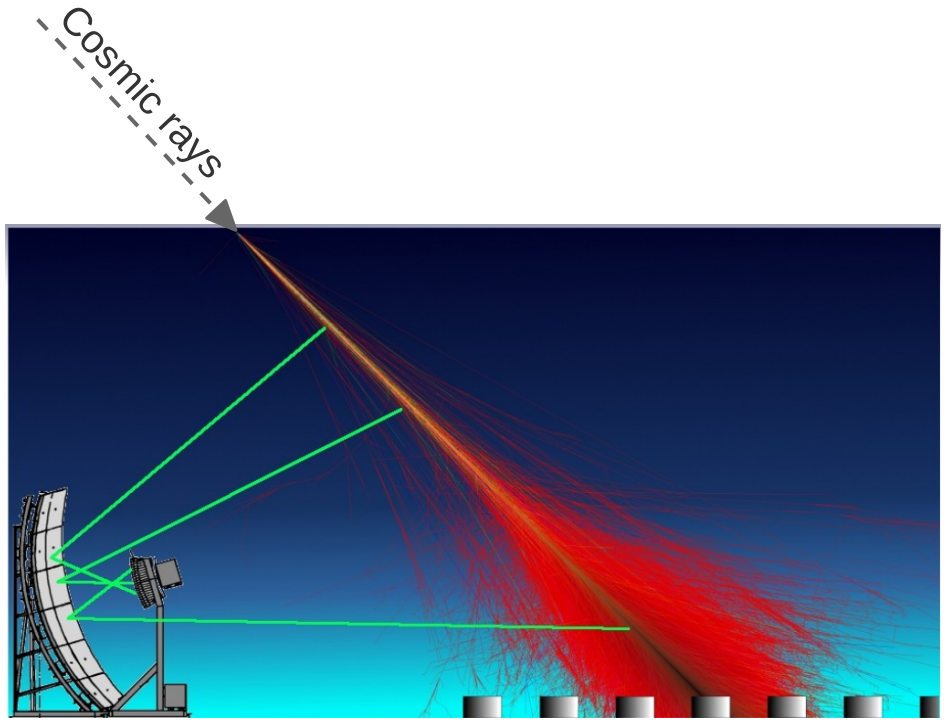
Karlsruher Institut für Technologie

Measurement of aerosols above the Pierre Auger Observatory using the side-scattered light from the laser of the Aeolus satellite

AtmoHEAD workshop 2022

Felix Knapp for the Pierre Auger Collaboration

The Pierre Auger Observatory



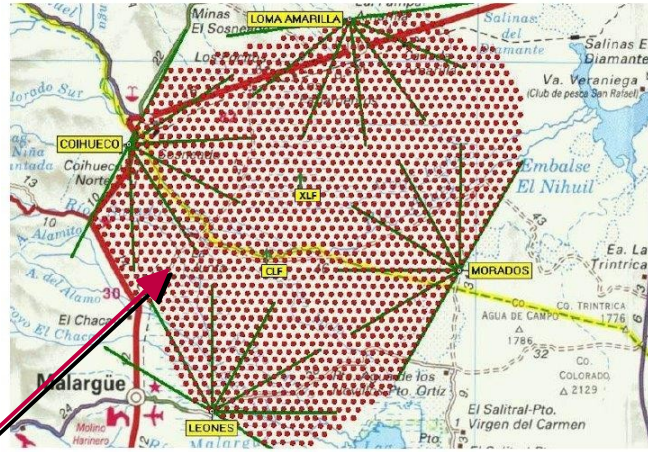
Fluorescence Detector

Surface Detector

The **S**urface **D**etector

- Array of 1660 tanks,
  each filled with 12t of water
- Charged shower particles create Cherenkov light in water,
  Measured with photomultiplier tubes

