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EUSO Duty Cycle: Moon and Sun Light Effects

Prepared by: F. Montanet
 Approved by: G. D'Ali
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EUSO-SIM Subsystem

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EUSO duty cycle: moon and sun light effects

F. Montanet

Abstract:

The major limitation on the EUSO duty cycle comes from the fraction of the time the field of view will be exposed to the sun light or to the moon light. A further limitation could come from the fact that the telescope shutter might have to be closed also when the ISS itself is exposed to either light source. We compute the year averaged duty cycle due to the light-shadow effect under different conditions, taking into account the exact position of the ISS, the sun and the moon minute per minute. This fine time step prediction allows also computing the distribution of the shutter opening times which can be as small as 1 minute.

Introduction:

Very roughly half of the time, EUSO will be overlooking night and during about half of that time, will the moon be above the horizon. Averaging on the sun and the moon positions, neglecting moon phases, this gives a crude 25% upper limit for the detector duty cycle. Obviously, at new moon, the background light might be sustainable up to a certain level and the moon phases have to be taken into account in some way.

On the other hand, it is unclear whether the telescope will be able to operate when exposed to direct light from either the sun or the moon, even if the field of view is well in the dark. As a matter of fact, because of the ISS high altitude (~ 400 km), it enters or exit the umbra cone when the sun or the moon are still 19.8° below the horizon at sea level.

Estimating the background light level in these conditions is difficult, because it depends both on the possible stray light from parasitic reflections on the telescope baffle, as well as on large angle scattering on the rarefied gas surrounding and below the ISS. The results presented in this note will therefore make the hypothesis that the ISS should be **out of direct sunlight**. This naively reduces the duty cycle to $[(180^\circ - 2 \times 19.8^\circ) / 360^\circ] = 39\%$, for the sun only instead of 50%.

In fact, it is important to realize that this naive calculation is wrong and based on an idealized situation, neglecting the variation of the orbit inclination with respect to the ecliptic plane, as well as its orientation with respect to the sun illumination. As we will see, a detailed calculation shows that there are periods of time during a sidereal year when the ISS is constantly in the sunlight. The year averaged duty cycle due to sunlight is found to be **34.25%** instead of 39%.

As far as the moon is concerned, we have chosen two different hypotheses:

1. A strict cut as for the sun for which observation time is restricted to the moon being below the ISS horizon, namely with a zenith angle bigger than $90^\circ + 19.8^\circ = 109.18^\circ$.
2. A less stringent cut assuming that a fraction of the time when the moon is above the horizon, say at new moon for example, the background will be low enough to be acceptable. The background evaluation is obtained using rough estimate of the flux of background light backscattered by the ground and the atmosphere, depending upon the moon zenith angle and phase angle.

For the purpose of this calculation, we have chosen to compute for each time step, the relative positions of the ISS, the sun and the moon, minute per minute for a year long period. From these positions, one can obtain the actual crossing time of the earth umbra cone with a 1 minute precision as well as the moon phases.

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Ephemerides

We have used the SLALIB positional astronomy library [1] to compute the pointing vectors to the sun and to the moon centre. SLALIB is a very accurate and complete set of routines to compute positions of solar system or stellar objects, convert between coordinate systems or calendars etc. It provides much more functionalities and accuracy than really needed here but it is simple enough to use and shortcuts a lot of complex coding (and mistakes that usually follow).¹

We first define the time and date in the Modified Julian (MJ 2000) calendar and compute the moon and the sun position in the fixed equatorial coordinate system (i.e. right ascension α , declination δ). Using the time and the observatory position (the ISS longitude, latitude and height, see below), the equatorial coordinates are then transformed to local (geodetic) horizon coordinates, namely azimuth Az and elevation El or zenith angle θ_z .

The sun and the moon eclipse times are then defined using a simple cut on the zenith angle:

- ISS in the umbra $\theta_z > \pi - \arcsin(R/(R + H)) = 109.18^\circ$
- ISS in the light $\theta_z < \pi - \arcsin(R/(R + H))$

were R is the earth radius and H the ISS height above ground level.

Computing the ISS position

The basic trajectory of the ISS is a geosynchronous orbit, obviously a keplerian ellipse, inclined 51° with respect to the equatorial plane. This ellipse is rotating around the pole axis in the solar inertial frame with a precession period of roughly 72 days.

In real life, things are considerably more complicated. On top of the main central forces, many additional perturbing forces have to be taken into account if we want to be able to accurately predict the position of the satellite. These additional forces will act to change our satellite's orbital path from that of a true ellipse. First of all, the earth is not a point mass because of its oblateness and because of its non uniform density. Furthermore, one cannot, ignore the gravitational effects of the sun and the moon. There are non-gravitational forces to consider, as well. The primary one, for rather low-earth orbit like in the case of the ISS and because of its large span, is atmospheric drag.

