		2010-Dec-14	03:33:38.736	58.6	–71.2075	14.0908	567.4	–71.2682	14.1028	6,239.2	–70.6283	–71.9303	14.3359	13.8703
226		2010-Dec-14	03:42:19.728	60.3	–36.7463	18.5150	606.0	–36.7729	18.5225	7,124.1	–36.4666	–37.0804	18.7846	18.2610
227		2010-Dec-14	04:08:31.085	65.3	–69.6942	–22.5564	752.9	–69.7510	–22.5442	7,129.0	–69.1497	–70.3659	–22.3171	–22.7713
228		2010-Dec-14	04:29:48.077	69.4	–79.3223	14.0664	924.3	–79.4927	14.0928	6,599.4	–78.3618	–80.7579	14.3550	13.8326
229		2010-Dec-14	04:35:39.811	70.6	–88.8405	–16.7434	984.0	–89.1960	–16.6949	6,251.8	–87.0938	***	–16.5620	–16.8124
230		2010-Dec-14	04:43:03.475	72.0	–47.6181	20.3271	1,070.0	–47.6757	20.3401	6,314.7	–47.3484	–48.0051	20.5787	20.1022
231		2010-Dec-14	04:52:12.115	73.8	–51.3137	20.0467	1,197.3	–51.3832	20.0618	7,269.3	–50.9778	–51.7925	20.3371	19.7874
232		2010-Dec-14	05:23:56.112	80.1	–67.8410	–32.1908	1,988.3	–67.9851	–32.1612	7,717.4	–67.3491	–68.6339	–31.9047	–32.4175
233		2011-Jan-08	23:42:08.899	52.1	–56.5196	–8.1396	445.8	–56.5411	–8.1305	7,630.4	–56.0921	–56.9953	–7.8817	–8.3792
234	120	2011-Jan-09	01:17:55.104	68.5	–56.0662	–37.0070	888.0	–56.1118	–36.9923	7,438.5	–55.6153	–56.6135	–36.7224	–37.2624
235		2011-Feb-11	04:14:25.498	63.4	–85.0053	–34.7970	677.1	–85.0931	–34.7850	7,653.1	–83.9426	–86.3359	–34.5360	–35.0312
236	121	2011-Feb-26	09:39:28.483	76.2	69.4954	14.4771	1,354.9	69.5791	14.5083	6,389.7	70.0400	69.1248	14.7234	14.2933
237	122	2011-Feb-26	10:38:26.304	68.5	48.4341	6.9360	842.5	48.4577	6.9585	6,936.7	48.7628	48.1540	7.1882	6.7290
238		2011-Mar-12	00:37:43.162	24.1	–56.9835	–13.9117	147.4	–56.9899	–13.9096	7,548.5	–56.6011	–57.3818	–13.6565	–14.1628
239		2011-Mar-12	01:11:18.528	30.6	–63.4526	9.2472	194.6	–63.4641	9.2497	7,373.1	–63.0267	–63.9065	9.4987	9.0009
240		2011-Mar-12	02:57:33.034	51.8	–63.2553	21.0987	419.1	–63.2829	21.1037	7,233.6	–62.8311	–63.7401	21.3653	20.8427
241		2011-Mar-12	04:03:53.914	64.9	–30.6070	1.7707	705.8	–30.6309	1.7786	7,817.6	–30.3522	–30.9101	2.0369	1.5205
242	123	2011-Apr-08	01:32:17.808	59.7	–46.3571	–2.2003	563.2	–46.3800	–2.1945	7,403.5	–46.0647	–46.6967	–1.9505	–2.4385
243		2011-Apr-08	02:42:24.797	73.3	–18.4711	7.7261	1,102.3	–18.5066	7.7390	6,968.3	–18.2701	–18.7433	7.9720	7.5061
244		2011-May-09	04:08:54.067	75.8	–48.1146	10.3102	1,230.3	–48.1593	10.3353	6,921.5	–47.8551	–48.4649	10.5638	10.1068
245	124	2011-May-10	03:40:20.064	62.0	–25.9731	–29.4848	578.0	–25.9859	–29.4685	6,241.7	–25.7343	–26.2380	–29.2172	–29.7206
246		2011-May-11	02:22:52.090	40.2	–50.0733	–18.1899	256.0	–50.0765	–18.1820	6,707.2	–49.7447	–50.4103	–17.9357	–18.4289
247		2011-May-27	10:03:01.382	57.3	16.7745	6.0409	514.2	16.7834	6.0564	6,844.4	17.0192	16.5479	6.2873	5.8256
248		2011-Aug-22	09:37:52.579	32.6	67.1193	–11.6211	201.9	67.1326	–11.6162	7,302.0	67.9389	66.3594	–11.3748	–11.8577

*** Calculation not possible due to proximity to lunar limb.

Table 4. Three hundred lunar impact flashes observed from November 2005 to January 2014 by the NASA Lunar Impact Monitoring Program. See the text for a description of the columns (Continued).

