ARTIFICIAL LUNAR FLASHES AS AN USEFUL TOOL IN BENCHMARKING SMALL OPTICAL TELESCOPES

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Lunar Flashes (LFs) are considered as an efficient instant indicator of near Earth asteroids' activity. This phenomenon occurs when usually small meteoroid collides with Moon's surface triggering short living burst seen on the dark part of the Moon. Most of the LFs recorded from Earth have usually brightness between 7th and 9th magnitude. They are hard to observe close to terminator where due to atmospheric dispersion and internal stray lights the darkness of unilluminated part becomes too bright.
There are a few institutions specialized in recording of such events. They mainly use large mirror telescopes with high sensitivity cameras but the recent progress in sCMOS technology allows to apply such efficient cameras for detection of LFs with much smaller telescopes.

LF considered as transient event last only a fraction of a second, thus the time needed for downloading the image must be minimized thereby optimizing the time for lunar observation. The high number of short time exposures requires an efficient pipeline for on the fly checking if there are recorded events fitting LFs' pattern.
Recently some of the institutional observatories released the software dedicated to detection of LFs deployable also for smaller telescopes and commercially available sCMOS.
When the bright part of the Moon's affects the majority of the unilluminated surface the observations are withheld. These situations occurs about one week before and after the full moon but exact time in Moon's calendar depends on a few factors like local conditions (e.g. humidity) and the construction of the telescope. One of the major goals in LFs detection is to extend the observable time and record potential LFs as close as possible to the terminator.

In these tests we focused on four telescopes with different technical designs, apertures and budgets (see tab.1). We wanted to compare some basic results obtained during registration of artificial LFs generated on the screen of the computer. The results were then calibrated to get comparable numbers across the range of tested optics.

Telescope	**Orion Optics AG16**	**Celestron RASA 36**	**Takahashi TOA-150**	**Bresser Messier 152**
Construction	Newtonian w/ corrector	Rowe-Ackermann Schmidt Astrograph	Triplet Orto Apochromat	Petzval Achromat
Focal length (mm)	1520	790	1100	760
Diameter (mm)	400	356	150	152
FL/Diameter	3,8	2,2	7,3	5,0
Scale (arcsec/pixel)	0,80	1,54	1,10	1,59
FoV (arcmin)	25x16	49x31	35x22	51x32
Price (Euro)	14k	22k	15k	0,8k

Tab.1 Details of tested telescopes

Real-life LFs are observed very rarely (a few per month), therefore multifocal, objective tests would last for an unacceptable time. Additionally the various brightness and locations of LFs would complicate the assessment enormously. Taking account the limitations above we decided to perform the tests in repeatable, stable environment creating the simple testbed. An artificial Moon (AM) was constructed for purposes of these tests (see fig. 1 and fig. 2). AM is a software and a hardware hybrid.