Ignoring these perturbations for a low-earth orbit will result in significant errors. One of the main effects is that the ISS is “falling” gradually down, at a rate of roughly 11 km in 100 days.

A large literature exists on the theory of the motion of artificial earth satellite and numerous models have been worked out that aim at predicting satellites positions mostly using unfolding of perturbations effect, like the NORAD SGP model. During the 1970s, NORAD (the North American Aerospace Defence Command) developed a fully-analytical orbital model. With this model, known as SGP (for Simplified General Perturbation), a user can calculate a satellite's position and velocity at a particular time directly, without the need for numerical integration. The result is a considerable reduction in computational burden to support tracking the growing population of earth-orbiting satellites.

NORAD maintains general perturbation element sets on all resident space objects. These element sets are periodically refined so as to maintain a reasonable prediction capability on all space objects. In turn, these element sets are provided to users (historically in a compact 2 line format sets called Two Line Elements or TLE). In a publicly available report [2], NORAD summarises the method of propagating these element sets in time to obtain a

¹ Unfortunately, FORTRAN coding had to be used, because although it is possible to interface SLALIB to C, the publicly available version of the library has not yet been ported to C or C++.

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position and velocity of the space object and even provides the FORTRAN code to do so. We have used the code listed in this report as templates and have re-written a set of routines in FORTRAN as well as in C++ to compute the ISS position for any MJ date, starting from the ISS Two Line Elements. TLE sets can be fetched from different ftp or web sites and are updated daily.

This piece of code has been tested in different ways, but one of the most stringent tests was to calculate in real time the current position of the ISS and to compare the longitude and latitude obtained to those provided by one of the many real time software's available on the internet. For example, the agreement with the well spread and GNU licensed "Predict"² software was found to be within a fraction of a degree.

Moon phases and background

Moon magnitude phase curves:

The moon does not act as a simple lambertian spherical reflector and taking it as such would lead to large errors. Among other things, it has much stronger phase dependence, shows almost no limb darkening and presents a strong opposition effect. It is therefore unavoidable to use an empirical model fitted to real photometric data.

Many models of the moon brightness have been proposed, mostly in the seventies, when both precise photometric data and surface samples became available. Complex bi-directional reflectance functions have been fitted to the data and analysed to extract information on the nature of the moon powder like soil. The same kind of analysis is still being actively pursued to study the nature of other solar system asteroids and satellites.

Many measurements and parameterisation of the relative brightness of the moon as a function of the phase angle are available. The basic phase curve is rather simple but deviates quite significantly from that of a straightforward lambertian sphere. The magnitude ($\log_{10}(2.5 \times I_r)$) is quasi linear with the phase angle α for angles between 7° and 30° . For larger angles the phase curve is best fitted with a biquadratic form of the type:

$$\text{mag} = \text{mag}_0 + a_1 |\alpha| + a_4 \alpha^4,$$

where $\text{mag}_0 = -12.73$ is the absolute magnitude of the full moon, $a_1 = 1.5$ and $a_4 = 4.3 \times 10^{-2}$ if the phase angle α is expressed in radians ($-\pi$ to π) [3]. The half moon is about 10 times less luminous than the full moon. One should stress that although this model agrees quite well with photometric measurements its accuracy for phase angle close to π (new moon) is probably not very good. There are also three noticeable deviations between the data and this parameterisation, which will all be neglected in the following:

- At small angles ($\pm 7^\circ$ around the full moon), photometric data show a sharp increase in the moon brightness. The full moon is about 35% brighter than the above model or a simple extrapolation would predict. This is known as the opposition effect and is interpreted as due in part to a shadowing effect (surface roughness casting shadow reducing reflectivity except near zero phase), and to a coherent effect depending upon the size of the dust grains and on wavelength.
- Another deviation is a before-after full moon asymmetry the moon irradiance is slightly less after full moon than before full moon for symmetric phase angles. This is due to a larger proportion of darker "mare" in the western part of the moon face.

² <http://www.qsl.net/kd2bd/predict.html>

- A third effect is known as the *earthshine*. This is the faint light visible on the dark side of the moon when it is a thin crescent. Earthshine depends strongly on the phase of the Earth. When the Earth is full (at new Moon), it casts the greatest amount of light on the Moon, and the earthshine is relatively bright and easily observed by the naked eye. At exact new moon, the earthshine effect is about 1.5×10^{-4} less luminous than the full moon. The above function drops down to 2.7×10^{-4} of the value of the full moon and seems to slightly overestimate the moonlight flux at large phases.