MEO Flash No.	CR No.	Date (UT)	Time (UT)	Zen. Dist. (deg)	Measured Location		Refraction Correction (m)	Refraction-Corrected Location		Total Uncertainty (m)	Longitude Extremes		Latitude Extremes	
					Long. (deg)	Lat. (deg)		Long. (deg)	Lat. (deg)		(°E.)	(°W.)	(°N.)	(°S.)
249		2011-Aug-22	10:32:00.701	22.3	68.4812	27.6009	129.5	68.4997	27.6051	6,677.4	69.4579	67.5965	27.8675	27.3439
250	125	2011-Aug-23	07:39:06.912	66.1	39.3978	22.4928	711.5	39.4328	22.5080	8,197.2	39.8476	39.0210	22.8011	22.2155
251	126	2011-Aug-23	09:58:31.728	38.4	59.4972	1.7239	247.4	59.5136	1.7285	8,221.2	60.1701	58.8731	1.9997	1.4574
252		2011-Aug-25	10:30:47.520	54.6	33.1796	13.4751	427.3	33.1977	13.4804	6,519.8	33.4821	32.9144	13.6985	13.2625
253		2011-Oct-22	08:32:35.635	74.0	64.1784	1.9209	1,076.1	64.2787	1.9192	6,965.8	64.9569	63.6218	2.1478	1.6904
254		2011-Oct-22	10:09:12.384	55.2	54.0691	19.4523	441.4	54.0995	19.4541	6,638.4	54.5397	53.6644	19.6701	19.2380
255		2011-Oct-22	10:46:15.370	48.3	77.0452	–7.5652	344.0	77.1400	–7.5719	6,276.7	79.6416	75.4117	–7.3323	–7.8141
256		2011-Oct-22	11:17:16.253	42.9	55.9313	–25.9113	284.1	55.9487	–25.9085	6,796.2	56.5412	55.3697	–25.6243	–26.1942
257		2011-Oct-23	09:33:37.181	75.2	44.6630	37.0917	1,150.3	44.7373	37.0957	6,892.0	45.1444	44.3329	37.3477	36.8441
258		2011-Oct-30	00:36:19.872	82.0	–18.2294	–19.9560	2,186.2	–18.2750	–19.8981	8,192.0	–17.9608	–18.5900	–19.6110	–20.1857
259		2011-Oct-31	23:57:43.920	59.4	–13.2977	–2.5496	533.1	–13.3065	–2.4441	7,468.8	–13.0436	–13.5699	–2.1979	–2.6902
260		2011-Dec-29	01:06:27.014	67.8	–14.6652	–27.5662	820.5	–14.6930	–27.5543	7,173.0	–14.4119	–14.9745	–27.3017	–27.8074
261		2011-Dec-29	02:21:58.867	81.7	–58.5637	12.1714	2,318.3	–58.7495	12.2128	6,422.0	–58.2454	–59.2634	12.4435	11.9825
262		2011-Dec-30	01:47:38.400	64.0	–69.9969	–25.8177	696.6	–70.0611	–25.8028	6,777.0	–69.2987	–70.8542	–25.5954	–26.0094
263		2011-Dec-30	02:08:49.862	67.9	–33.4579	1.7642	839.0	–33.4917	1.7745	6,263.2	–33.2303	–33.7541	1.9835	1.5657
264		2012-Feb-28	03:27:07.690	69.9	–74.8177	16.1986	949.8	–74.9326	16.2103	6,585.2	–74.1783	–75.7209	16.4456	15.9755
265		2012-Mar-29	02:08:49.344	49.1	–18.6696	17.8179	390.8	–18.6829	17.8227	6,543.2	–18.4507	–18.9153	18.0474	17.5984
266		2012-Apr-28	04:00:21.629	69.0	–63.7605	2.4215	853.8	–63.8000	2.4363	6,765.5	–63.4075	–64.1965	2.6589	2.2136
267		2012-May-26	02:02:13.027	61.5	–58.2346	–1.1144	590.0	–58.2568	–1.1029	7,439.5	–57.8694	–58.6474	–0.8554	–1.3506
268		2012-May-27	01:55:32.563	52.7	–31.0801	–5.3499	416.1	–31.0891	–5.3394	7,481.5	–30.8191	–31.3597	–5.0869	–5.5923
269		2012-May-27	02:33:01.382	60.2	–62.0733	27.0102	553.5	–62.1046	27.0223	6,325.2	–61.7308	–62.4813	27.2353	26.8095
270		2012-May-27	03:17:18.701	69.1	–79.5923	–14.3289	832.2	–79.6389	–14.3127	7,103.5	–78.8091	–80.5129	–14.0423	–14.5843
271		2012-Jun-26	02:54:41.011	68.3	–52.0038	3.1966	765.0	–52.0218	3.2174	7,190.3	–51.6843	–52.3613	3.4542	2.9805
272		2012-Jun-26	03:00:07.085	69.3	–31.4417	21.9220	807.6	–31.4610	21.9454	6,419.4	–31.2116	–31.7109	22.1632	21.7279
273		2012-Aug-12	10:00:32.774	48.8	83.8402	24.4890	366.1	83.9902	24.4904	6,576.9	87.9832	81.8765	24.6761	24.2943
274		2012-Aug-12	10:06:51.898	47.5	84.5248	1.4950	350.1	84.6713	1.4956	6,684.2	***	82.1407	1.7123	1.2783
275		2012-Aug-24	02:36:07.747	74.5	–63.3245	–12.0028	1,069.2	–63.3479	–11.9712	6,983.7	–62.8266	–63.8790	–11.7331	–12.2096
276		2012-Oct-09	06:46:16.550	77.9	50.0890	–12.3457	1,528.1	50.1687	–12.3328	6,453.8	50.5657	49.7760	–12.1044	–12.5616
277		2012-Oct-09	10:57:14.602	29.5	66.6949	–27.5458	183.3	66.7098	–27.5435	6,234.1	67.6790	65.8033	–27.2575	–27.8328
278		2012-Oct-11	08:40:46.819	78.4	60.3067	–5.6550	1,550.3	60.4297	–5.6556	7,383.5	61.0604	59.8152	–5.4018	–5.9098