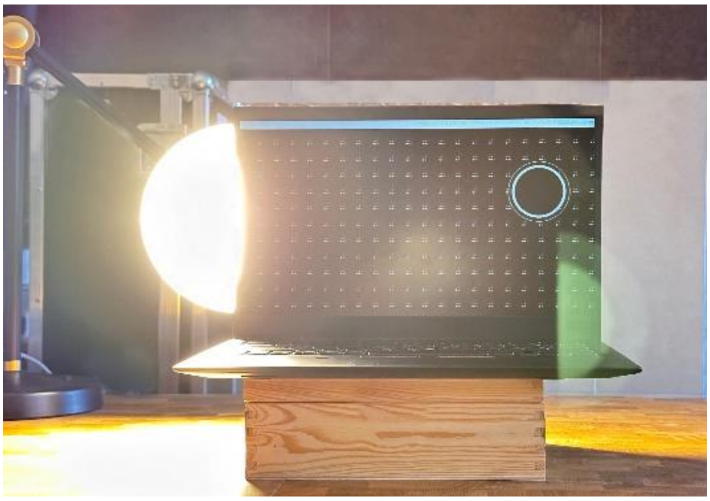

Fig. 1 Front view of artificial Moon

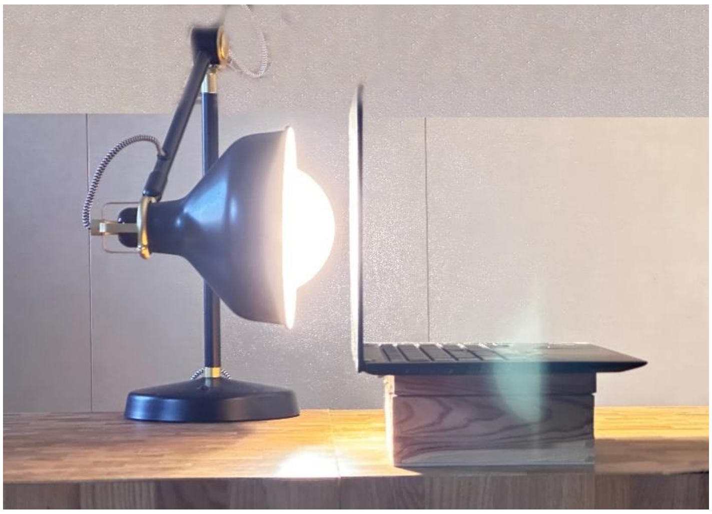

Fig. 2 Side view of artificial Moon

To simulate the bright part of the Moon we used a LED lamp, while to simulate the dark part we used the screen of a Lenovo X1 Carbon laptop (see tab. 2)

Artificial Moon	Brightness	Size
Bright part	LED bulb 21W, 2100 lumens	120mm diameter
Dark part	300 lits laptop screen	310x175 mm, 1920x1080 pixels

Tab. 2 Artificial Moon’s details

The lamp was placed behind the laptop simulating first and third quarter of the Moon’s phase in the way that lamp’s stream did not affect directly the screen.
6 mm -wide plastic frame of laptop’s screen separated lamp from active screen, which was placed 10 mm in front of the lamp.

In every setup we used the same sCMOS QHYCCD 174GPS camera (see tab. 3).

	Camera
Name	QHYCCD 174GPS
Sensor	SONY IMX174 CMOS
Pixel size	5.86um*5.86um
Pixel Area	1920*1200
Image Area	11.25mm*7.03mm

Tab. 3 Camera details

Initial assumption:

- For all three tests the distance between artificial Moon and the optics was 32 meters.
- For every telescope in the tests the data was obtained as an average values from five FITS images.
- The artificial Moon setup and camera settings were kept the same in all tests.
- Cameras gain was set on 0 in every exposure.
- As a universal unit representing the brightness measured on FITS images and used in this paper we used Analog To Digital unit (ADU). In the case of QHYCCD 174GPS the maximum value for ADU is 65504 and it indicates that the pixels are saturated.

The special pattern of events allowing to conduct three separate tests (A, B, C) on the laptop's screen was displayed with 0.9 Hz frequency. This dynamic display was programmed in Python (see fig. 3).