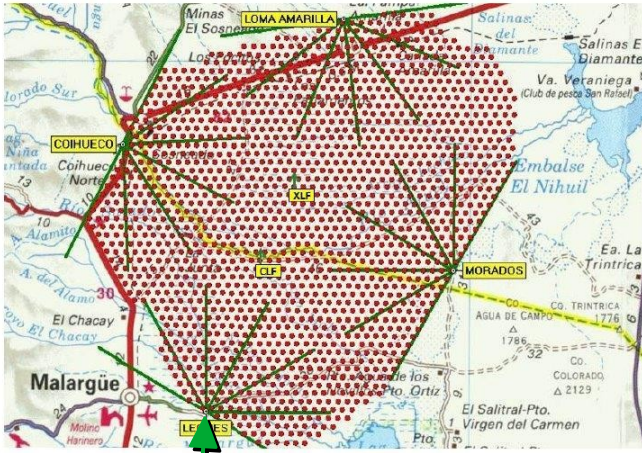
Only particles in SD,
Here no laser is visible



The **F**luorescence **D**etector

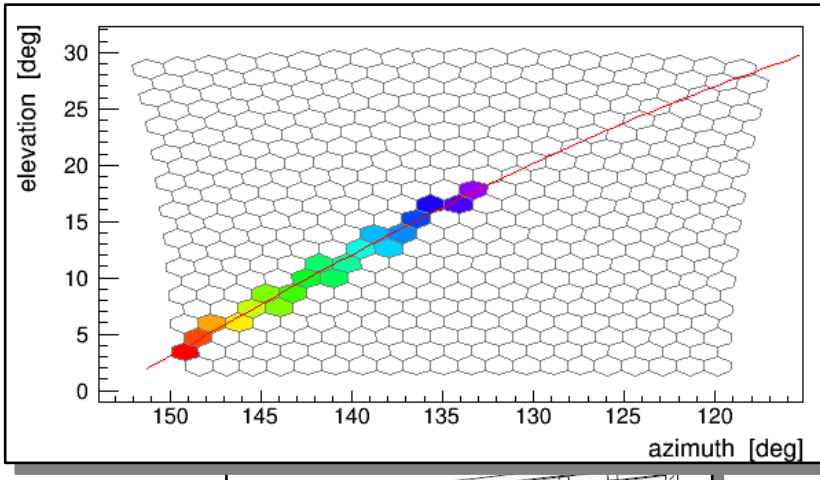
- Four stations with six telescopes each,
  fov: 30° $\times$ 30° $\rightarrow$ 180° total per station
- Measurement of (Fluorescence + Cherenkov) light

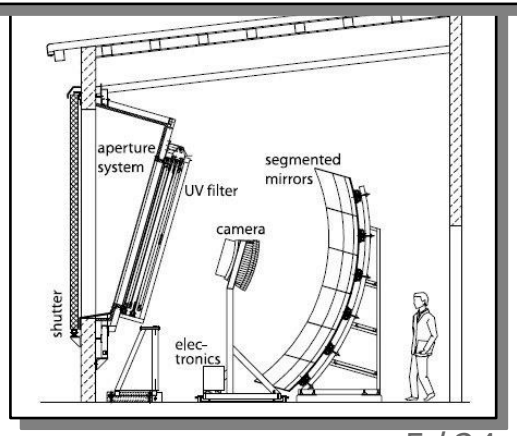
Here scattered laser appears



The **F**luorescence **D**etector

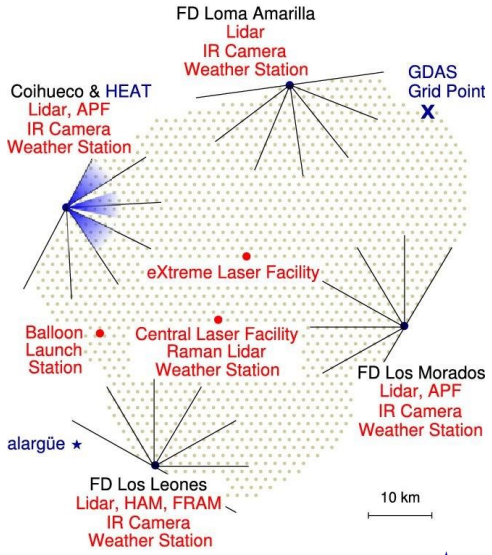
- Four stations with six telescopes each,
  fov: 30° × 30° → 180° total per station
- Measurement of (Fluorescence + Cherenkov) light
- Telescope:
  - Light enters window, hits 10m² spherical mirror
  - Focussing towards camera
    - 440 pixel, PMTs as light sensors
    - Arranged in hexagonal pattern
    - Shower (or laser beam) seen as track of activated pixels





