Numerical Simulation of Meteors as a Means of Debiasing AMOS Data

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Numerical Simulation of Meteors as a Means of Debiasing AMOS Data
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Objective

To **determine** the total meteoroid flux utilizing data from **AMOS**

- an **extrapolation** from collected data
- we need to
  - analyze the detection ability of AMOS
  - calibrate the system
  - **de-bias** the observations
- estimate the flux
Objective

To **determine** the total meteoroid flux utilizing data from **AMOS**

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  - **de-bias** the observations
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Two possible approaches

- correct sources of bias one by one
- **simulate** the population and try to match it to observational data
Algorithm

1. generate the meteoroid population
Algorithm

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2. simulate atmospheric entry and create Meteor objects
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3. compute virtual Sightings using locations of Observers
4. filter visible events and apply observational bias
   ▶ distance
   ▶ atmospheric attenuation
   ▶ limiting magnitude
   ▶ altitude
   ▶ ...

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Algorithm

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5. calculate the statistic and compare to AMOS data
6. adjust the particle distribution and observational bias parameters
Algorithm

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   - ...
5. calculate the statistic and compare to AMOS data
6. adjust the particle distribution and observational bias parameters
7. repeat
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Simulation

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Model

Designed by Whipple (1938), improved by Öpik (1955) and Ceplecha (2001)

We will assume

- spherical particles
- moving in a straight line

And we will need

- equations of motion
- equations of luminance
- to construct a virtual CCD image
- to compute the statistic
Equations of motion

- **braking equation**

\[ \frac{d \nu}{dt} = -\frac{\Gamma A}{m^{1/3} \rho^{2/3} \rho_{air} v^2} \]

- **equation of ablation**

\[ dm = -\frac{\Lambda A}{2Q} \frac{m^{2/3}}{\rho^{2/3} \rho_{air} v^3} \]

- **equation of luminance**

\[ L = \tau(v) \frac{\Lambda A}{4Q} \frac{m^{2/3}}{\rho^{2/3} \rho_{air} v^5} \]

\( \tau(v) \) determined by Jones & Halliday (2001)
Simulation of flight

Equations are solved by the Runge–Kutta integrator (RK4)

- until complete ablation of the particle
- properties recorded in every Frame (1/15 second)
- multiple integration steps between frames
Virtual observations

Next, we create observations

- multiple observers on the ground
- each represents an AMOS camera
- only the brightest frame is analyzed
Selection bias

Detection efficiency is not constant!

- probability of detection is higher for meteors that are
  - bright
  - fast
  - close to zenith
  - ...

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Selection bias – quantitative

Bias summarized in detection probability functions

- determine whether a meteor is detected
- magnitude dependence

\[ D(m; f, m_0, \omega) = \frac{f}{1 + e^{m-m_0/\omega}} \]

- altitudinal dependence

\[ A(\theta; \alpha) = (\sin \theta)^\alpha \]

- we need to establish values of parameters \( f, m_0, \omega, \alpha \)
- assume the effects are independent
AMOS limiting magnitude estimation

\[ f(x) = \frac{0.931}{1 + \exp \left( \frac{x - (-0.598)}{2.015} \right)} \]
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What is it

**All-Sky Meteor Optical Detection Efficiency Simulator**

- a suite of five **Python** scripts
- implements the described model
Evaluation

- we processed one model night
  - Perseids 2016 (August 11–12)
  - observed from Tepličné (48.6822° N, 19.8580° E, 700 m)
  - seven hours (19:00 – 02:00 UTC)
  - mass index $s = 1.8$, later varied

- 100,000 meteoroids are generated
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AMOS apparent magnitude distribution at TEPLICNE

Relative frequency vs. apparent magnitude (bin width 0.5)
AMOS apparent magnitude distribution at TEPLICNE

Relative frequency

apparent magnitude (bin width 0.5)

Simulation
AMOS
Magnitude DPF

\[ D(m; f, m_0, \omega) = \frac{f}{1 + e^{\frac{m-m_0}{\omega}}} \]

- a wide range of parameter combinations was searched
- fill factor \( f \) does not contribute any information
Magnitude DPF

\[ D(m; f, m_0, \omega) = \frac{f}{1 + e^{\frac{m-m_0}{\omega}}} \]

- a wide range of parameter combinations was searched
- fill factor \( f \) does not contribute any information
- find values of parameters where \( \chi^2 \) is minimal
- account for statistical noise
χ² comparison of magnitude distributions

Falloff rate (ω)

Limiting magnitude (m₀)
\( \chi^2 \) comparison of magnitude distributions

- Falloff rate \( (\omega) \)
- Limiting magnitude \( (m_0) \)
AMOS apparent magnitude distribution at TEPLICNE
There are way too many bright meteors...
Mass index $s$

There are way too many bright meteors...

- a natural reaction is to try another value of $s$
  - a full range 1.6 – 2.8 was tried
- best fit for $s = 2.15$
- no value below 2 is consistent with observations
AMOS apparent magnitude distribution at TEPLICNE

Relative frequency vs. apparent magnitude (bin width 0.5)

Simulation

AMOS
Altitudinal DPF

\[ A(\theta; \alpha) = (\sin \theta)^\alpha \]

- only a simple 1D fit
- a very well defined minimum at \( \alpha = 0.4 \)
\( \chi^2 \) comparison of altitude distributions
Results
Total flux

Finally, we may calculate the total flux

- simulation is run again with AMOS’s optimal DPF parameters

\[
A(\theta) = (\sin \theta)^{0.4}
\]

\[
D(m) = \frac{0.93}{1 + e^{m+0.1 \over 0.35}}
\]

- the number of meteors is scaled to match observations
Total flux

Finally, we may calculate the total flux

- simulation is run again with AMOS’s **optimal DPF parameters**

\[ A(\theta) = (\sin \theta)^{0.4} \]

\[ D(m) = \frac{0.93}{1 + e^{m+0.1 \over 0.35}} \]

- the number of meteors is **scaled** to match observations

- 135 000 particles per 1 000 000 km² h
- 0.338 kg per 1 000 000 km² h \( \approx \) 43 kg h⁻¹ over entire Earth
- all particles in size range 1 mm – 1 m
Comparison to known values

- results consistent with recent estimates
  - Blaauw et al., 2016: 98 000 particles per 1 000 000 km² h
  - Molau, 2017: 47 000 particles per 1 000 000 km² h (but up to 6.5 m)
- high fraction of small particles ($s = 2.15$)
- more precise evaluation is needed
- a larger observational dataset would also help
## Conclusion

Conclusion
Summary

- we have designed and implemented the simulation
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- it is a surprisingly good method
  - correct geometry and luminance data and statistic
  - observations comparable to real data
  - and the results are aesthetically pleasing
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  - correct geometry and luminance data and statistic
  - observations **comparable** to real data
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- flux values are not perfect
  - we were able to estimate the flux
  - a good fit was found
we have designed and implemented the simulation

- it is a **surprisingly good** method
  - correct geometry and luminance data and statistic
  - observations **comparable** to real data
  - and the results are aesthetically pleasing

- flux values are not perfect
  - we were able to estimate the flux
  - a good fit was found
  - mass index seems to be much higher than known values
  - a much larger observational dataset is needed
Thank you for your attention

*The scientist is not a person who gives the right answers, he’s one who asks the right questions.*

Claude Lévi-Strauss
*Le Cru et le Cuit, 1964*
**References**


- **Luciuk, M.**: Meteor Showers. 
  
