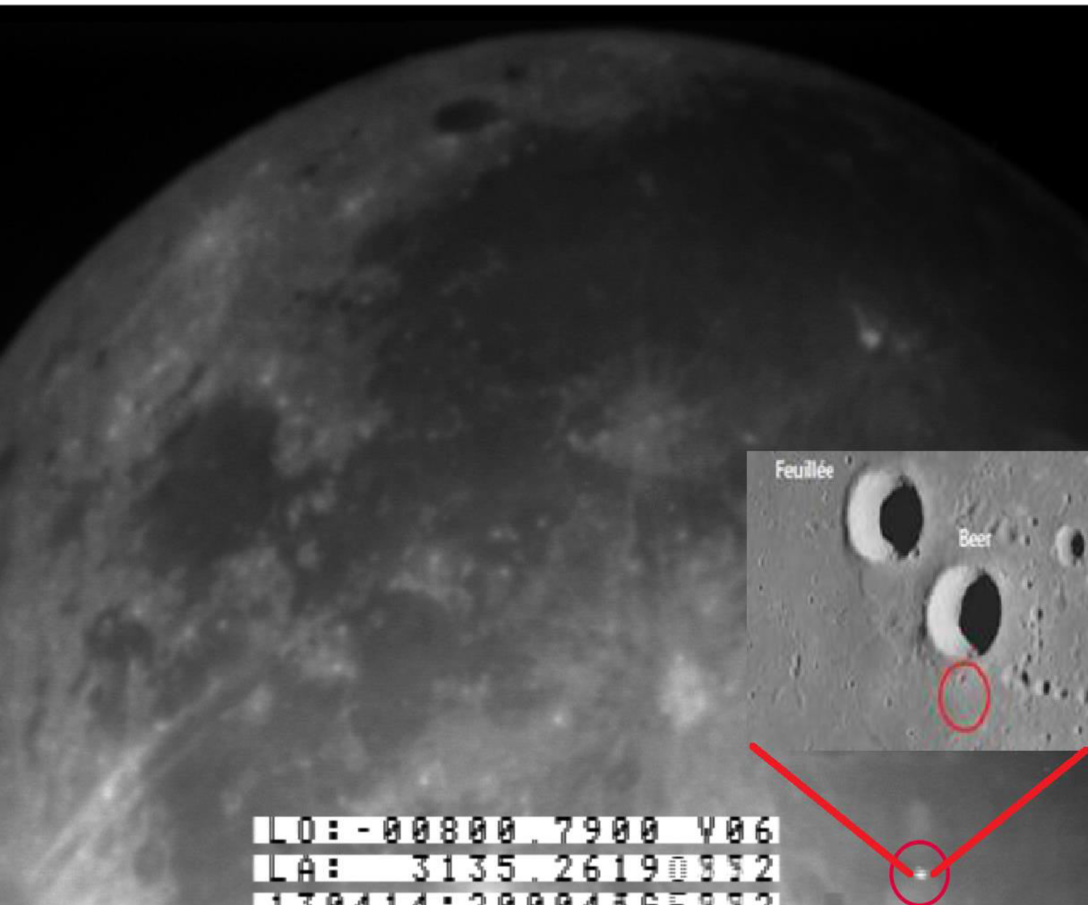
Lunar Impact workshop ESTEC ESA Center Noordwijk, 2-3 June, 2015

Localization of lunar impact flashes : implications for lunar seismology



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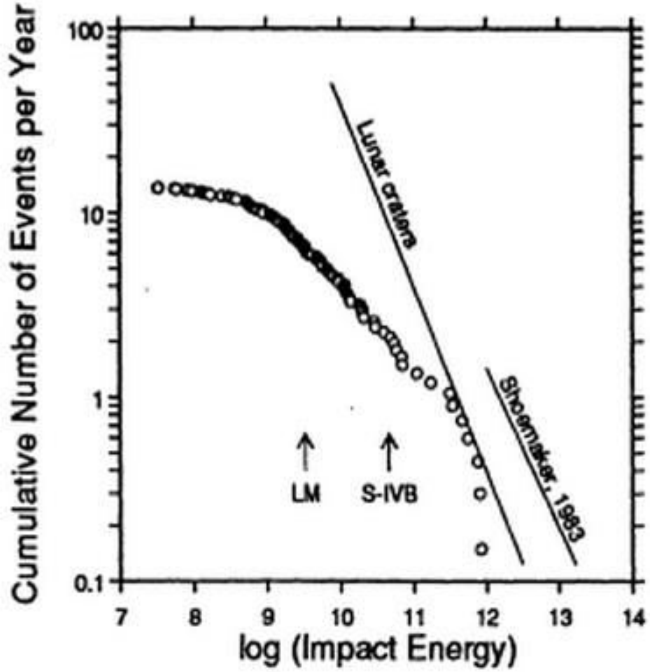
Seismically detected meteoroids impacts on the Moon

- Significant part of progresses in understanding the lunar interior structure are based on **Apollo lunar seismic network data**.