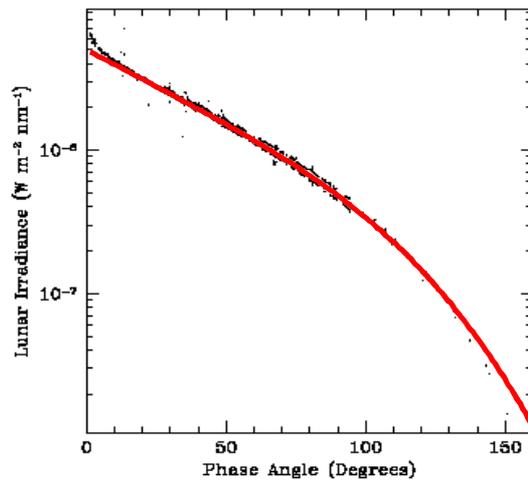


Figure 1: Lunar absolute irradiance at 555 nm as a function of the moon phase from the ROLO photometric measurements [4]. The strong phase dependence, the opposition effect, the east-west asymmetry are clear seen. The simple parametric phase curve from [3] is overlaid in red for comparison.

For our purpose of computing low illumination background what matters mostly is to predict with some accuracy the moonlight at large phase angles (near new moon). Although data at large phase angle are rare, the phase dependence above does a fairly good job down to 120° and the comparison with earthshine data indicates that if anything, it overestimates slightly the large phase irradiation.

Lunar irradiance modelling:

Converting a relative magnitude to a photon flux in a given spectral range requires the knowledge of a precise photometric calibration. The moon has been often used as a calibration source for photometric instruments but absolute calibration data in the 300-400 nm range are scarce. The most relevant radiometric information we could find comes from the ROLO program (a terrestrial robotic lunar observatory) [4]. Observation are routinely made since 1996 over a range 350-950 nm using 23 passband filters, correcting for the atmosphere attenuation and normalising the data to bright stars of known magnitude. The magnitude as function of the phase at 555 nm is shown in Figure 1 and is compared to the parametric function from [3] which compares quite well. The conversion from magnitude to irradiance units ($\text{W}/\text{m}^2/\text{nm}$) is given by the relation:

$$\text{Ir}[\text{W} / \text{m}^2 / \text{nm}] = 10^{0.4(-\text{mag}-26)}$$

The full moon (linear extrapolation neglecting the opposition effect) corresponds to:

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$$I_{r_0} = 10^{0.4(12.73-26)} \approx 5 \times 10^{-6} \text{ W / m}^2 / \text{nm}$$

The same authors give the relative reflectance of the moon for the different passband filters normalised to 1 at 555 nm. The reflectance drops almost linearly from 1 at 555 nm to 0.62 at 350 nm. This allows us to define the photon flux from the full moon at the top of the atmosphere integrated over the range 300 to 400 nm:

$$\begin{aligned} \Phi_0 &= 5 \times 10^{-6} \times \frac{10^{-9}}{1.6 \times 10^{-19} \times 3.54 \text{ eV}} \times 0.62 \times 100 \text{ nm} \\ &= 5.5 \times 10^5 \gamma_{300-400} / \text{m}^2 / \text{ns} \end{aligned}$$

The flux dependence as a function moon phase is given by the empirical expression:

$$\Phi(\alpha) = 5 \times 10^6 \times 10^{-0.4(1.5|\alpha| + 4.3 \times 10^2 \alpha^4)} \gamma_{300-400} / \text{m}^2 / \text{ns}$$

were α is the phase angle in radians.

Moonlight background:

According to simulations [5], the reflection of UV light on the earth is mainly due to the atmosphere. Assuming a clear sky atmosphere with a total transmission of 0.4 and a surface albedo of 0.1, the fraction of an incoming isotropic light flux which is scattered upward by the atmosphere is ~30%, the rest (~70%) is transmitted-scattered downwards. From this ~70%, only 7% is reflected by the ground, and 5% is transmitted to the top of the atmosphere. The total albedo is thus ~35%. In the case of moonlight, the situation is complicated by the fact that the incoming beam is not isotropic but unidirectional.

We will use a very crude model the reflection of the moon light by the atmosphere, which should be refined in the future. We will consider the atmosphere as an isotropic diffuser, so that the elementary flow $d\phi_{\text{moon}}$ emitted by an elementary surface dS of atmosphere is given by:

$$\phi_{\text{Moon}} = \iint \frac{\Omega}{2\pi} A \cos \theta \Phi(\alpha) dS = \frac{A \cos \theta}{2\pi} \iint \Omega dS$$

where $\cos(\theta)$ is the moon zenith angle cosine, and $\iint \Omega dS$ is the solid angle of EUSO. Then, the Moon background in photons/ m^2 / ns / sr in the 300-400 nm range is:

$$\begin{aligned} \text{BG}_{\text{Moon}}(\theta, \alpha) &= \frac{A \cos \theta}{2\pi} \Phi(\alpha) \\ &\approx 2.8 \times 10^5 \times \cos \theta \times 10^{-0.4(1.5|\alpha| + 4.3 \times 10^2 \alpha^4)} \gamma_{300-400} / \text{m}^2 / \text{ns} / \text{sr} \end{aligned}$$