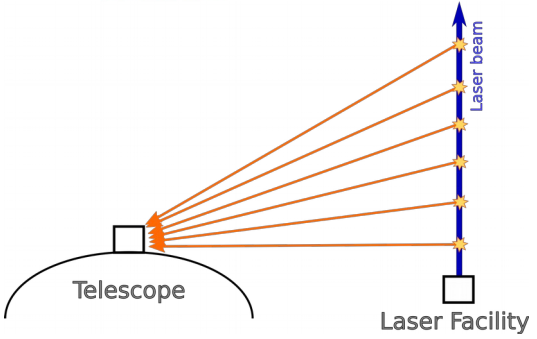
See talk on Wednesday by Bianca Keilhauer

Atmospheric Monitoring in the Pierre Auger Observatory



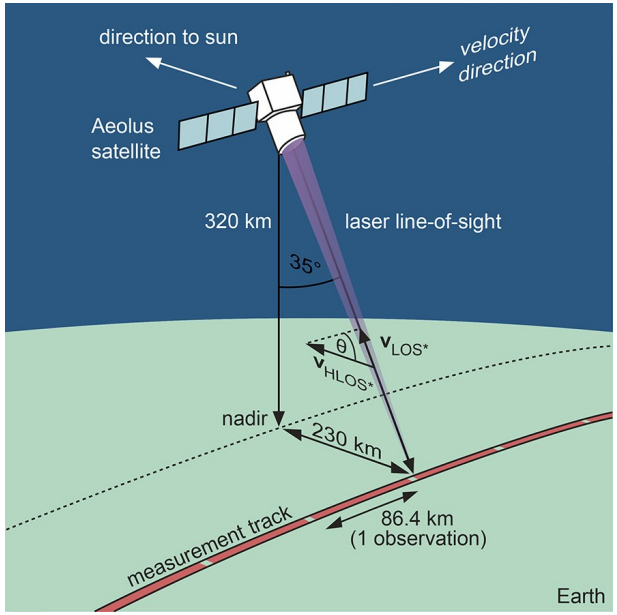
- Good knowledge of atmosphere is crucial
- Laser facilities (CLF and XLF)
  - 355nm-Laser in center of the Observatory
  - Laser shots from ground upwards,
    scattered light measured in **F**luorescence **D**etector
  - measurements taken regularly during FD-measurements

  → Attenuation of light gives info about aerosols
- Also lidar systems at each FD-station, weather stations, ...

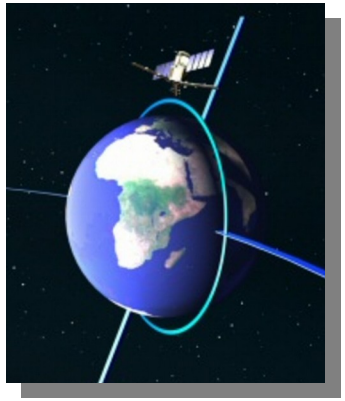


The Aeolus Satellite

- ESA-satellite for wind profile measurements
- Equipped with UV-lidar (λ=355nm), emitted under 35° to nadir