- (Oberst and Nakamura, 1989) : A New Estimate of the Meteoroid Impact Flux on the Moon from 91 seismically detected meteoroids.

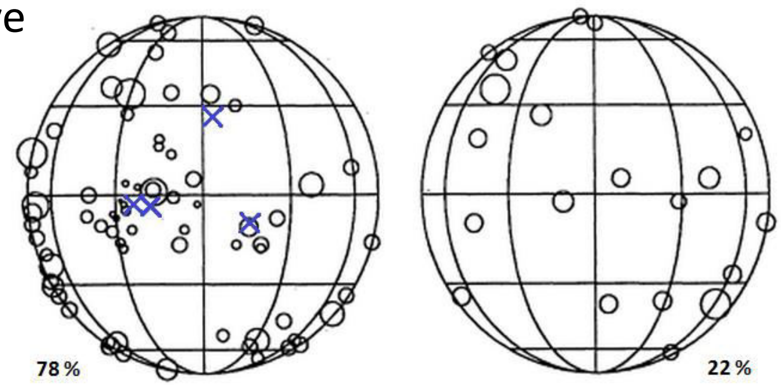
  Energy range : **$3\ 10^{11}$ J < E < 10^{12} J**

- (Oberst and Nakamura, 1991) : the 1974 Leonid shower produced signals consistent with impacts of meteoroids in the mass range from 0.1 to 1 kg.



- Only 10% of detected sources provides accurate arrival-time readings for their locations.

- Most event are located on the western lunar hemisphere. Is this bias is simply related to the fact that those events are closer to the least sensitive station; "the westernmost Apollo12" only, or it is to consider also a near side/far side asymmetry amplified by the Earth's gravitational field.