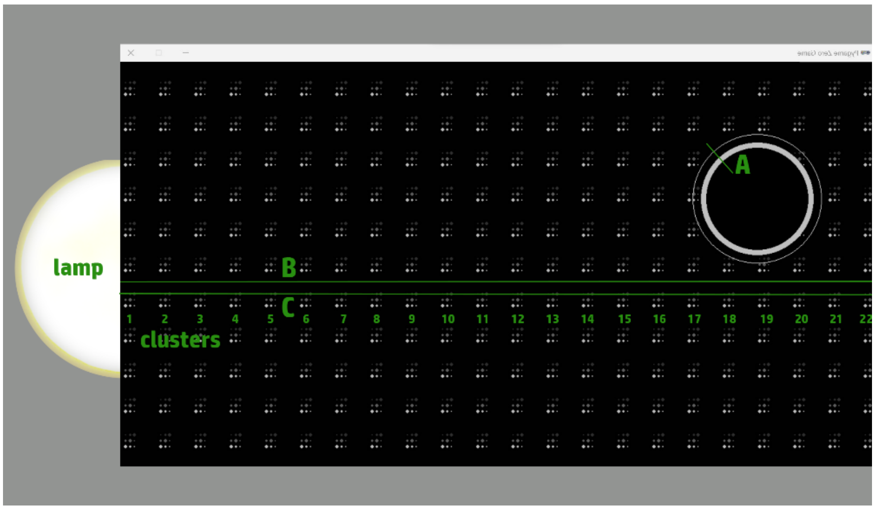

Fig.3 This figure describes where tests A, B and C were performed in the relation to the lamp- simulating the bright part of the Moon.

Test A:
Here we aimed to compare the signal to noise while recording short lasting events - blinking rings. With the period of 1100 ms for 150 ms we displayed consecutively four coaxial rings from the largest to the smallest. The display time for one ring is 40 ms whereas exposure time is slightly longer - 50 ms. From all frames in the series only those frames with adjacent rings (smaller and larger) were taken into account. This was made to confirm that measured middle ring is recorded in its full period (see fig. 4)

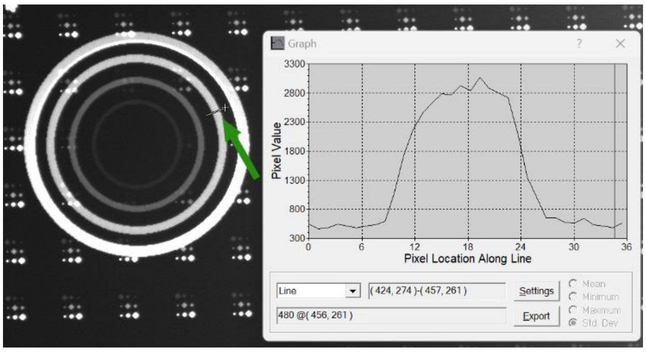

Fig. 4 Measured ring is situated 250 mm from the bright edge of the screen (terminator in artificial Moon) and thus very slightly affected by the lamp's light.

Rings' SNRs on images taken with all four telescopes were measured and shown next to 1/f-numbers for corresponding telescopes (see tab. 5 and chart 1.)

