De-biasing CILBO meteor observational data to mass fluxes

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The goal of this paper is to estimate for different mass ranges the percentage of meteors that are not detected by video observations and to derive un-biased mass fluxes. The work is based on the data from the Canary Island Long-Baseline Observatory (CILBO), which is a double-station camera setup for meteor observations and a project by Detlef Koschny at the European Space Agency. Moreover the work by Drolshagen et al. and Ott et al. (2014) on the meteor observational data by the CILBO is used. In a paper presented at the IMC 2014 Drolshagen et al. used a formula by Verniani (1973) to determine the mass of the detected meteoroids and plotted the velocity distribution for big meteoroids only. They found that it fits the reference velocity distribution from the ECSS (European Cooperation for Space Standardization) Space Environment Standard which indicates that it is a realistic model. The data set that Drolshagen et al. and Ott et al. were using (1 June 2013 – 31 May 2014) was expanded to a longer time range and the mass of each meteoroid detected by the CILBO was calculated applying the formula by Verniani. Afterwards the velocity distribution of the CILBO data was plotted for different mass ranges and compared to the ECSS velocity distribution to estimate the missing percentage for different meteoroid mass ranges. For the smallest masses a very large fraction of the meteoroids were not detected by the CILBO double-station. In a second step the number of meteoroids in each mass range was corrected to account for the slower meteoroids. From these results, the 'de-biased' flux was derived and compared to the flux model by Grün et al. (1985). The slope of the 'de-biased' CILBO flux is similar to the one of the Grün et al. model but the calculated flux values are higher.

1 Introduction

This paper is based on the work by Drolshagen et al. (2014) and Ott et al. (2014). They analysed the data collected in one year (1 June 2013 – 31 May 2014) from the CILBO (Canary Island Long-Baseline Observatory) double station camera setup for meteor observations, which has been active since July 2011. The CILBO system is located on the Canary Islands and consists of two automated stations with image-intensified video cameras (ICC – Intensified CCD camera). One of the two stations is positioned on Tenerife (ICC7) and the other is located on La Palma (ICC9). Since both cameras are pointed towards the same area in the atmosphere at 100 km height, a meteor that was observed in the overlap of the fields of view of both cameras can be registered, making the calculation of the trajectory and velocity of the meteor possible. *Figure 1* shows the setup of the CILBO system (Drolshagen et al., 2014). A more detailed description on the CILBO setup can be found in Koschny et al. (2013). Operational experiences with the CILBO double station and information on the current work of the Meteor Research Group are presented in Koschny et al. (2014) and Koschny et al. (2015).

Drolshagen et al. compared the velocity distribution of the detected meteors by the CILBO to the theoretical velocity distribution at 100 km above the Earth´s surface as given by the European Cooperation for Space Standardization (ECSS) and discovered that the velocity distribution is heavily biased towards fast and large meteoroids (Drolshagen et al., 2014). This is due to the fact that meteoroids need to have a certain kinetic energy to form a visible meteor trail. The mentioned bias was verified by Drolshagen et al. by noticing that the velocity distribution of larger meteoroids, which have higher kinetic energies, fits the theoretical velocity distribution.

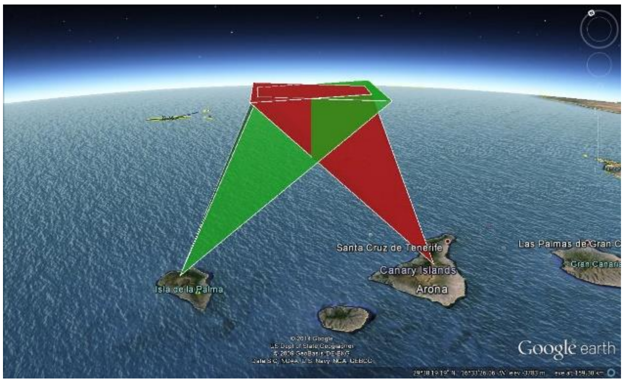

Figure 1 – CILBO double station camera setup including the fields of view of both cameras and the overlapping volume in which simultaneous meteor detections are feasible. Camera ICC9 is located on La Palma (left island) and camera ICC7 on Tenerife (right island). The setup was generated using Google Earth. (Drolshagen et al., 2014).

The corresponding masses were calculated using a mass formula by Verniani (1973). The bias towards meteors with high velocities resulted in an imprecise mass influx derived for the CILBO.

