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MIDAS: Software for the detection and analysis of lunar impact flashes

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ABSTRACT

Since 2009 we are running a project to identify flashes produced by the impact of meteoroids on the surface of the Moon. For this purpose we are employing small telescopes and high-sensitivity CCD video cameras. To automatically identify these events a software package called MIDAS was developed and tested. This package can also perform the photometric analysis of these flashes and estimate the value of the luminous efficiency. Besides, we have implemented in MIDAS a new method to establish which is the likely source of the meteoroids (known meteoroid stream or sporadic background). The main features of this computer program are analyzed here, and some examples of lunar impact events are presented.

1. Introduction

According to different estimates, between 40 and 80 tons of interplanetary matter impact Earth every year (Williams and Murad, 2002). Most of this is in the form of meteoroids: fragments mostly coming from asteroids and comets and with sizes raging from 100 μm to 10 m. Fireball networks estimate the flux of interplanetary matter impacting our planet by studying the behavior of meteoroids in Earth's atmosphere. Thus, different researchers have estimated the impact hazard for our planet by analyzing fireball events simultaneously imaged from several meteor observing stations (see e.g. Ceplecha, 2001; Madiedo et al., 2014).

Meteoroids also impact the Moon, but since this is an airless body, even the smallest meteoroids collide with the lunar surface at high speeds. These violent collisions generate a short duration flash that can be detected from Earth (Ortiz et al., 1999). So the Moon can be used as a giant detector that provides information about meteoroids impacting the lunar surface. In this way, the impact flux on the Moon can be calculated, and this can be extrapolated to infer the impact flux on Earth (Ortiz et al., 2006; Madiedo et al., 2014b). This method has the advantage that the area covered by one single detection instrument is much larger than the atmospheric volume monitored by meteor detectors employed by fireball networks. However, the results are highly dependent on a parameter called the luminous efficiency, which accounts for the fraction of the kinetic energy of the impactor that is converted into visible light during the impact. Currently this luminous efficiency is not known very accurately, and several estimates have been obtained and employed by different researchers (Bellot Rubio et al., 2000; Ortiz et al., 2002; Swift et al., 2011).

As a continuation of the lunar impacts survey started in 1997 by the second author (Ortiz et al., 1999, 2000), our team is performing since 2009 a monitoring of the night side of the Moon by means of small telescopes and high-sensitivity CCD video cameras (Madiedo et al., in press). In the framework of this project, which is called Moon Impacts Detection and Analysis System (MIDAS), we have also developed a new software package to identify and analyze lunar impact flashes. Here we describe this software and analyze some results, with special focus on techniques that can be useful to improve the detectability of impact flashes and to estimate the likely source of the meteoroids.

2. Instrumentation and data reduction techniques

Since 2009 we are monitoring the night side of the Moon from our observatory in Sevilla, in the south of Spain (latitude: 37.34611°N, longitude: 5.98055°W, height: 23 m above the sea level). This observatory employs two identical 0.36 m Schmidt–Cassegrain telescopes that image the same area of the Moon, but also two smaller Schmidt–Cassegrain telescopes with diameters of 0.28 and 0.24 m, respectively. All of them are manufactured by Celestron. The telescopes are equipped with monochrome high-sensitivity CCD video cameras (model 902H Ultimate, manufactured by Watec Corporation, Japan). These employ a Sony ICX429ALL1/2 in. monochrome CCD sensor and produce interlaced analog imagery according to the

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CCIR video standard. Thus, images are obtained with a resolution of 720 × 576 pixels and a frame rate of 25 frames per second (fps). No optical filter is employed. GPS time inserters are used to stamp time information on every video frame with an accuracy of 0.01 s. In addition, f/3.3 focal reducers manufactured by Meade are also used in order to increase the lunar surface area monitored by these devices. Major lunar features are easily visible in the earthshine and so these can be used to determine the selenographic coordinates (i.e., latitude and longitude on the lunar surface) of impact flashes. In 2013 we installed an additional telescope at La Hita Astronomical Observatory, in central Spain (latitude: 39.56833°N, longitude: 3.18333°W, height: 674 m above the sea level). This Newtonian telescope also employs a Watec 902H Ultimate camera and has a diameter of 40 cm.

The data acquisition and reduction pipeline is summarized in Fig. 1. As can be seen, the video stream must be digitized in order to analyze the images later on. The video footage is stored on a multimedia hard disk. Then, they are sent to a PC workstation for further processing and analysis. Impact flashes are very short in duration (most of them are contained in just one or two video frames). So, their identification by eye is not practical and computer software is required to automatically detect impact candidates. With this aim we developed the MIDAS software (Moon Impacts Detection and Analysis Software) (Madiedo et al., 2010). This package, which is also employed for data manipulation and reduction of confirmed flashes, is described below.

2.1. The MIDAS software

The MIDAS software was mainly developed to process live video streaming and also AVI video files containing images of the night side of the Moon in order to automatically detect flashes produced by the impact of meteoroids on the lunar surface.