	AG16	RASA36	TOA150	BM152
SNR	12.57	22.57	7.84	10.07
f-number	3.8	2.2	7.3	5

Tab. 5 SNR values for rings and f-numbers

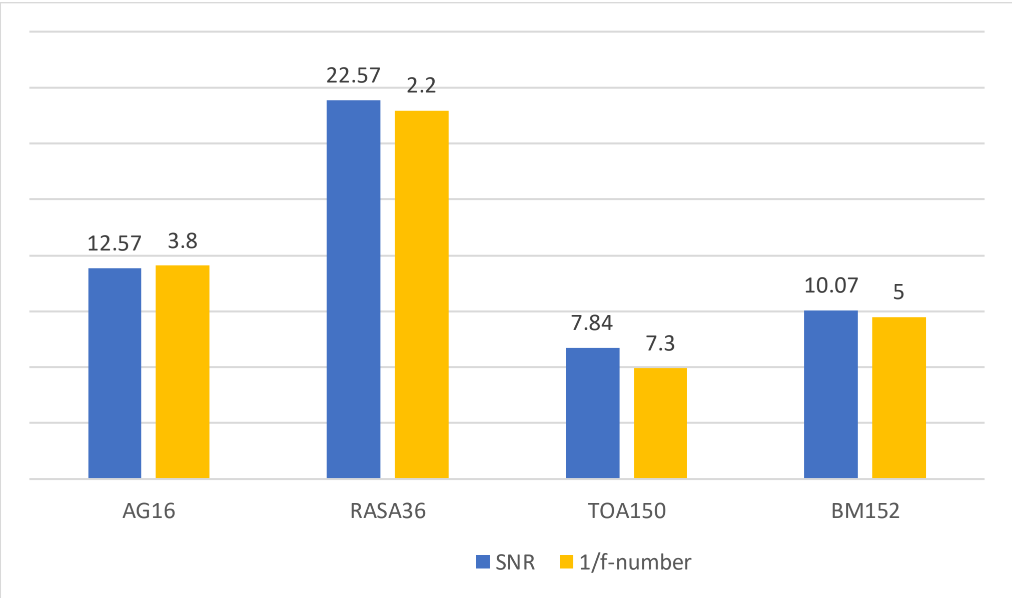

Chart 1. Rings' SNRs and 1/f-numbers for corresponding telescopes.
On top of the blue bars are measured SNR values and on the top of the yellow bars are f-numbers declared by producers.

On top of the blue bars SNR values are shown while on the top of the yellow bars indicate the f-numbers specified by the producers. It is interesting how neatly this two sources of data confirm relationship between them. The relations between measured SNR values is almost identic as the relations between 1/f-numbers.

In this first test we see that for short lasting events like artificial LFs the theoretical assumptions about telescopes performance are applicable. The highest SNR was obtained for the fastest RASA36 telescope. On other hand the lowest SNR value was recorded for the slowest TOA130 telescope.
Because the main goal of LF's observations is to record the greatest number of events the ability to detect the dimmest, with low SNR is highly desired. RASA36 telescope delivers the highest SNR for the same event.

Test B:
In this test we evaluated the changes in the background brightness across the screen from bright part of AM, close to terminator to the distant part of the screen.
We have observed, that there is similarity in the curves obtained with this method compared to the curves across the real Moon. This confirms that presented model of artificial Moon acceptably simulates the surface of natural satellite for these purposes (see fig.5).

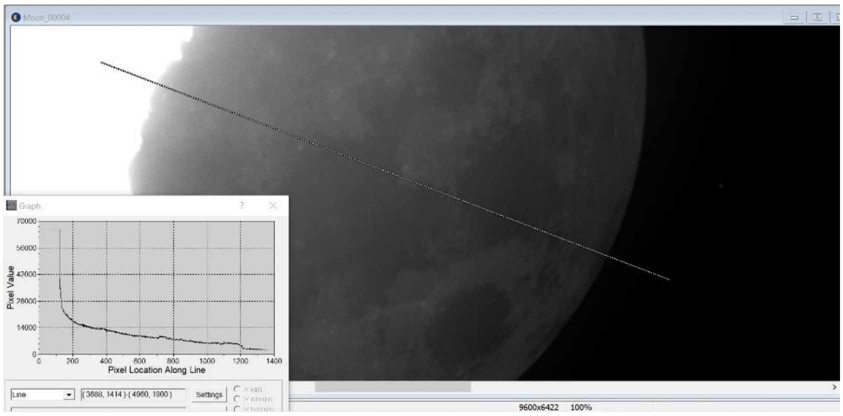

Fig. 5 Brightness curve across real Moon taken with TOA150

Due to different focal length of the scrutinized telescopes there are significant changes in the field of view and scale of AM. In case of two telescopes (AG16 and TOA150) the whole image of AM did not fit in one field of view. Therefore data from two fields were merged to present it on an one chart. Data from the four telescopes were scaled to the size of one “universal telescope” (see chart 2)