In this paper a method for de-biasing the data is presented. The CILBO data set was extended towards a longer time range and includes all meteors that were detected by both stations simultaneously from January 2012 to June 2015, which lead to a total number of 13415 meteors. The resulting mass influx derived using the CILBO data is presented.

2 The bias towards fast and large meteoroids

Figure 2 shows the normalized velocity distribution of all meteors detected by the CILBO double station from January 2012 to June 2015 compared to the theoretical velocity distribution at 100 km height. The moving average for the number of meteors in the 1 km/s velocity bins was calculated to compensate for statistical errors. The errors Δn_{CILBO} were calculated using equation (1). As already discovered by Drolshagen et al. both normalized distributions differ largely from one another, which is due to the bias towards fast and large meteoroids.

$$\Delta n_{CILBO} = \sqrt{n_{CILBO}(v)} \qquad (1)$$

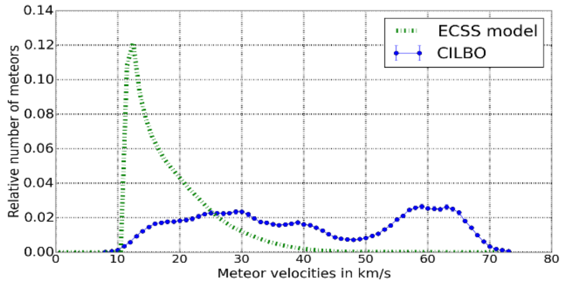

Figure 2 – Normalized velocity distribution of all 13415 CILBO meteors compared to the normalized theoretical velocity distribution by the ECSS standard for 100 km altitude.

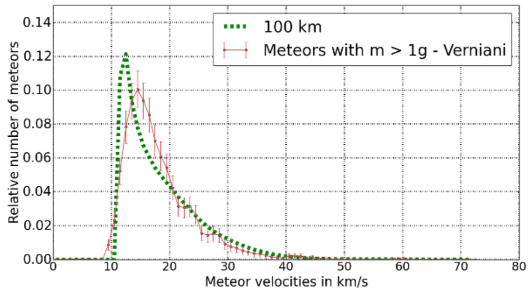

Figure 3 – The normalized theoretical velocity distribution of meteors in 100 km height (green, dashed line) and the normalized velocity distribution of all 836 meteors which were caused by meteoroids heavier than 1 g (red, dotted line). The mass was calculated using the formula by Verniani.

Adopting the idea by Drolshagen et al., the normalized velocity distribution of all heavy meteors with masses ≥ 1 g was compared to the theoretical velocity distribution at 100 km hight as it is shown in *Figure 3* including the moving average and the error calculation. For the calculation of the corresponding meteoroid masses formula (2) by Verniani (1973) was used. Where *m* is the mass of the meteoroid outside the Earth's atmosphere, *M* is the absolute magnitude at maximum light and *v* is the velocity of the meteor. Verniani analysed the records of almost 6000 meteors, which were recorded under the Harvard Radio Meteor Project. When calculating the mass of each meteoroid only meteors with velocities in the range 10 – 72 km/s and magnitudes brighter than 6 were used, since all other values are considered being unphysical. Due to this limitation 92 of the 13415 meteors were sorted out.

$$m = 10^{\frac{-M + 64.09 - 10 \cdot \log(v)}{2.5}} \qquad (2)$$

Figure 3 shows that the theoretical velocity distribution by the ECSS report approximates the distribution of the CILBO data for meteoroids with large masses. Therefore the ECSS model may be used as reference baseline for the described de-biasing procedure. When looking at the normalized velocity distribution of the smallest meteoroids with $m < 3.69 \cdot 10^{-6}$ kg compared to the normalized theoretical distribution, as shown in *Figure 4*, there are only meteor detections at high velocities. This emphasises the conclusion that small meteoroids will only achieve the needed kinetic energy to form an ionization trail, if they have very high velocities, which also explains the maximum at around 60 km/s in the distribution of all meteors in *Figure 2*.

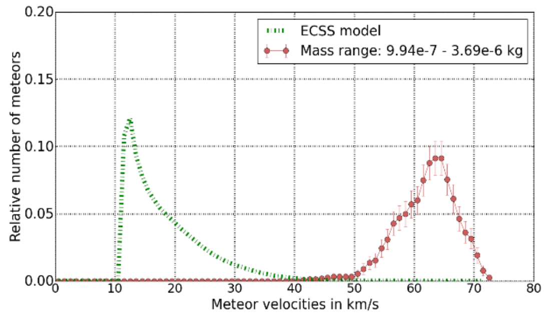

Figure 4 – Normalized velocity distribution for the smallest meteoroids ($m < 3.69 \cdot 10^{-6}$ kg) of the CILBO data (red, dotted line) compared to the normalized theoretical velocity distribution (green, dashed line).

