Detection of Lunar Impact Flashes using maximum-based image stacking

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ABSTRACT

The detection of meteoroid impacts on the lunar surface provides critical constraints on the meteoroid flux in the Earth–Moon system and informs risk assessments for future lunar missions. Currently used detection software packages in ground-based lunar impact research primarily rely on analysis of individual image pixels, searching for statistically significant deviations in space or time domain that can be associated with Lunar Impact Flashes (LIFs).

In this work, we present an alternative detection method based on *maximum-value image stacking*, very well suited to highlight impulsive, localized brightness increases associated with lunar impact events. Unlike traditional averaging techniques, the maximum stacking algorithm retains peak intensity values across image sequences, enhancing the visibility of transient phenomena.

We apply the method to real observational datasets recorded during a period of particularly high lunar impact rate (the Geminids meteoric shower peak on December 13–14) and demonstrate its ability to identify impact candidates. Comparative analysis shows that maximum-based stacking improves detection probability for brief and weak events while maintaining computational simplicity. This technique represents a complementary tool for lunar impact monitoring and can be readily integrated into existing detection pipelines.

Note. This paper was completed on December 31, 2025.

1 Introduction

Meteoroid impacts on the lunar surface produce short-lived optical flashes detectable by ground-based telescopes, with typical durations in the order of 0.1 s. These observations, usually performed on the non-illuminated side of the Moon to ensure sufficient contrast, provide valuable constraints on the size–frequency distribution of impacting bodies and contribute to the understanding of impact processes on airless planetary surfaces.

Monitoring systems such as ALFI[1] and LunarScan have significantly increased the number of reported LIFs. Their detection strategy is based on the analysis of statistically significant brightness deviations in time or space domain for individual pixels in the image frames. However, false positives caused by detector artifacts (hot pixels), cosmic rays, or satellite streaks frequently occur, while faint or short-lived events may remain undetected.

In this paper, we demonstrate how an alternative image-processing approach based on *maximum-value stacking* is particularly well suited for the detection of transient and impulsive events such as LIFs.

2 Data

The analysis was conducted using real lunar observational datasets acquired during the 2025 Geminids peak (13–14 December). Observations were performed using a 0.25 m f/5.6 Ritchey–Chrétien telescope equipped with a high-sensitivity sCMOS detector. The resulting field of view was approximately $27' \times 27'$, covering nearly the full lunar disk. No optical filters were used in order to maximize sensitivity to faint impact flashes.

The datasets consist of time-ordered video sequences, each 10 minutes long for convenience in data handling, acquired at a frame rate of 20 fps (exposure time 50 ms) to ensure proper time resolution. Processing included image registration to correct for lunar motion and stacking based on

[1]ALFI project webpage: `https://users.aber.ac.uk/atc/alfi.htm`

the maximum pixel value. No dark-frame subtraction or flat-field correction was applied.

3 Methodology

3.1 Maximum-based image stacking

Let $I(x, y, t)$ represent the intensity of pixel (x, y) at time t within a sequence of N registered frames. The maximum-stacked image $I_{\max}(x, y)$ is defined as:

$$I_{\max}(x, y) = \max_{t \in [1,N]} I(x, y, t) \quad (1)$$

This operation preserves the highest recorded intensity at each pixel location, effectively retaining short-lived brightness enhancements associated with lunar impact flashes. In contrast, mean-based stacking, commonly used in astronomical imaging, tends to attenuate impulsive signals while improving the signal-to-noise ratio (SNR).

Image registration and maximum-based stacking were performed using Astrosurface software package[2]. The stacking procedure usually decomposes the image into sections (alignment points) which are aligned and stacked separately. It is very important for the success of the procedure that each alignment point uses the same image set for stacking; in other words, the "Multi-point" alignment shall be avoided, and only the "Global" must be used.

3.2 Workflow

The detection workflow consists of the following steps:

1. Feeding of the image sequences to the stacking software;
2. Image alignment with sub-pixel accuracy;
3. Maximum-value stacking over the full video duration;
4. Spatial and photometric analysis to reject single-pixel noise events and other artifacts;
5. Temporal verification using the original image sequence.

[2] Astrosurface software homepage: `https://astrosurface.com/page-it.html`

The output of step 3 is a single stacked image of the lunar night side, in which detector artifacts, cosmic rays, and candidate impact flashes are simultaneously present. The filtering steps (4–5) are currently performed via visual inspection; discriminating a potential LIF from artifacts is indeed quite easy for the trained eye. Given the known spatial location of candidate events, their temporal occurrence is determined by manual review of the corresponding video footage. It should be pointed out that knowledge of the exact flash location greatly reduces the amount of manual work required.

4 Results

Figures 1 and 2 show representative maximum-stacked images produced using the proposed method (output of step 2; see Section 3.2).

The stacking process enhances transient artifacts such as hot pixels and cosmic ray tracks, which appear as single-pixel or elongated linear features. Despite the presence of these false detections, localized transients consistent with lunar impact flashes are clearly visible. Their point spread function is approximately Gaussian, in contrast to the flat profiles of detector-related artifacts. It must be emphasized, furthermore, that the stacked image has a SNR higher than that of the individual frames, allowing the application of high-pass filtering to further enhance the visibility of fine details.

5 Discussion

Maximum-based stacking significantly improves sensitivity to weak and short-lived lunar impact flashes, at the cost of enhancing sporadic noise sources. Cosmic ray events typically produce elongated linear structures, while detector artifacts remain fixed in detector coordinates and may appear anywhere in the frame, including sky background regions. In contrast, genuine lunar impact flashes appear as compact features with a stellar (Gaussian) point spread function, internal to lunar surface and persisting for one or a few consecutive frames.