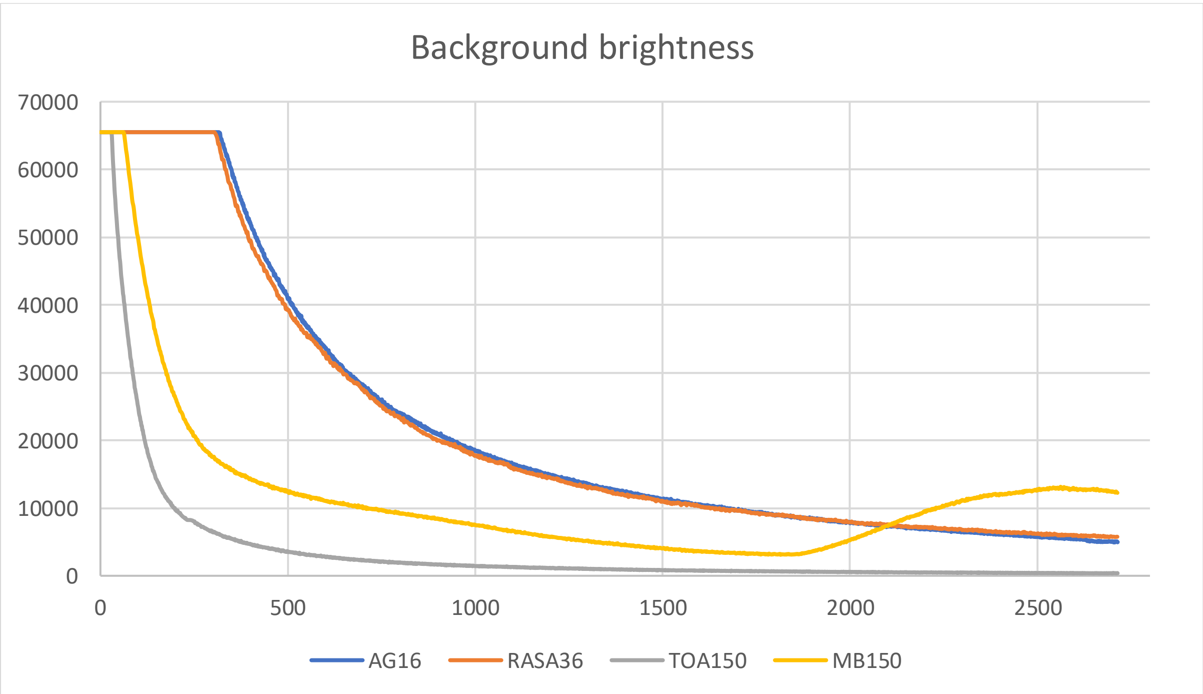

Chart 2.Background brightness across the line from the lamp to the far edge of the screen. The left part of the chart shows maximal, saturated values (ADU 65504). Data from four telescopes were scaled to fit into the X axis. On Y-axis are ADU values.

The left part of the chart, with high flat values presents the zone where the pixels are saturated by intensity of the lamp’s light. The length of these lines depends on the design of the telescopes. The images taken with the fast telescopes were more prone to saturate in the left bright zone.
The right part of the chart ends with the last pixel next to laptop’s frame, furthest from the lamp.

It is noteworthy that for two refractors (TOA150 and BM150) the numbers of saturated pixels are more than 10 times lower than for RASA36 and AG16. It is interesting that curves and number of saturated pixels for RASA36 and AG16 are very similar despite the significant difference in the f-numbers and designs. RASA36 accumulates 3 times faster light than AG16 but for both instruments number of saturated pixels was similar.

The curve for TOA150 is well behaved, but on the other hand it has a clear drawback: very low f-number: f/7.3.

The background profile for BM150 with f/5.0 is as expected, except for the fact that on the distant side from the lamp a bright reflection is recorded degrading the right part of the image. Any attempts to analyze this part of the image were unsuccessful. The low quality baffles and poor coating are probably the main reasons explaining this adverse effect.

Test C:

In this test we analyzed SNRs in ADU values for the series of artificial LFs across the screen.

A special pattern of pixels was designed to check the performance of the scope across different exposure times. We focused on the three dimmest artificial LFs since the brightest ones showed very high SNR, which was trivial to measure. The analyzed LFs have size ranges from 2 to 6 pixels and our rough calculation indicate that have brightness of 75 nits (see fig. 6 and chart 3).