In other words, the full moon at the zenith of EUSO would produce 28000 photons/ m^2 /ns/sr. If one consider 2.5 μ s time bins (GTU), this corresponds to the following rate in photoelectrons per pixel and per GTU :

$$\begin{aligned}
BG_{\text{Moon}}(\theta, \alpha) &\approx 523 \times \cos \theta \times 10^{-0.4(1.5|\alpha| + 4.3 \times 10^2 \alpha^4)} \text{ pe/pixel} / 2.5\mu\text{s} \\
&= 4.7 \times \cos(\theta) \text{ pe/pixel} / 2.5\mu\text{s} \quad \text{at half moon} \\
&= 0.14 \times \cos(\theta) \text{ pe/pixel} / 2.5\mu\text{s} \quad \text{at new moon}
\end{aligned}$$

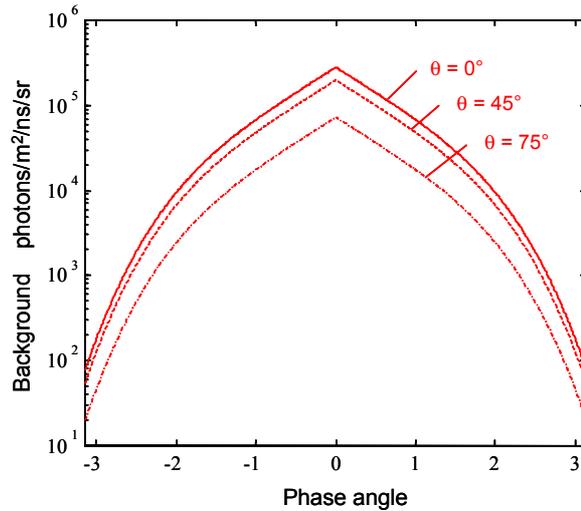


Figure 2: Background photons induced by moon light only, in the EUSO acceptance as a function of the moon phase angle and for different moon zenith angles.

Putting everything together

Using the previously described procedure, we compute for a year long period and minute per minute, the position of the ISS, the zenith angle of the sun and of the moon at this position and time, and the moon phase α . The moon light flux and the moon background are then estimated from the above formulae. The decision is then taken to open or close the shutter depending on the selected criterion: a) moon and sun hidden, or b) sun hidden and moon background below the limit. The length of the exposures is then computed, summed and counted, day by day and year long statistics are produced.

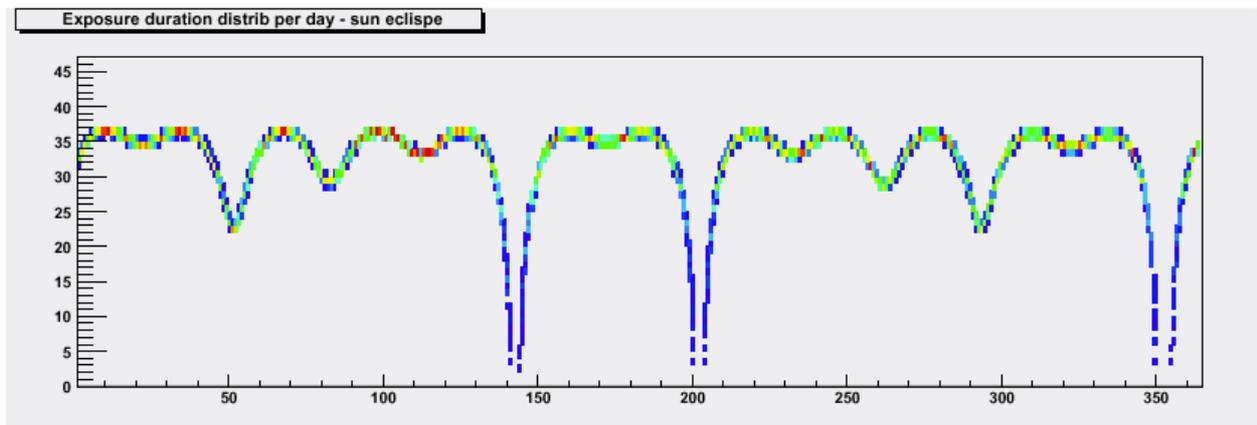


Figure 3 : Distribution of the exposure durations in minutes for each day in one year if the sun only is taken into account. The periods when the exposures are dropping to zero correspond to the days when the orbit axis is almost aligned with the sun direction.