The proposed method is therefore best employed as a candidate-generation stage within a multi-step detection pipeline. On the other side, some current limitations include:

1. the need for manual review of image se-

Figure 1: *Maximum-stacked lunar image obtained from a sequence of registered frames. Numerous point-like and linear artifacts caused by hot pixels and cosmic ray events are visible, while a localized transient consistent with a lunar impact flash is clearly detectable in the Mare Crisium region. A slight high-pass filtering has been applied for clarity.*

quences to determine the exact timing of candidate events;

2. sensitivity to tracking inaccuracies, which can degrade image alignment and stacking quality (see Fig. 3);
3. in bright areas (such those close to lunar terminator) the flashes detection can be difficult, due to maximum-based stacking procedure and lowered constrasts.

6 Conclusions

We discussed how a maximum-value image stacking technique can be used for the detection of lunar impact flashes and demonstrated its effectiveness using real observational data. The method proved successful as a support of existing LIF detection softwares in searching for additional impact candidates.

Future improvements will focus on automation of the manual work involved in filtering real impact events, as a stand-alone software package or as integration implemented in existing programs.

References

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Figure 2: *Maximum-stacked lunar image obtained from a sequence of registered frames. Close to lunar eastern limb, a candidate LIF is clearly visible among various artifacts (hot pixels, satellite streak).*

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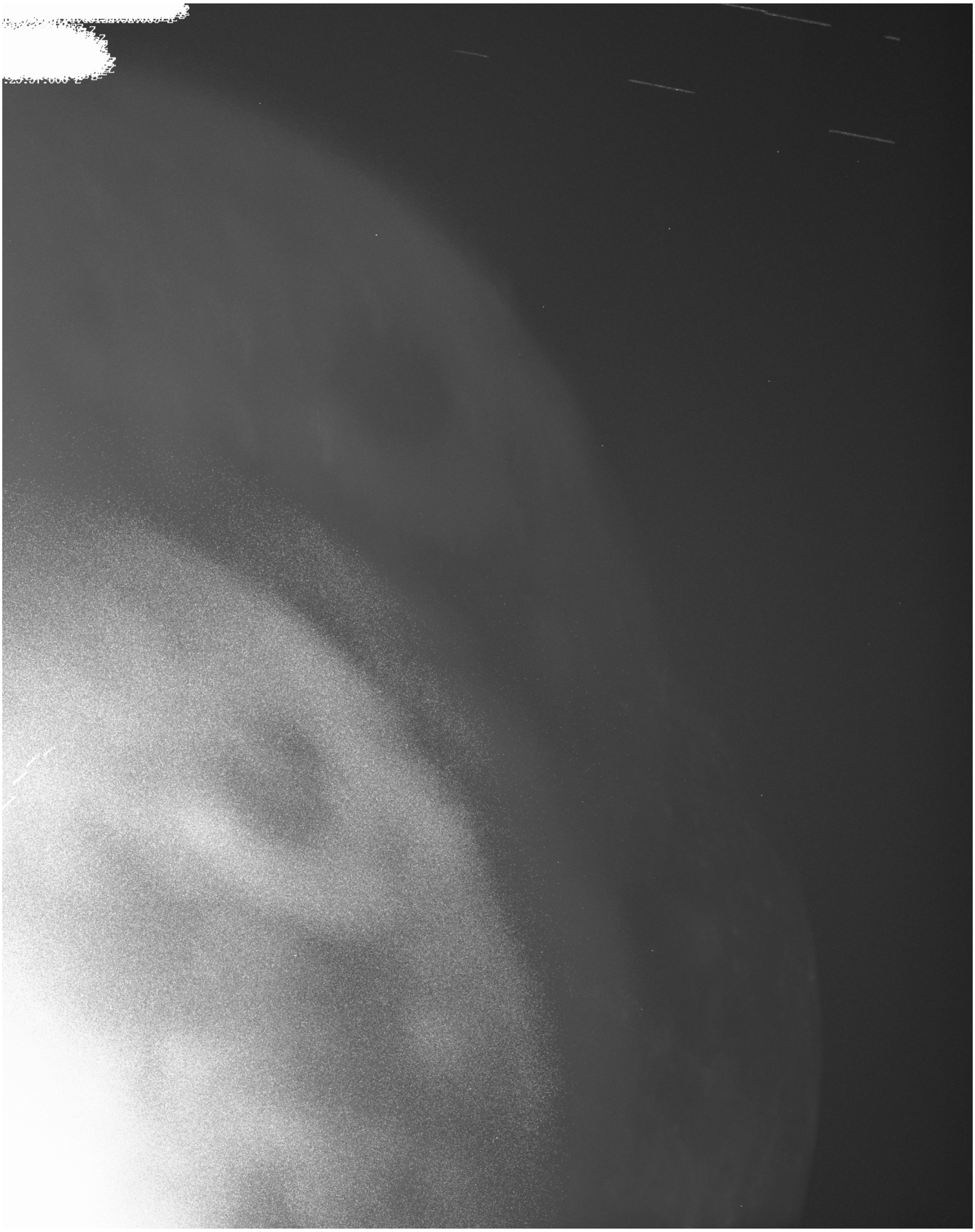

Figure 3: *Maximum-stacked lunar image obtained from a sequence of registered frames affected by tracking inaccuracies. Misalignment results in duplicated lunar features and prevents reliable detection of localized transients.*