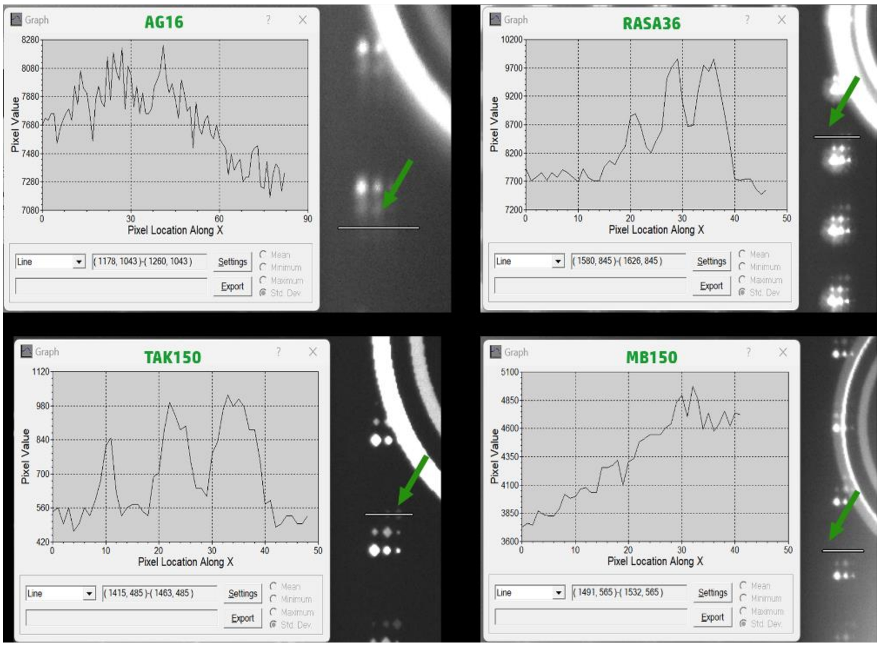

Fig. 5 ADUs profiles for four clusters of artificial lunar flashes.