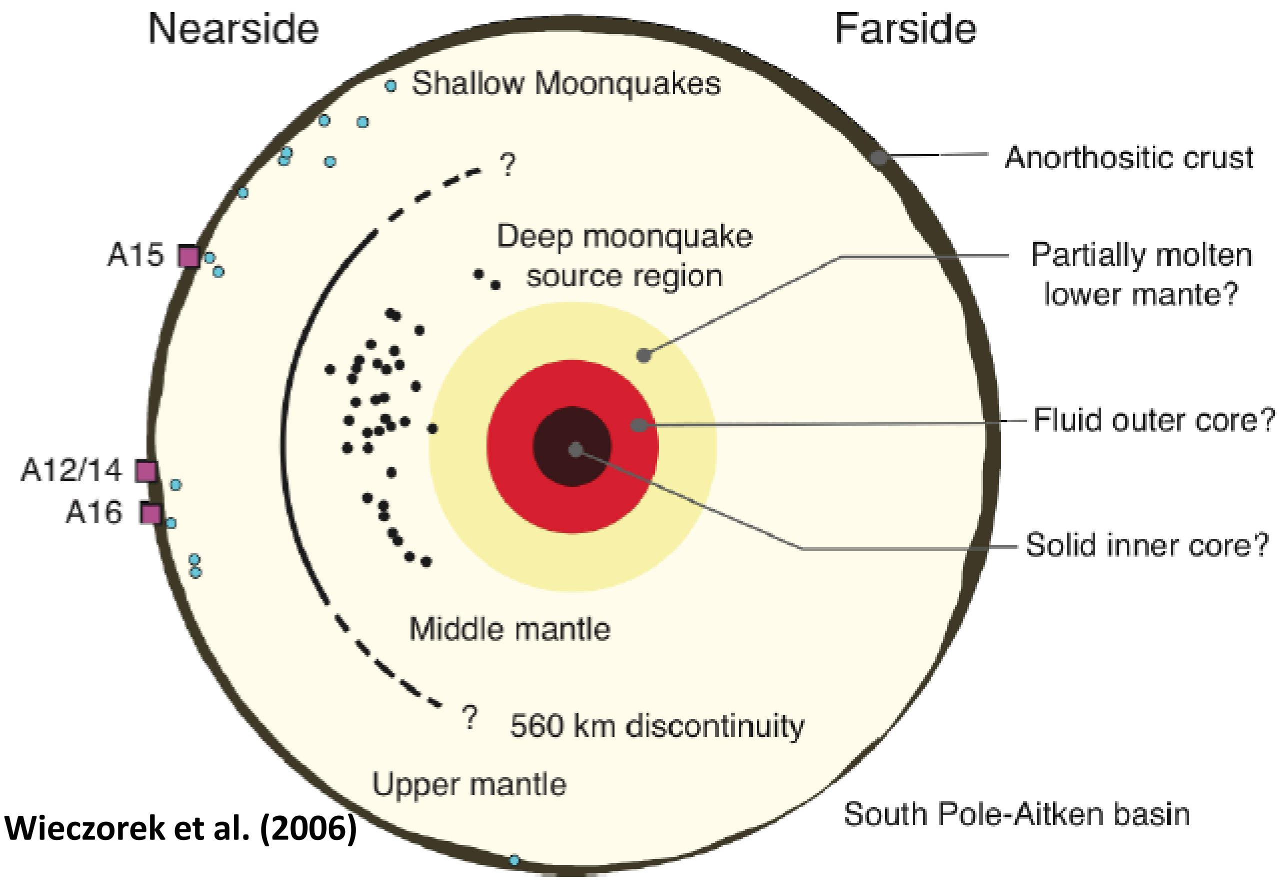


looking forward to future far side stations

Several points of interest expect their clarifications from future lunar exploration

Cardinal questions "?" :

- Uniform crust thickness (30 to 60 km). (Lognonné and Johnson 2007)
- A possible discontinuity at ≈ 560 km below the surface.
- The structure below the deep moonquake source region is weakly constrained.
  - The existence of a molten zone above the core (Weber et al. 2011, Garcia et al. 2011)?
  - Structure of Moon's liquid core and solid inner core ?



Wieczorek et al. (2006)

Lunar flashes and Seismic waves

- Lunar flashes provide independent positions and times of the seismic source, leading to improvements in the determination of the crustal structure(Chenet et al.,2006; Yamada,R et al.,2011)

- The space/time location of the impact flashes allows to reduce the uncertainty on the seismic source location.

- Such data becomes indispensable in the case of a one-seismometer mission.

- The independent space/time determination of the seismic source, allow to investigate the internal structure using only a single seismic station rather than two or three.

- In particular, the timing of the impact is determined at **0.01 s** of uncertainty, better than **0.05 s** which is the usual sampling rate of broadband seismometers,

And the depth of the seismic source is known : **Impact localization**

- Because impacts are more easily detected by seismometers at short epicentral distances these combined seismic wave/flashes observations would strongly constrain the crustal structure.

- In addition, the estimate of source energy allows to infer intrinsic attenuation of seismic waves and its variations.

Precise positioning of the flash at the surface of the Moon

- Flashes are observed on the non-illuminated fraction of the lunar disk

  → Video frames are featureless, precluding the direct identification of lunar surface features.

- Precise astrometry would be necessary and would require modeling of the lunar configuration at the time of observation and of the geometric distortion of the optical system.

  → Our observation observations are performed soon after or before the new Moon, the Earthshine is luminous enough to develop an alternative approach.

1) First step (stacked images) : Increase the signal to noise ration and decrease the resolution due to changes in observation conditions and atmospheric turbulence.

Precise positioning of the flash at the surface of the Moon

- Due to the non-perfect tracking of the lunar movement, slight changes in the observation geometry are possible when stacking the images.

- The sub-pixel shift of each image relative to the first frame (base frame) was determined by fitting the correlation peak obtained in the Fourier space to a 2-dimensional Gaussian
  Schaum and McHugh (1996) and Baratoux et al. (2001).