*** Calculation not possible due to proximity to lunar limb.

Table 4. Three hundred lunar impact flashes observed from November 2005 to January 2014 by the NASA Lunar Impact Monitoring Program. See the text for a description of the columns (Continued).

MEO Flash No.	CR No.	Date (UT)	Time (UT)	Zen. Dist. (deg)	Measured Location		Refraction Correction (m)	Refraction-Corrected Location		Total Uncertainty (m)	Longitude Extremes		Latitude Extremes	
					Long. (deg)	Lat. (deg)		Long. (deg)	Lat. (deg)		(°E.)	(°W.)	(°N.)	(°S.)
279		2012-Oct-19	00:22:50.477	76.1	–54.3696	–8.8972	1,220.9	–54.4044	–8.8633	7,310.6	–53.9620	–54.8521	–8.6209	–9.1057
280		2012-Oct-21	00:29:01.478	59.9	–16.8393	12.4370	530.8	–16.8503	12.4532	7,156.6	–16.5895	–17.1115	12.6999	12.2068
281		2012-Oct-21	02:55:28.013	79.9	–42.3981	–18.5618	1,738.2	–42.4543	–18.5224	8,164.7	–42.0463	–42.8653	–18.2483	–18.7966
282		2012-Nov-08	07:53:57.782	72.9	47.3710	–22.3149	1,056.6	47.4314	–22.3118	7,280.8	47.9025	46.9664	–22.0264	–22.5983
283		2012-Nov-08	08:21:56.900	67.4	66.9149	–2.4728	780.0	67.0033	–2.4768	7,323.3	67.8966	66.1565	–2.2289	–2.7252
284		2012-Nov-08	09:18:42.163	56.5	47.3296	–21.9691	488.8	47.3563	–21.9664	6,911.8	47.8024	46.9156	–21.6964	–22.2373
285		2012-Nov-10	09:07:43.795	83.1	16.4693	18.5848	2,618.2	16.5675	18.5986	6,660.4	16.8164	16.3190	18.8232	18.3742
286		2012-Nov-10	09:55:10.243	74.1	73.6646	8.8431	1,105.6	73.8488	8.8332	6,422.3	74.9731	72.8237	9.0311	8.6348
287		2012-Nov-10	10:39:17.194	66.0	79.3168	12.3799	705.0	79.5369	12.3643	6,294.1	81.9779	77.8154	12.5314	12.1937
288		2012-Nov-10	11:16:10.070	59.6	47.5329	11.9399	533.7	47.5620	11.9439	6,290.2	47.9087	47.2180	12.1495	11.7384
289		2012-Nov-10	11:17:14.698	59.4	17.9351	9.9626	529.9	17.9536	9.9682	6,242.6	18.1809	17.7266	10.1742	9.7622
290		2012-Nov-16	23:36:05.242	70.2	–59.9193	–24.3914	852.9	–59.9426	–24.3669	7,538.1	–59.3587	–60.5380	–24.1114	–24.6226
291		2012-Nov-16	23:58:07.162	73.4	–16.0613	7.6047	1,031.2	–16.0880	7.6302	6,566.0	–15.8553	–16.3210	7.8514	7.4093
292		2012-Nov-17	23:54:55.613	62.8	–68.9183	–21.5863	604.6	–68.9451	–21.5680	6,352.7	–68.2113	–69.7095	–21.3678	–21.7679
293		2012-Nov-19	00:33:26.813	57.7	–24.7071	0.6938	499.6	–24.7208	0.7063	6,296.9	–24.4784	–24.9638	0.9153	0.4973
294		2012-Dec-18	00:03:41.875	51.7	–9.2300	0.9687	408.0	–9.2414	0.9771	7,020.9	–9.0004	–9.4826	1.2105	0.7438
295		2013-Mar-17	02:17:00.010	61.1	–26.3177	33.1655	612.9	–26.3460	33.1715	6,728.5	–26.0483	–26.6445	33.4324	32.9114
299		2013-Mar-17	02:33:17.971	64.3	–54.6733	–13.2292	704.9	–54.7124	–13.2235	7,263.2	–54.2719	–55.1580	–12.9751	–13.4722
300		2013-Mar-17	03:14:21.062	72.4	–38.9973	–32.1172	1,071.4	–39.0434	–32.1056	7,033.9	–38.6824	–39.4063	–31.8264	–32.3857
296		2013-Mar-17	03:50:53.981	79.4	–24.1566	20.6644	1,829.5	–24.2277	20.6842	7,409.4	–23.9396	–24.5164	20.9427	20.4261