3 Method of de-biasing meteor observational data

The fact that small meteoroids are detected at high velocities, leads to the conclusion that the velocity distribution at the highest velocities can be assumed to be correctly distributed and should follow the slope of the theoretical ECSS model. Therefore the idea was to look at the velocity distributions of detected CILBO meteors in certain predefined mass bins and to multiply the normalized theoretical velocity distribution by a certain factor, in such a way that its slope at high velocities fits the slope of the CILBO velocity distribution of each mass bin. This factor will be called the de-biasing factor, by which the percentage of meteoroids entering the Earth's atmosphere, which are not detectable by the CILBO, can be estimated for each mass bin.

The steps for finding the most applicable scaling factors are explained in the following. A requirement was introduced, that the number of meteoroids in each mass bin must be at least 300 to make sure that the velocity distribution of the meteors is still distributed with a sufficient statistical reliability. Having the new mass bins, the next step was to calculate the moving average as well as the corresponding error values and to normalize the CILBO velocity distribution. To scale the ECSS curve in such a way that it fits the CILBO velocity distribution at high velocities, the velocity range had to be defined, in which the binned CILBO velocity distribution was assumed to be correct, meaning that all meteors in this velocity range are considered to be detected by the double station. To do so the first step was to multiply the theoretical velocity distribution by different factors, ranging from 1 to 3000 and to compare each scaled distribution to the values in the highest velocity bins of the CILBO distribution. Starting from the 69 km/s bin towards smaller velocity bins the number of bins was counted in which the scaled ECSS curve lay in the error range of the CILBO bins. This was repeated for each scaled ECSS curve. The starting point was set to 69 km/s and not to the maximum velocity 72 km/s due to the fact that the number of meteors at higher velocities than 69 km/s was very small. Mass bins which contained a high number of meteors lead to very small error bars of the CILBO velocity distributions, which was why, the error range was extended by a factor of two, if there were more than 500 meteors in a mass bin. The factors for the scaled distributions, that showed the most intersections with the data including the error bars, as well as the velocity range in which those error intersections were found, were saved. A final de-biasing factor was found by calculating the least squares deviation in this previously defined velocity range between the saved scaled ECSS curves and the corresponding normalized CILBO velocity distribution.

Figure 5 shows the normalized velocity distributions for four exemplary mass ranges in comparison to the scaled ECSS velocity distribution with the calculated de-biasing factor.

Figure 5 shows that the scaling method already works pretty well but could be further improved. To visualise the distribution of the factors, *Figure 6* shows the scaling factors in dependence of the minimum of each mass range. A fit $f_v(m)$ was made through the factor distribution, to account for further statistical fluctuations between the de-biasing factors.

The de-biasing function $f_v(m)$ can now be applied to the number of detected meteors in a certain mass bin. *Figure 5(a)* shows the velocity distribution of the 561 smallest meteoroids in the mass range $9.94 \cdot 10^{-7}$ kg to $3.69 \cdot 10^{-6}$ kg. The new de-biasing factor for the minimum mass given by the derived de-biasing function $f_v(m)$ is 5745. Since there were 561 meteors detected in this exemplary mass range, this number must now be multiplied with 5745 to find the true number of meteoroids entering the Earth's atmosphere in this mass range: $561 \cdot 5745 = 3.223 \cdot 10^6$. Although only 561 of the smallest meteoroids were detected by the CILBO double station, there should have been more than 3 million meteoroids entering the Earth's atmosphere in this mass range for the time period considered.