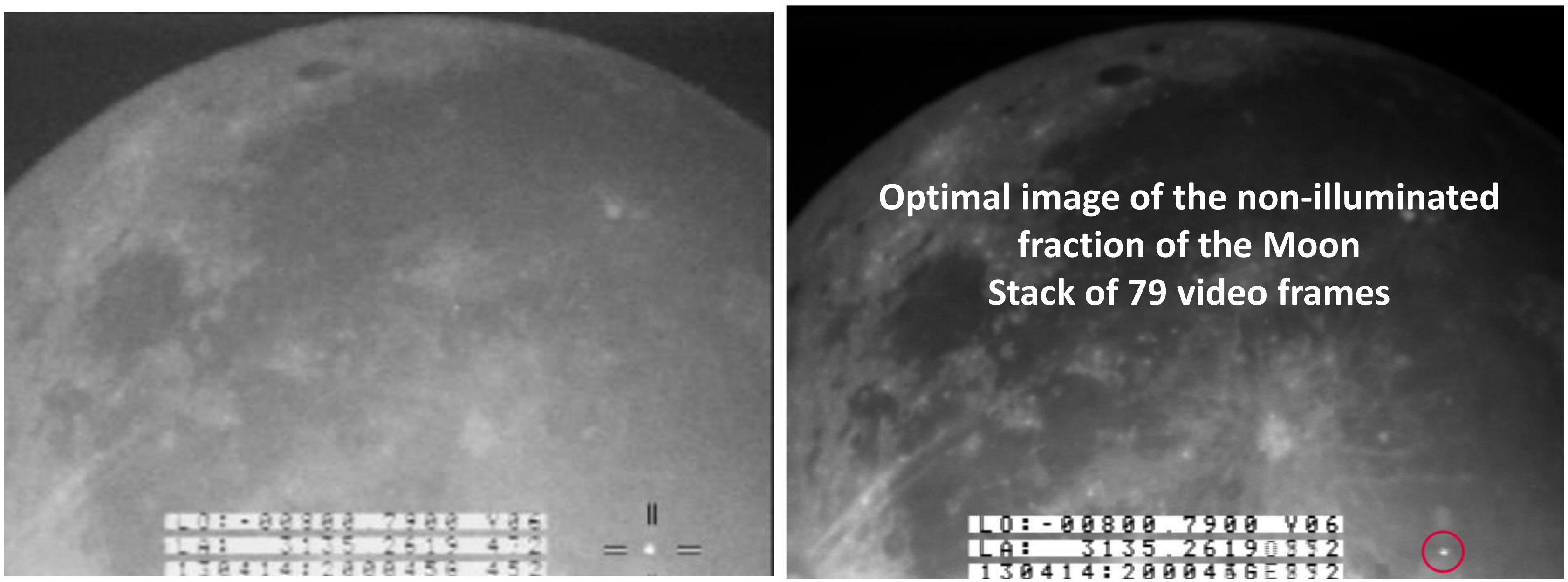


Illustration of the benefit of stacking images for the identification of surface features in the Moon that are illuminated only by the Earthshine

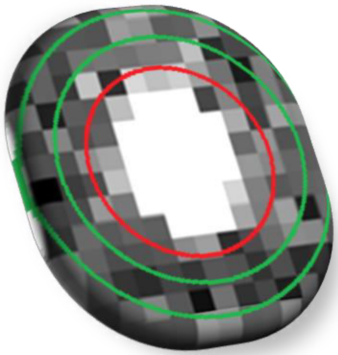
→ Smaller-scale lunar features are easily identified after application of the procedure.

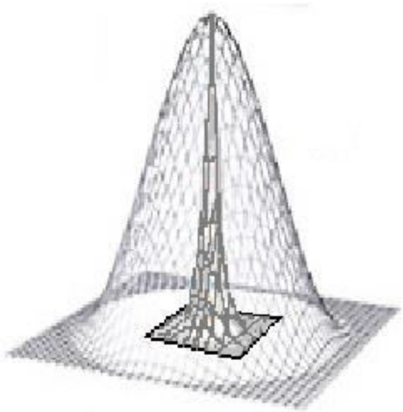
Precise positioning of the flash at the surface of the Moon

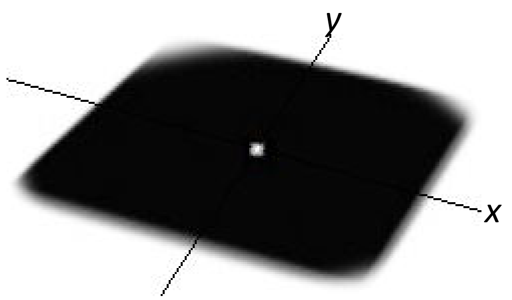
2) Second step (fitting the signal)

• The accuracy of the positioning is limited by the size of the flash, which is usually spread over several pixels.

→ To increase further the positioning, the signal of the flash is fitted to a 2-dimensional Gaussian firstly for each frame (previously shifted to the base image) where the flash is present and to the stacked frames.







Raw pixel data   Gaussian fit function   Localized flash

• The barycenter of the flash is given as the rounded to the nearest integer of the average centers of the 2-dimensional Gaussian functions.