297		2013-Mar-18	00:56:14.006	34.8	–79.6153	–2.4474	235.6	–79.6565	–2.4463	6,896.8	–78.4039	–81.0922	–2.2160	–2.6768
301		2013-Apr-16	01:27:29.578	47.2	–50.9514	–16.5835	362.3	–50.9664	–16.5785	6,409.3	–50.6251	–51.3103	–16.3486	–16.8089
298		2013-Apr-16	01:43:47.971	50.5	–27.3916	–7.9348	406.8	–27.4045	–7.9289	7,329.9	–27.1344	–27.6751	–7.6809	–8.1772
302		2013-Sep-10	00:53:46.608	73.4	–17.3350	4.6846	1,028.8	–17.3509	4.7151	7,521.0	–17.0961	–17.6059	4.9638	4.4665
303		2013-Nov-08	01:15:08.093	72.8	–35.6386	18.5644	1,002.3	–35.6780	18.5903	8,062.1	–35.3242	–36.0335	18.8848	18.2965
304		2013-Nov-29	10:49:23.635	68.1	77.2158	–12.4978	798.3	77.4270	–12.4970	7,042.0	80.2785	75.5220	–12.2403	–12.7559
305		2013-Nov-29	10:53:08.275	67.5	40.7099	17.6256	773.2	40.7491	17.6338	6,506.1	41.0744	40.4256	17.8550	17.4128
306		2013-Nov-29	11:07:24.240	65.1	76.2047	–2.7655	690.0	76.3582	–2.7630	6,749.4	78.2681	74.8365	–2.5370	–2.9894
307		2013-Dec-27	10:42:20.189	58.1	51.6847	–7.7552	523.1	51.7109	–7.7463	7,180.5	52.1752	51.2528	–7.5060	–7.9868
308		2014-Jan-03	23:56:58.128	70.2	–73.0197	19.9745	866.0	–73.1817	20.0041	8,197.9	–71.8058	–74.7521	20.3517	19.6611

*** Calculation not possible due to proximity to lunar limb.

7. CONCLUSION

A geolocation workflow has been developed to determine the location of lunar impact flashes and their associated craters. The workflow has been applied to 300 flashes observed by the NASA Lunar Impact Monitoring Program from 2005 to 2014. Applying this method to the bright impact flash observed on March 17, 2013, yields a location in good agreement—within approximately 3 km, after a differential refraction correction—with the crater discovered by LRO. The crater locations determined from this work will hopefully be confirmed by future LRO discoveries of new craters as it continues its mission. The 'ground truth' crater locations determined by LRO will provide future opportunities to test the geolocation technique described in this TM.

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14. ABSTRACT Meteoroids impacting the lunar surface produce a flash of light detectable by Earth-based instruments. The NASA Lunar Impact Monitoring Program has recorded over 330 impact flashes in simultaneous telescopic observations of the earthshine portion of the lunar disc. A geolocation workflow has been developed to determine the location of lunar impact flashes and their associated craters. The workflow has been applied to 300 flashes observed by the NASA Lunar Impact Monitoring Program from 2005 to 2014. Applying this method to the bright impact flash observed on March 17, 2013, yields a location in good agreement with the associated fresh impact crater discovered by the Lunar Reconnaissance Orbiter.					
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