One of the advantages of this software is its ability to perform different tasks simultaneously. Thus while the impact flash identification process is in progress, the user can view, edit, and even analyze impact suspects previously detected by MIDAS. The main kernels and features of this package are explained below.

2.1.1. Video pre-processing

In general (Fig. 1), the source AVI video files need to be pre-processed before performing the flashes identification procedure. For instance, since our cameras generate interlaced video it is convenient to de-interlace it. In this way, typical undesired artifacts produced in the images by the video interlacing technology are removed. Video deinterlacing is also particularly useful when the photometric analysis of impact flashes is performed, as explained below. During the

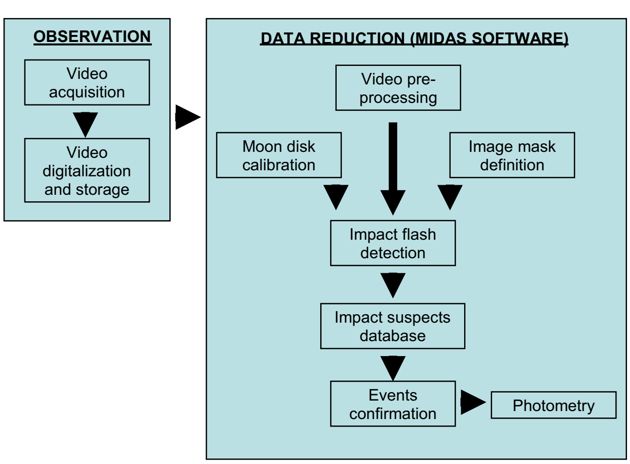

Fig. 1. Summary of the lunar impact flash detection and analysis process.

deinterlacing process, the software extracts both interlaced video fields (top and bottom) and generates another AVI file where these fields are included as independent frames placed one after the other. This automatically doubles the frame rate of the original video rate. In our case, since CCIR cameras are employed, we go from 25 to 50 fps.

Video pre-processing also addresses some issues that may interfere with the impact flash detection process and, specifically, with the detectability of fainter flashes. With this aim, over 20 images and video processing filters have been implemented in MIDAS. Thus, for instance, the significant amplification of signal of our CCD video cameras (up to 60 dB according to the manufacturer's specifications) can give rise to a large number of false detections, and different approaches can be employed to address this issue. For instance, images can be smoothed by MIDAS by means of a median filter, which averages every pixel according to the brightness of the surrounding pixels within a given user-specified radius. One of the drawbacks of this method is that it gives rise to blurred images. Besides, it poses some difficulties to the detectability of fainter flashes, since these events appear in very small pixel clusters whose brightness is significantly reduced in the resulting images when these are averaged with the less-luminous surrounding pixels. Video reduction to 2:1 size is an alternative useful technique implemented in MIDAS for image smoothing (Cudnik, 2009). According to this technique, both the width and height of each video frame are halved. When resampling the video to the new size, the intensity of each pixel in the output frames is calculated by applying a cubic spline interpolation filter to the intensity of the closest 16 source neighbor pixels (Keys, 1981). The main benefits of video reduction to 2:1 size are that image noise is decreased and that the video processing time is significantly reduced: the total number of pixels to monitor and so also the processing time decreases by a factor of 4. When employing this video size reduction technique it should be taken into account that, since impact flashes cover more than one single pixel in the images, these features do not disappear during the 2:1 reduction process and so these can still be easily identified in the resulting video. However, the so-called temporal smoothing has proven to be a more efficient method to deal with false positives arising from noisy images. This method, which produces sharper images, applies a transformation filter to the video file, so that each frame is substituted by a weighted composition of m frames around it. In particular, the temporal smoothing technique implemented in MIDAS employs the following equation:

$$I_n^{out}(x,y) = \frac{\sum_{i=n-m}^{n+m} I_i^{in}(x,y)\cdot W(i)}{\sum_{i=n-m}^{n+m} W(i)} \quad (1)$$

where $I_n(x, y)$ is the intensity (pixel value, ADU) for the pixel located at the position (x,y) in frame n. The weighting function W employed by MIDAS is given by

$$W(i) = \max\left\{0, \alpha - \frac{\left|I_i^{in}(x,y) - I_n^{in}(x,y)\right|}{2^\beta}\right\} \quad (2)$$

In Eq. (2), α and β are together with parameter m in Eq. (1), the free user-selectable parameters of the temporal smoothing transform. The size of the window around each video frame (i.e., the number of frames taken into account to smooth each frame) is given by the parameter m. As can be seen, Eq. (2) assigns a larger weight to the central frame in this window and yields smaller contributions for adjacent frames. However, the larger is β, the stronger is the contribution of adjacent frames with respect to the central one. Another consequence of Eq. (2) is that if the pixel luminosity of any adjacent frame with respect to the central one is too large (so that $W(i)$ yields a negative value), the contribution of this adjacent frame is zero since $W(i)$ must be always set to 0 in that case. Then, it is easy to notice that the parameter α is related