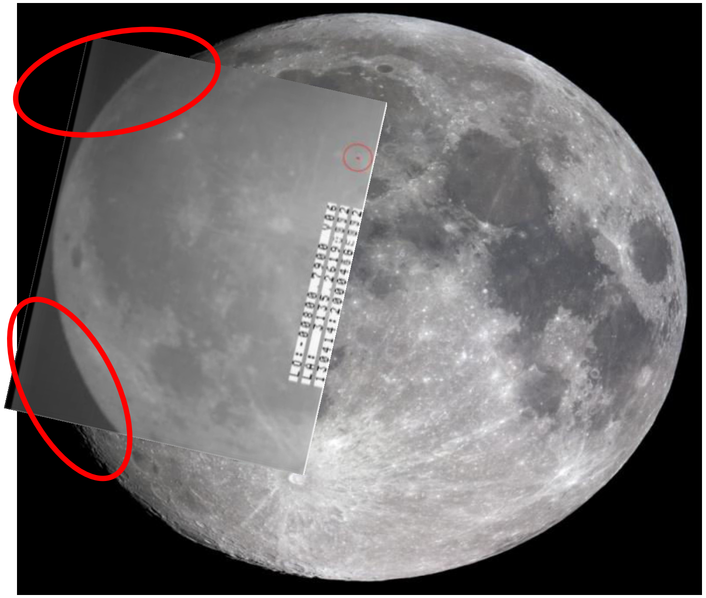
Precise positioning of the impact at the surface of the Moon

→ An image with the flash represented as a single illuminated pixel is then generated.

- We note that a possible mismatch may remain between the barycenter of radiation and the actual position of the impact.
- This possible shift would result from the viewing angle of the expanding vapor plume and is maximum close to the limb, where image resolution also strongly decreases.
- The two flashes reported in this study are optimally situated on central region of the lunar disk and this effect is neglected here

3) Third step (stacked images)

- Once the optimal image of the non-illuminated fraction of the Moon has been produced, tie-points are manually selected with an image of the full-Moon.
- A ground-based image of the Moon (4304 9 4307 pixels) obtained from telescopic observations was selected for this purpose.