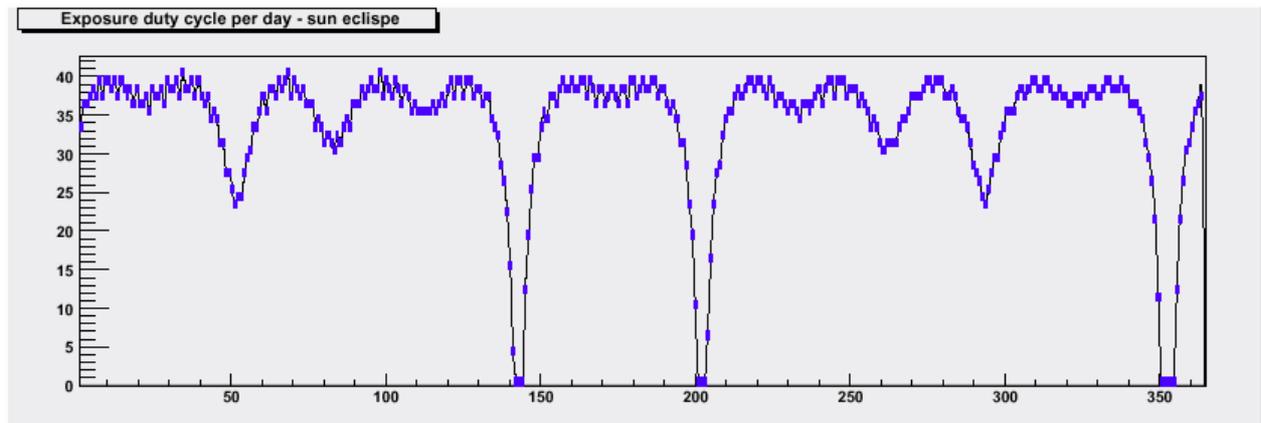


Figure 4: The same distribution but this time taking only the moon into account by requesting it to out of sight. Again, there are periods when the orbit is facing the moon and when data taking wont be possible.

Figure 3 shows the distribution of the exposure period durations for each day for one year. Figure 5 shows the day averaged duty cycle (fraction of active time during one day) for one year if one only takes the sun into account. One realize looking at these curves that because of the precession of the orbit, there are a two to three periods of a few days during in one year when the orbit axis is almost aligned with the sun direction. This means that these periods are completely lost for data taking. This effect reduces the naïve 39% duty cycle due to the sun only to a more realistic 34.6%. The same phenomenon is also true for the moon if it is required to be eclipsed. Note that an analytic description of these fancy curves can be easily produced using a simplified model of the orbit and earth rotation.

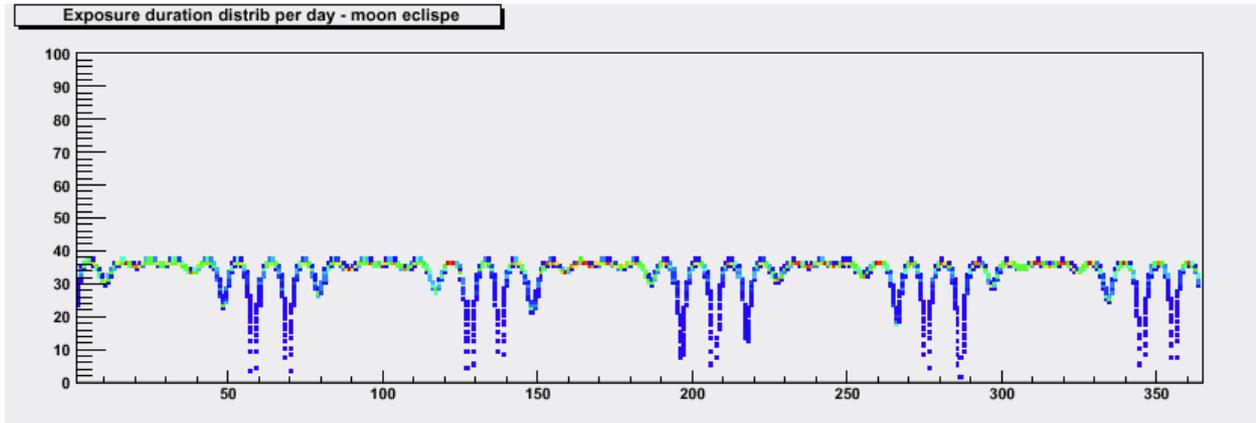


Figure 5 : The day averaged duty cycle in percent (fraction of active time during one day) for one year if one only takes the sun into account.