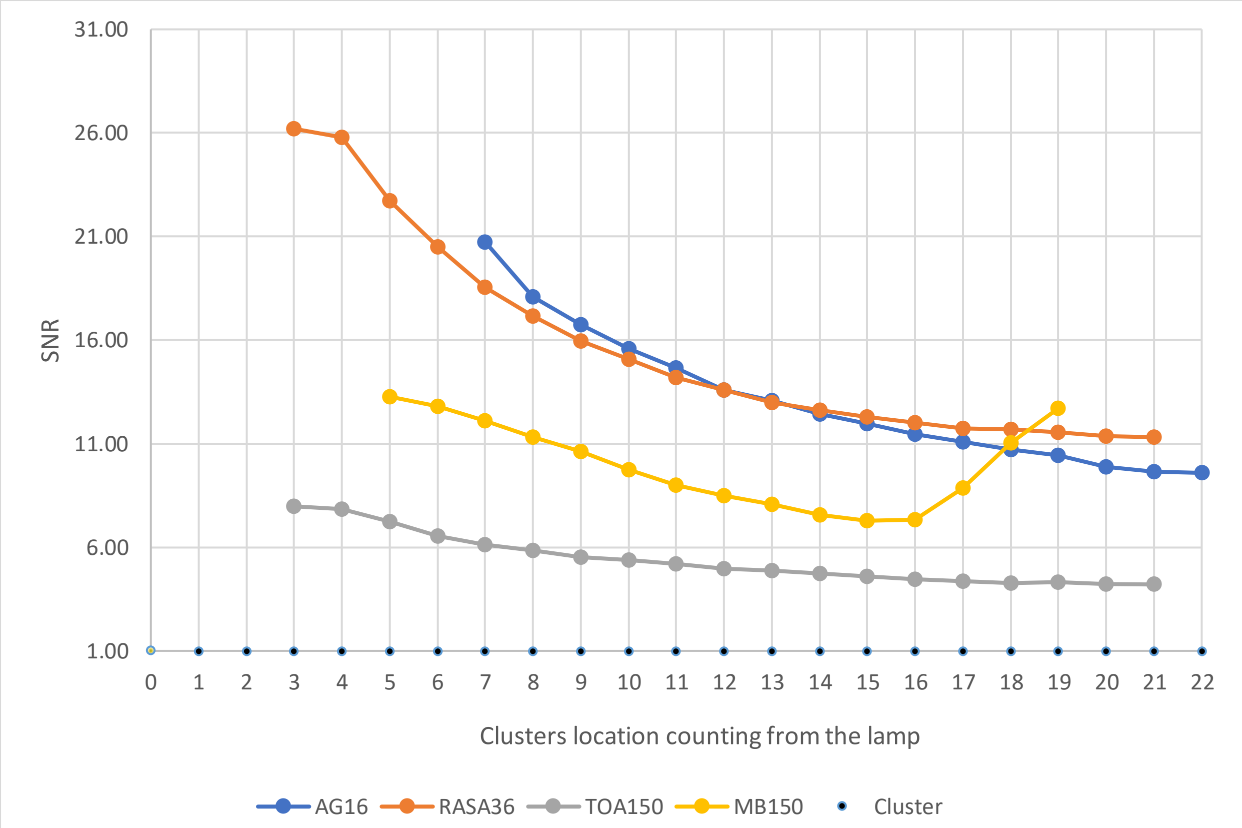

Chart 3. SNR of measured clusters for four tested telescopes. On X-axis are the clusters' positions counted from the lamp on the left.

Conclusions:
Two factors are important for efficient LFs recording. The first factor is the minimum distance from the terminator where we can detect the clusters.
Here we see that TOA150 and RASA36 allowed for measurement starting from 3rd clusters. Unfortunately 1st and 2nd clusters drowned in the background light. For BM150 and AG16 it was 5th and 7th cluster respectively, what is obviously worse result comparing to TOA150 and RASA36.
The second important factor is SNR. The higher the SNR is, the higher chance for a LF detection. Here we see that AG16 and RASA36 produce much higher SNR values compared to the rest of the designs.
RASA36 produces the highest SNR values and at the same time allows for measurements for the closest clusters, despite the fact that there is a significant amount of saturated pixels. The separation between very bright background and the LF occurs right after the end of saturation zone. On the other hand AG16 provides acceptable results, when observing further from the terminator. We should underline that SNR measured close to the terminator may be influenced by lamp illumination and therefore its values are affected by significant errors.

Shortcoming:

For three setups the telescopes were settled on astronomical mounts about 1.5 meter above the ground and the artificial Moon 1.0 meter above the ground. Due to technical limitations bulky AG16 was placed right on the ground. After the session with AG16 the material was analyzed revealing poor quality of the images, what probably caused worser than expected results for test C, therefore the test with LFs should be repeated for AG16 in stable environment. It is important to underline that the tests with blinking circle (A) and background curve (B) were not affected by this technical shortcoming.

Considerations:

It would be interesting to repeat some of the tests with analytical software dedicated to detection of LFs. With this approach we could establish a full pipeline of observational process. It would be interesting to compare the numbers of positive and false detections across different optical designs.
The tests with LFs should be repeated for AG16 in stable environment.

The distance between telescopes and AM was too short. It should be extended for two reasons:

- for some telescopes it was troublesome to obtain focus with only 32 meters distance without complicated extenders for the attached camera.
- for TOA150 and AG16 due to small fields of view observer was forced to merge and overlap two separate images of the AM.

We have shown that with the use of simple software observers can recreate complicated events on the laptops' screen simulating artificial LFs. It can be interesting challenge to design elaborated dynamic patterns testing the limits of optical setups and detection software.