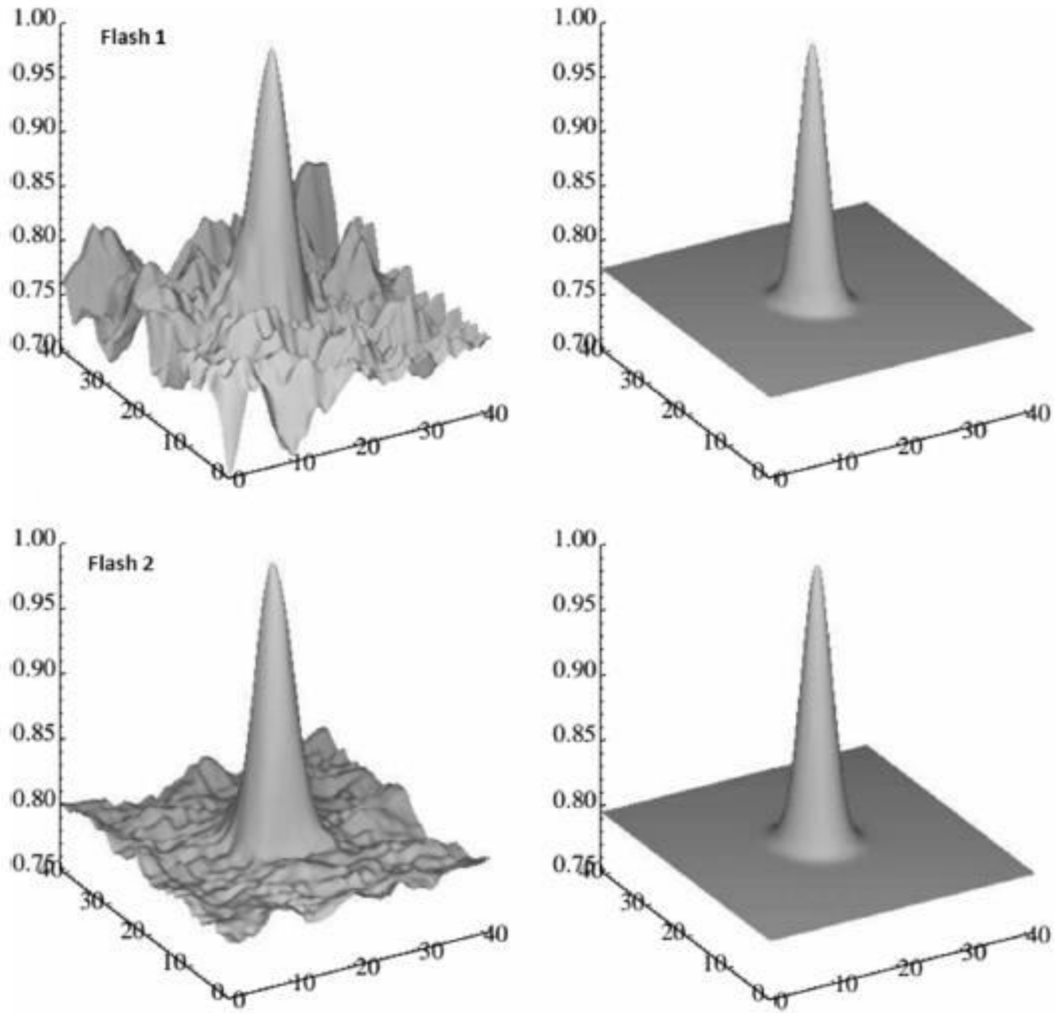


- Ties points are used to perform a rotation, change of scale and translation transformation of the stacked frames and of the frames on which the flash occurs (converted into a single-pixel flash) into this reference geometry.

- Some mismatches may be related to the lunar liberation movement. The reference image must be chosen carefully

Precise positioning of the flash at the surface of the Moon

- Application



Left : Shade surface representation of the intensity of the peak corresponding to the flash 1 and 2.
Right : corresponding Gaussian fit of the peak used for the sub-pixel determination of the flash position at the moon surface .

Precise positioning of the flash at the surface of the Moon

- Application

Video frame reference	Sample	Line
Flash1		
sf00030	100.51	195.22
sf00031	100.11	196.35
Stacked frames	100.44	195.56
Flash 2		
sf00107	540.56	23.33
sf00108	540.48	23.33
sf00109	540.61	23.04
sf00110	541.23	23.22
Stacked frames	540.57	23.26

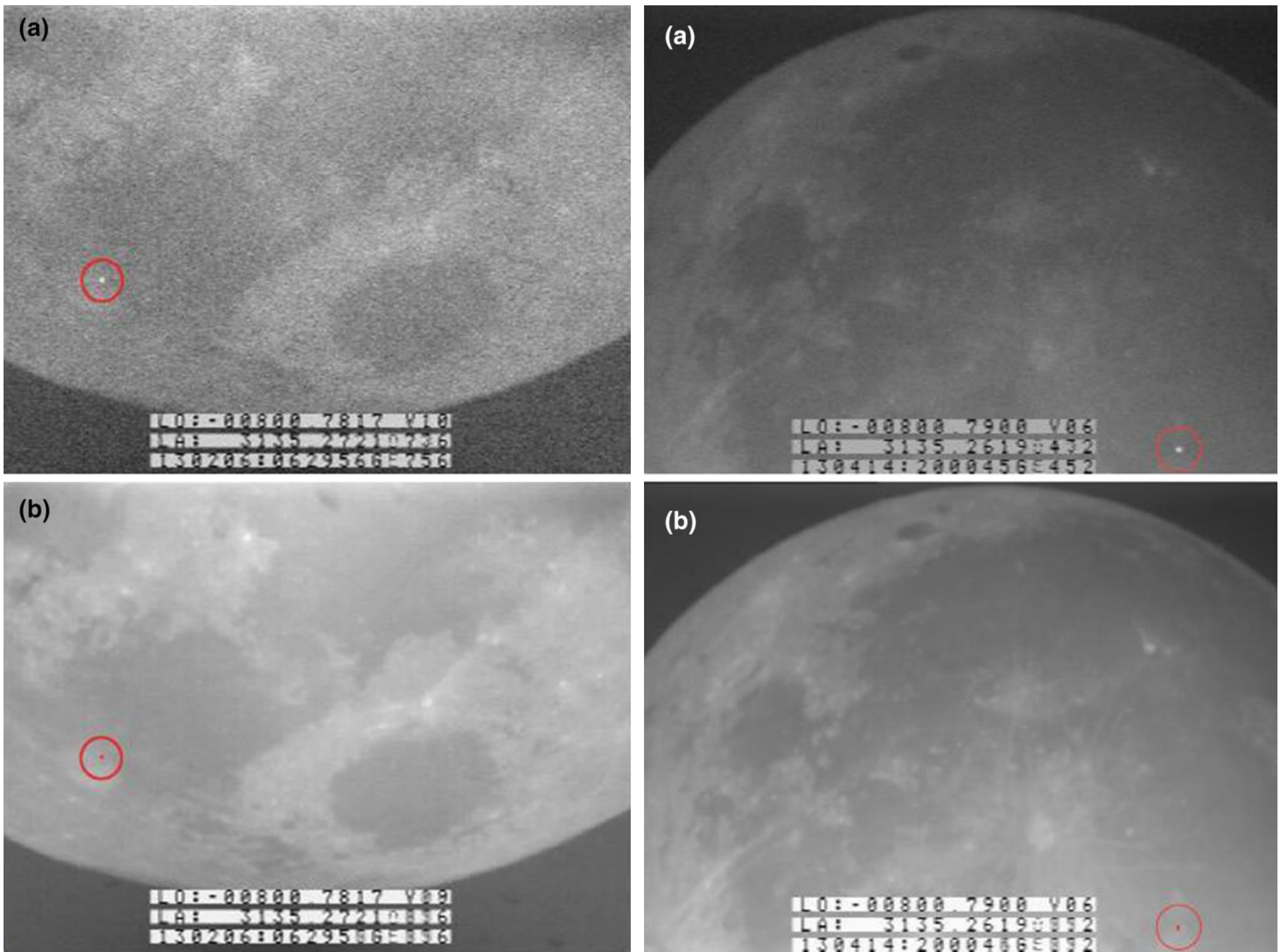
The estimated pixel coordinates on the video frames of the lunar impact flashes 1 and 2