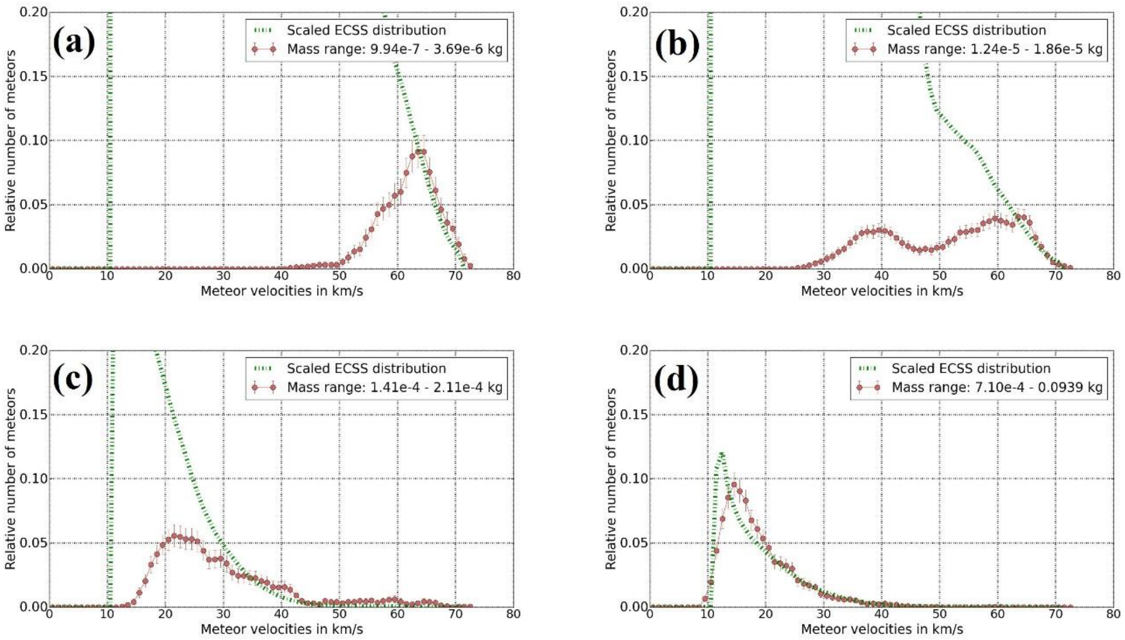

Figure 5 – Velocity distributions of the meteors detected by the CILBO in mass range (a) $9.94 \cdot 10^{-7}$ kg to $3.69 \cdot 10^{-6}$ kg, (b) $1.24 \cdot 10^{-5}$ kg to $1.86 \cdot 10^{-5}$ kg, (c) $1.41 \cdot 10^{-4}$ kg to $2.11 \cdot 10^{-4}$ kg, (d) $7.10 \cdot 10^{-4}$ kg to 0.0939 kg, which were calculated using the formula by Verniani (red, dotted line), and the theoretical velocity distribution that was multiplied by the calculated de-biasing factor (a) 1240, (b) 499, (c) 4, (d) 1 (green, dashed line).

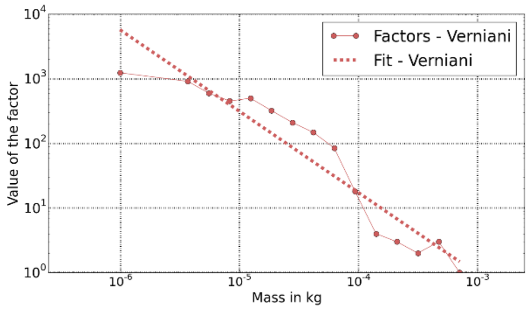

Figure 6 – De-biasing factor values in dependence of the mass in kg. The factors were derived for the velocity distribution of the mass ranges calculated using the mass formula by Verniani (red dots). A fit through the distribution is shown as dashed line.

4 The flux

To determine the mass influx of the CILBO according to Ott et al. (2014) the area covered by both cameras in 100 km, *A*, as well as the effective observing time when both cameras were active *T* = 15375624 s was needed. The area *A* was already determined by Ott et al., who found a value of 2943.71 km^2. The derived flux values lie in the mass range 10^{-6} kg to 10^{-1} kg. This mass range corresponds to sizes of 1 mm to 50 mm in diameter when assuming a density of 2.5 g/cm³. Flux values in this range are rare, which is why the CILBO flux covers an uncharted field. Drolshagen et al. (2015) gives a detailed overview on different flux models as well as on the total mass influx per day. For more information on the determination of the CILBO flux see Ott et al. (2014). *Figure 7* shows the cumulative CILBO flux in logarithmic mass bins compared to a flux model by Grün et al. (1985), who derived his model using micro lunar crater data, infrared measurements of interplanetary dust and in situ measurements. The cumulative number in each bin is plotted over the corresponding minimum mass bin value.