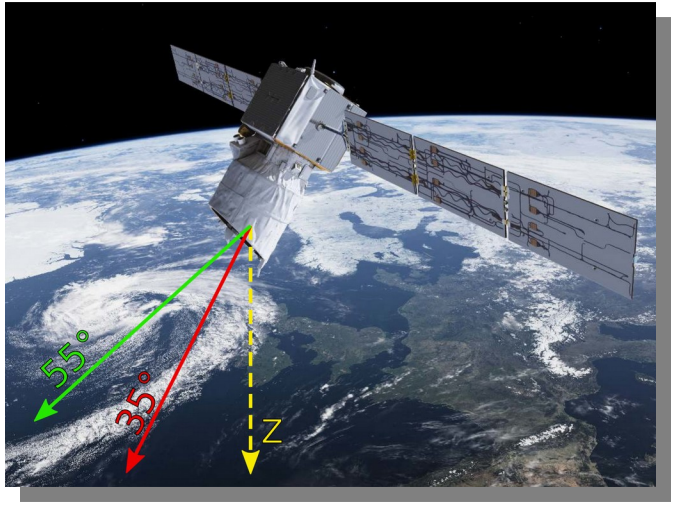


The Aeolus Satellite

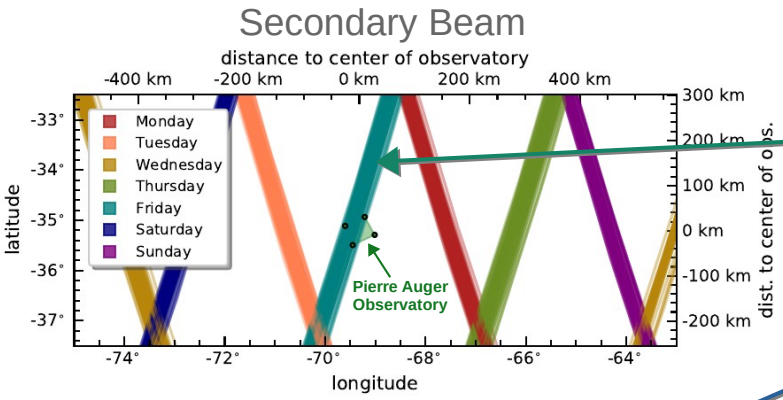


- ESA-satellite for wind profile measurements
- Equipped with UV-lidar (λ=355nm), emitted under 35° to nadir
- Additionaly: Secondary beam at 55° (internal reflection of main beam)

  → Aeolus laser like a “moving” CLF

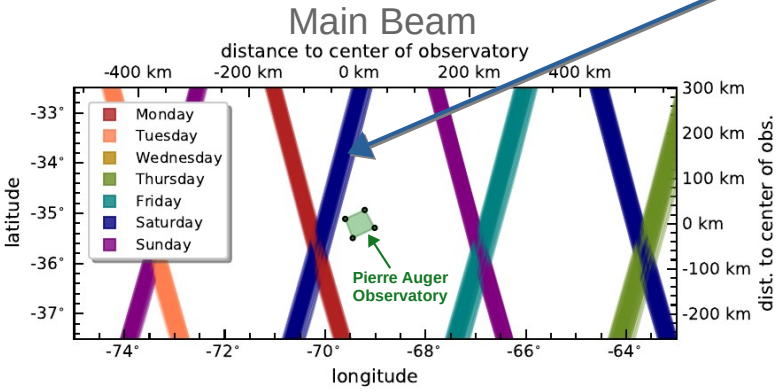


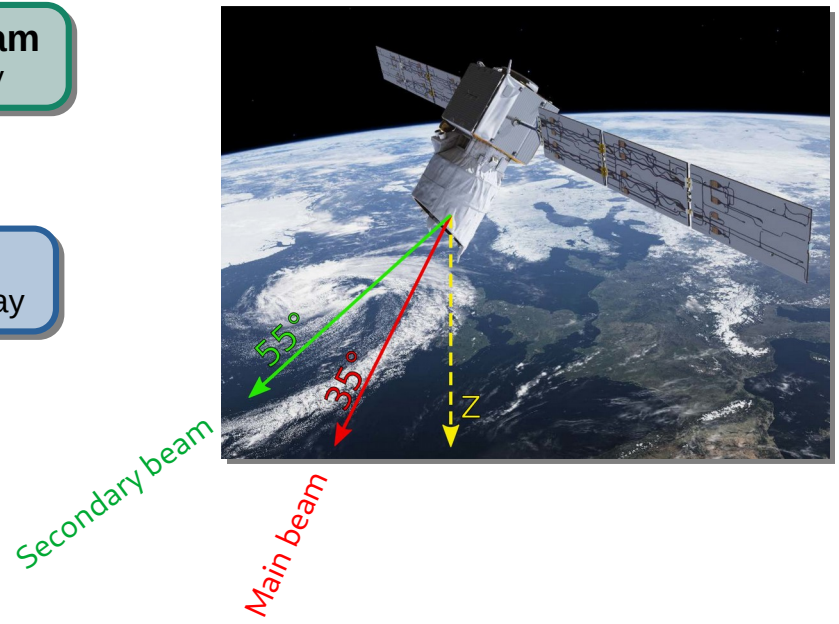
The Aeolus Laser in the Pierre Auger Observatory