Differences in positioning remain at the sub-pixel level. This confirms that the uncertainty on the position of the flash is better then one pixel

Precise positioning of the flash at the surface of the Moon

- The video frames where each flash reaches its maximum intensity and the stacked images on which the position of flashes, as given by the center of the Gaussian function, is represented by a single illuminated pixel (in red).

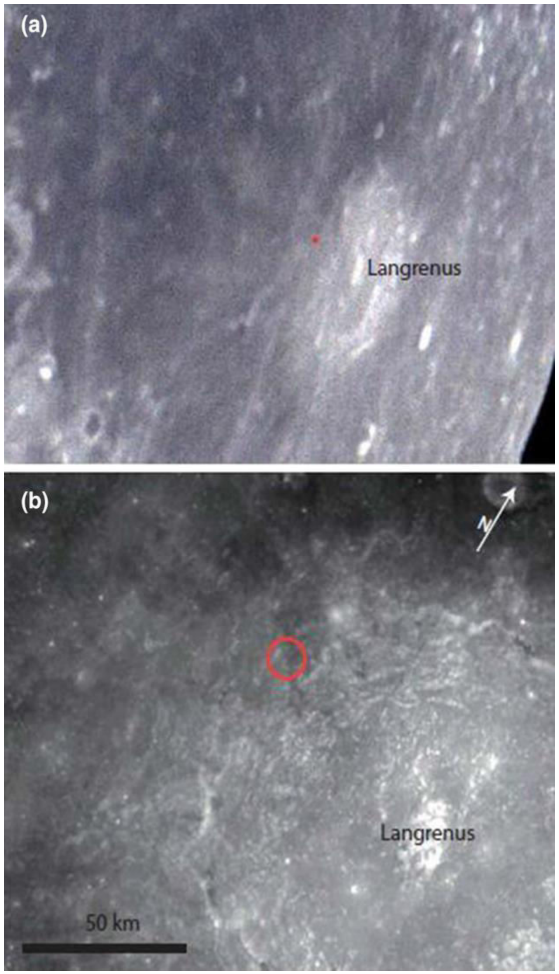
FLASH 1 | FLASH 2



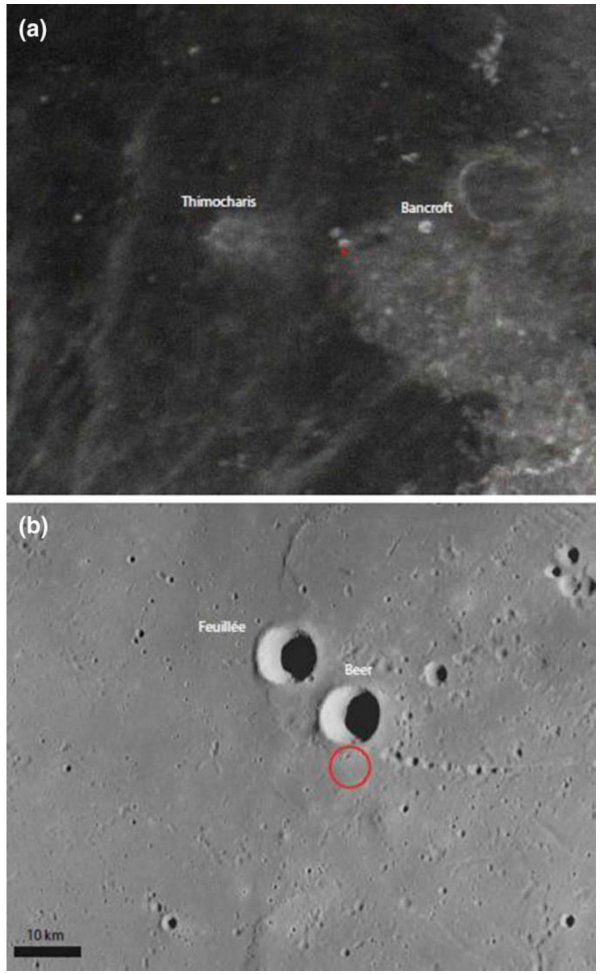
Precise positioning of the flash at the surface of the Moon