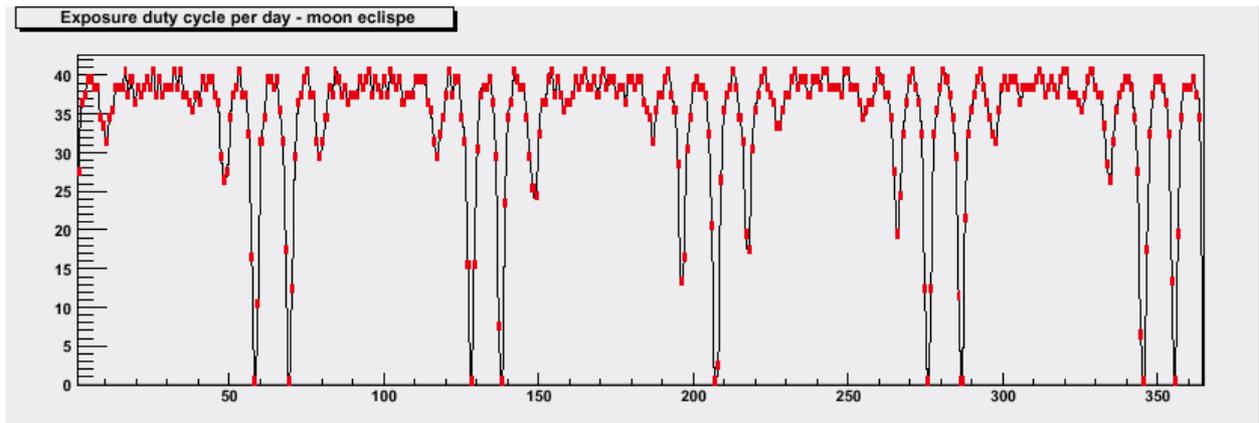


Figure 6: The day averaged duty cycle in percent (fraction of active time during one day) for one year if one only takes the moon into account requiring it to be hidden ($\theta_{zenith} > 109.18^\circ$).

Figure 6 shows the day averaged duty cycle for one year only taking the moon into account and requiring it to be hidden ($\theta_{zenith} > 109.18^\circ$).

The moon background as a function of the day is shown in Figure 7. Only the envelope of the background curve is visible, the actual curve oscillate with a period corresponding to the orbit revolution between zero and the maximum of the curve as seen in the inlet on the same picture. Accepting some additional background light from the moon enables to run longer periods in the valleys of this histogram. Figure 8 shows the same variables than Figure 6 but accepting up to 100 photons/m²/ns/sr from moonlight.

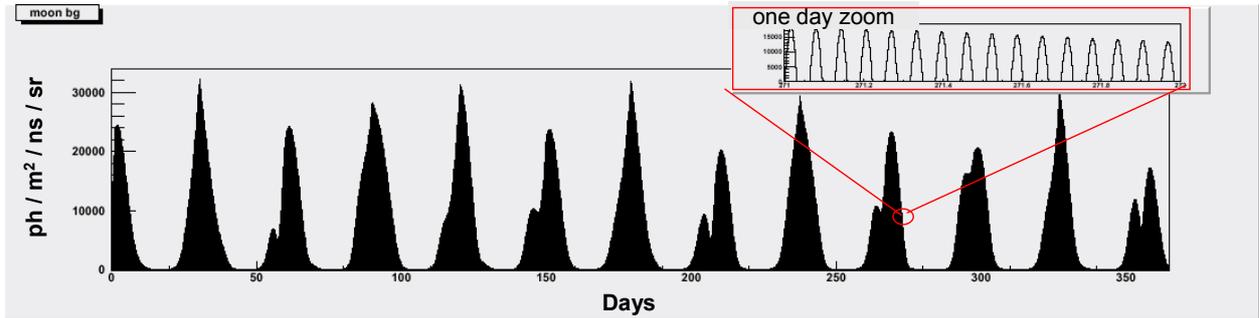


Figure 7: The moonlight induced background in 1 minute bins for one year. The inlet shows a one day zoom where the $\cos(\theta)$ modulation can be seen.

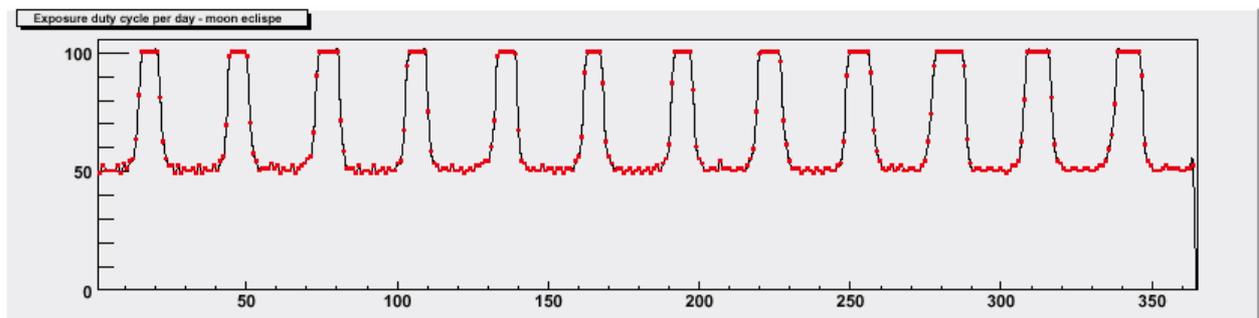


Figure 8 : The day averaged duty cycle in percent (fraction of active time during one day) for one year if one only takes the moon into account asking that the moonlight background is less than 100 photons/m²/ns/sr.