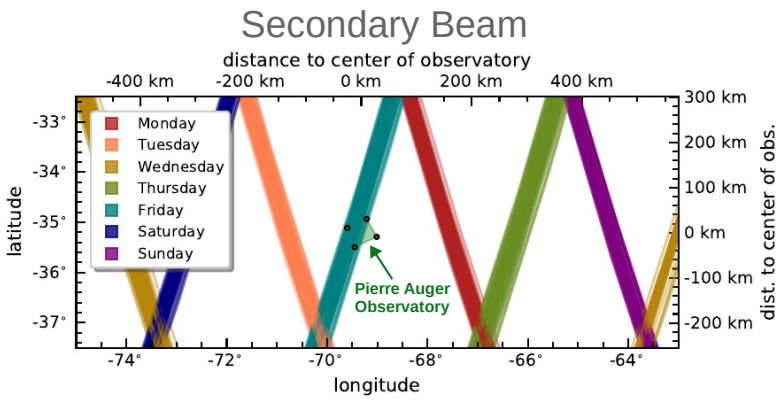
Secondary Beam
visible on Friday

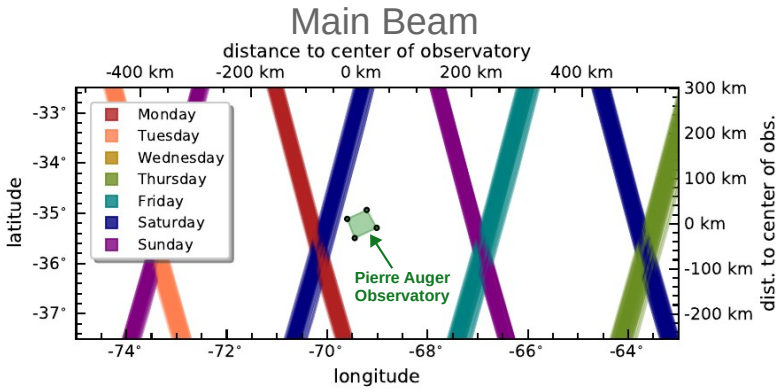
Main Beam
visible on Saturday

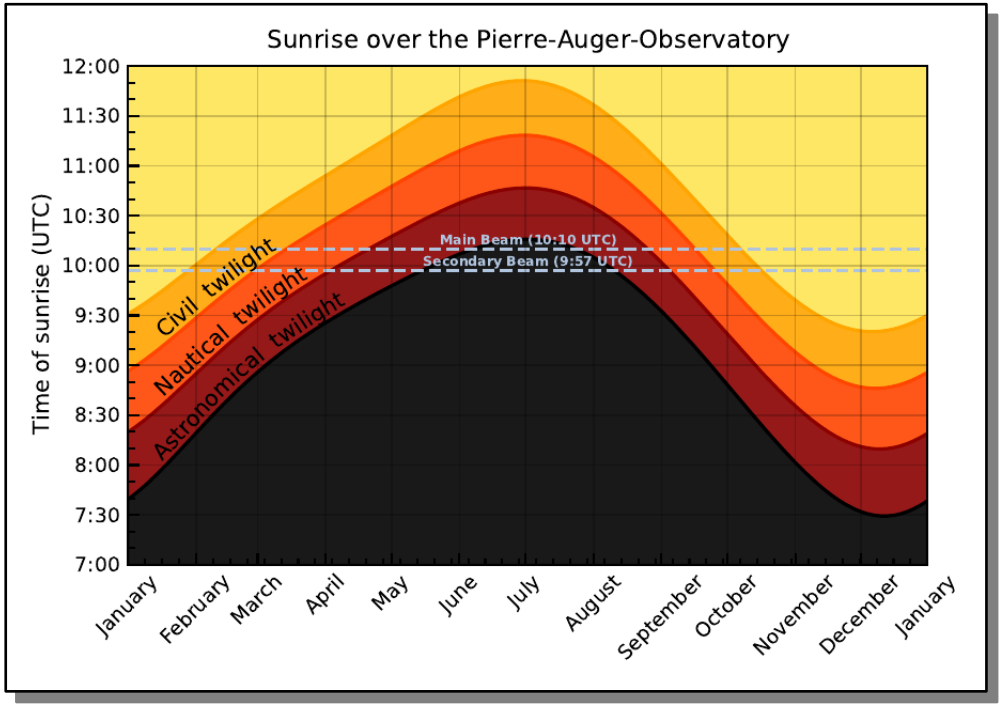




The Aeolus Laser in the Pierre Auger Observatory