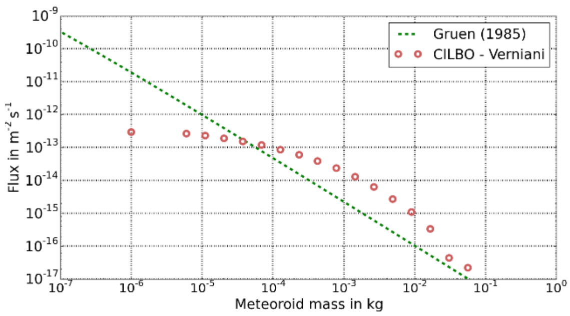

Figure 7 – The cumulative flux over the mass. The CILBO flux in logarithmic bins compared to the model by Grün et al..

Figure 7 shows the fact that the number of small meteoroids is underestimated. When comparing the slope of the CILBO flux to the one by the Grün et al. model, it can be seen that they are nearly parallel in the mass range 10^{-3} kg < *m* < 10^{-2} kg. The CILBO flux values in this region are about one order of magnitude higher than those determined by Grün et al.. The fact that the slope of the CILBO flux differs for masses > 10^{-2} kg is due to the low occurrence of meteoroids in this mass range. The decrease of the CILBO flux slope for meteoroid masses < 10^{-3} kg can be considered as a result of the bias towards fast and large meteoroids. Therefore the derived factor function $f_V(m)$ is used to de-bias the flux and to find the actual number of meteoroids in the logarithmic mass bins as described in *Section 3*. After the de-biasing was applied to the 13323 observed meteors the estimated actual number of meteors that should have appeared from January 2012 to June 2015 was 4425020 when considering the total mass range from 10^{-6} kg to 10^{-1} kg. The resulting flux is presented in *Figure 8*. The de-biased CILBO flux values are compared to the biased CILBO flux values as well as to the flux model by Grün et al..

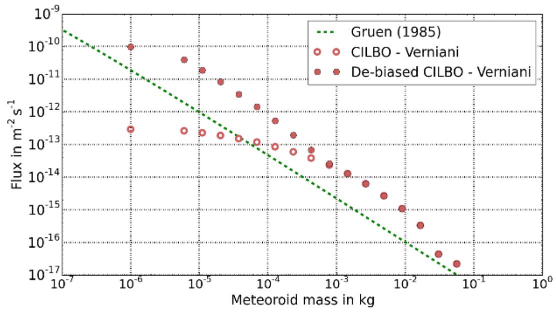

Figure 8 – The flux over the mass. The red hollow dots represent the original biased CILBO flux calculated with the mass formula by Verniani. The filled red dots the corresponding de-biased flux values. All distributions are compared to the flux model by Grün et al. (green, dashed line).

After the de-biasing was applied, the CILBO flux values for masses < 10^{-3} kg are now also nearly parallel to, and around one order of magnitude larger than, the ones from the Grün et al. flux model. The fact that the flux value in the smallest mass bin does not follow the slope of the other flux values is explainable since the flux is plotted over the smallest mass value and there are only a few meteoroids with masses of 10^{-6} kg and the majority of the meteoroids are of greater masses.

5 Conclusion and future work

From the CILBO data obtained from January 2012 to June 2015, which includes usable information on more than 13000 simultaneously observed meteors, a method for de-biasing the mass influx was derived. The de-biasing method is based on the velocity distribution of the CILBO data in certain mass ranges calculated with a mass formula by Verniani as well as on the theoretical velocity distribution by the ECSS standard. The de-biasing method works well but can be further improved by optimising the determination of the de-biasing factors from the velocity distributions. Larger velocity bins for the comparison of the CILBO velocity distributions to the scaled ECSS distribution should be considered for statistical reasons.

After applying the de-biasing the total number of meteoroids that entered the Earth's atmosphere in the considered time range was increased to more than 4.4 million meteors. Therefore only 0.3% of all meteoroids entering the Earth's atmosphere with masses > 10^{-6} kg are detectable by the CILBO double station. Most undetectable meteors are of small masses. The de-biasing factor increases the detected number of meteoroids with masses $m < 9.67 \cdot 10^{-4}$ kg. Therefore all meteoroids with masses $m \geq 9.67 \cdot 10^{-4}$ kg can be considered to always be detectable.

The de-biased CILBO flux values match the slope of those by the Grün et al. flux model. The CILBO flux values are one order of magnitude larger than those obtained by the Grün et al. model. A closer look on the determination of the area covered by both cameras of the CILBO should be taken. Furthermore the magnitude determination and the functionality of the cameras are improvable, which also influences the total number of meteor detections by the CILBO and therefore the flux. First findings regarding this are shown in Albin et al. (2015).

The mass formula by Verniani is based on radar observations. Different formulas for the mass calculation should be considered.

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