Of course, both conditions on the sun and the moon have to be combined. This is again done on a minute per minute basis. This is necessary because of the strong correlation effects between the moon phase and the zenith angles of the sun and the moon. Figure 9 shows the day averaged duty cycle for one year asking the sun and the moon to be hidden (both $\theta_{\text{zenith}} > 109.18^\circ$, in white), and accepting increasing amount of moonlight induced background (100, 300 and 500 photons/m²/ns/sr). Basically, except around new moon, when the sun is up the moon is down and vice versa. If one asks both the sun and the moon to be below the horizon, there is a large fraction of the year, **124 full days**, when either one or the other of the two light sources will prohibit running the detector. The year average duty cycle with these strict conditions is only **12.86%**.

On the other hand, the duty cycle increase quickly if one accepts a minimum additional background on top of the other backgrounds. The main other backgrounds are the airglow (~ 300 - 600 photons/m²/ns/sr), the Zodiacal Light (~ 180), diffuse star light and planets (~ 190). The values for the year average duty cycle with different background conditions are summarized in the

Table 1 and the background limit dependence is shown in Figure 10.

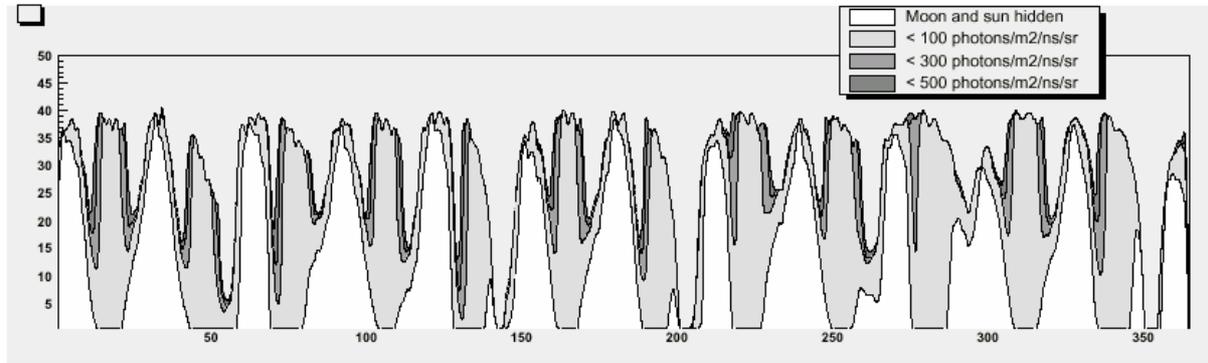


Figure 9: The day averaged duty cycle for one year asking the sun and the moon to be hidden (both $\theta_{zenith} > 109.18^\circ$, in white), and accepting increasing amount of moonlight induced background (100, 300 and 500 photons/m²/ns/sr).