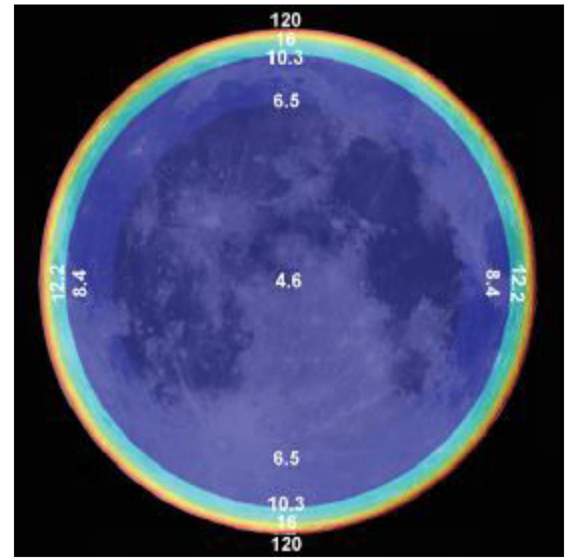
- Final comparison with this pixel positions on the reference image with high-resolution images of the Moon allows us to determine precisely the position of the flash (Figs. 11 and 12).

FLASH 1



FLASH 2





Average spatial resolution on the Moon surface

	Flash 1	Flash 2
Impact coordinates	08.15° ± 0.15°S 59.1° ± 0.15°E	26.81° ± 0.15°N 09.10° ± 0.15°W

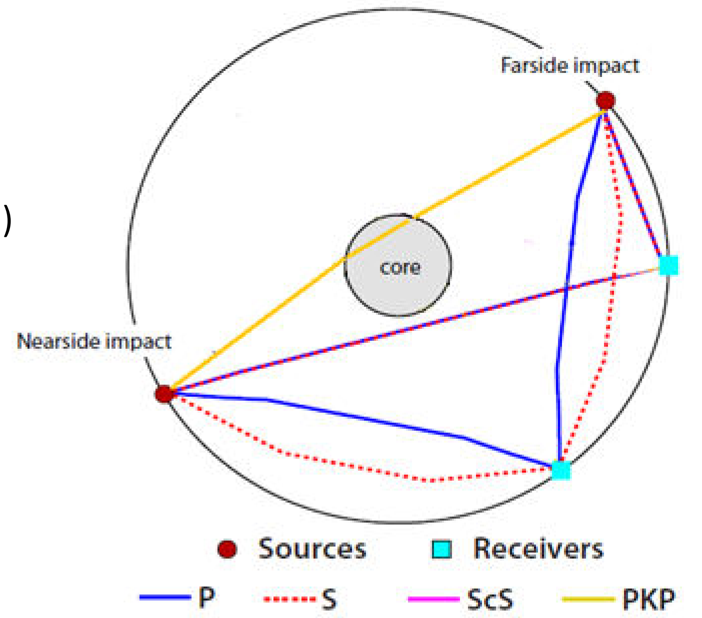
5 km of uncertainty

Precise positioning of the impact at the surface of the Moon

Result :
Seismic body wave travel time uncertainties due to 5 km impact mislocation, as a function of seismic phase and epicentral distance (in degrees).

Body wave travel time errors computed in VPREMOON model (Garcia et al. 2011)

Body waves	10° (s)	30° (s)	60° (s)	90° (s)	120° (s)	150° (s)	180° (s)
P	0.65	0.62	0.52	0.42	0.3	0.15	–
S	1.12	1	0.92	0.72	0.42	0.25	–
ScS	0.03	0.04	0.15	0.2	0.25	0.3	–
PKP	–	–	–	–	0.13	0.11	0.03



→ For a **5 km** epicentral distance uncertainty, the error induced on the travel times is a factor 6 smaller than the average 3 s travel time reading error ascribed to body wave phases detected by ALSEP Apollo seismological network (Gagnepain-Beyneix et al. 2006).

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