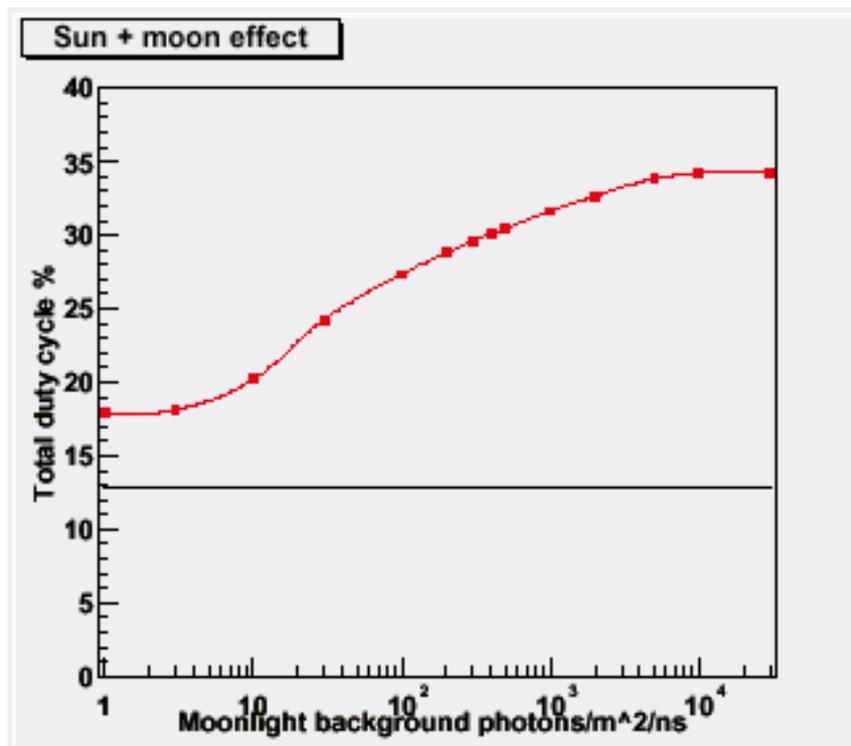


Figure 10: The year average duty cycle as a function of the moonlight induced background limit.

Table 1 : The duty cycle for different background conditions.

| Moonlight induced background limit | | Sun zenith < 109.18° | Moon effect only | Moon +Sun |
|------------------------------------|-------------------------|----------------------|------------------|-----------|
| photons/m ² /ns | photoelectrons/pixel/μs | % | % | % |
| Moon zenith < 109.18° | | 34.25 | 34.61 | 12.87 |
| 1 | 7×10 ⁻⁴ | | 51.13 | 17.96 |
| 3 | 2×10 ⁻³ | | 51.93 | 18.11 |
| 10 | 7×10 ⁻³ | | 55.22 | 20.21 |
| 30 | 0.02 | | 60.59 | 24.25 |
| 100 | 0.07 | | 65.52 | 27.32 |
| 200 | 0.15 | | 68.25 | 28.79 |
| 300 | 0.22 | | 69.83 | 29.55 |
| 400 | 0.30 | | 70.96 | 30.06 |
| 500 | 0.37 | | 71.87 | 30.44 |
| 1000 | 0.75 | | 74.95 | 31.62 |
| 2000 | 1.5 | | 78.42 | 32.65 |
| 5000 | 3.7 | | 84.49 | 33.84 |
| 10000 | 7.5 | | 91.17 | 34.25 |
| 30000 | 22 | | 99.95 | 34.25 |

Opening time distribution:

Another byproduct of this study is the distribution of the opening times (Figure 11). The shutter protecting telescope will require some time for opening and closing. This implies that short periods of exposure will be problematic or completely lost. One sees from Figure 11 that another drawback of using a stringent cut for the moon is that a large fraction of the active time consists of very short openings (~1/3rd of the openings are shorter than 10 minutes adding up to 8.6 % of active time). If one accepts 100 photons/m²/ns/sr, this fraction drops to 1.8 % of the active time and 10 % of the opening. From the figure, one can see that when accepting even a small amount of background, shorter openings are concatenated together and that the peak at 35.80 minutes long openings (the longest time for the ISS to travel through the umbra) has increased quite a lot.

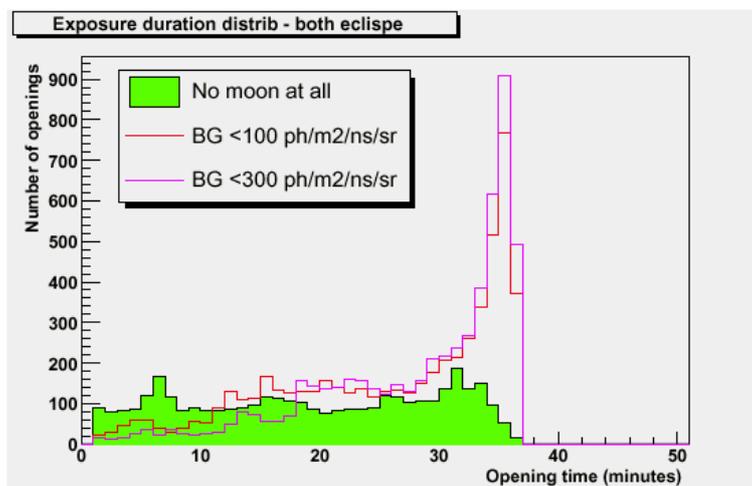


Figure 11: The distribution of the individual exposures durations (or opening times). This shows the number of openings as a function of there duration.

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Conclusions

In conclusion, we have shown that the average duty cycle for EUSO due to the sun and moonlight is 12.86% if both the sun and the moon are requested to be safely below the horizon from the ISS. Accounting for the variation of the moonlight flux with the moon phase angle, and computing the moonlight fraction reflected by the earth atmosphere, one can estimate the additional background induced by moonlight. Accepting even a quasi negligible additional background allows to improve the duty cycle to **more than 18 %**. With <100 photons/m²/ns/sr, the duty cycle reaches **27%**. The other positive effect of such a decision is that the active time consists of much fewer short periods of exposure and much less time lost in manoeuvring the shutter.

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