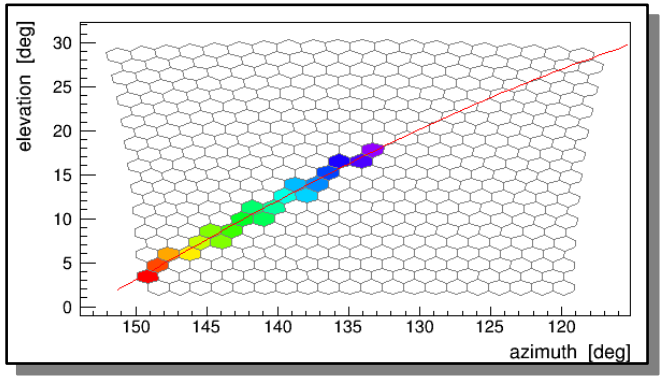


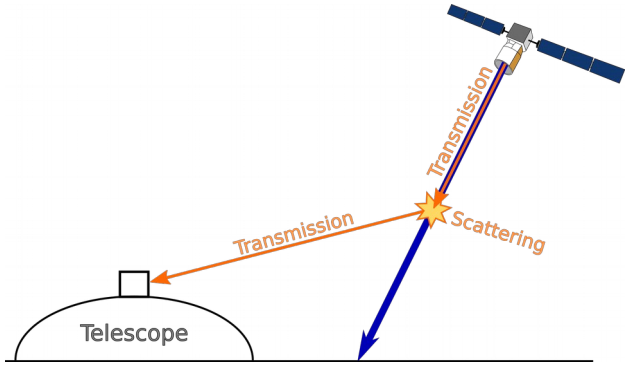


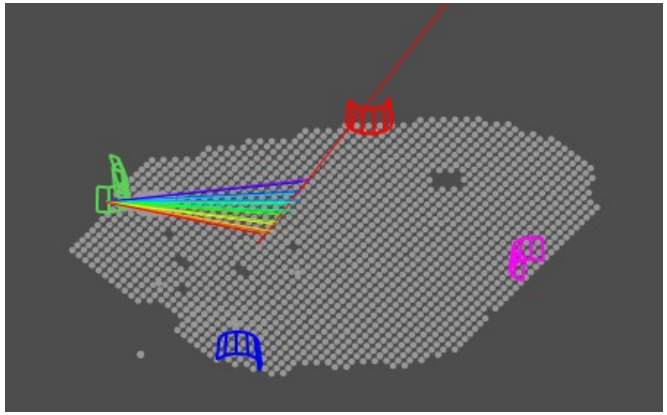


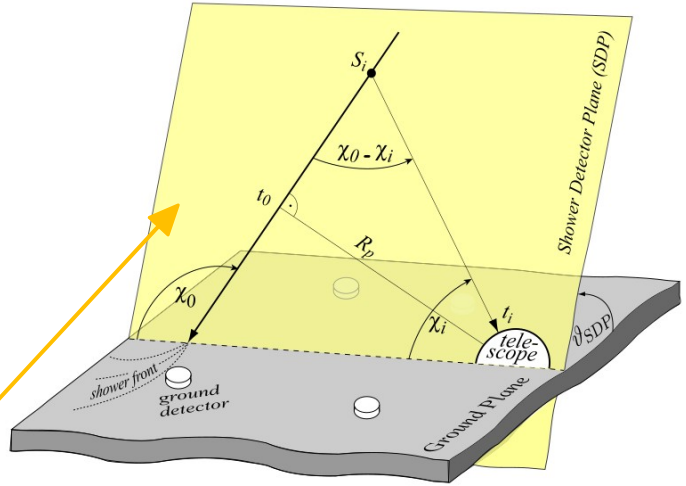
Only visible from May to August

Laser Geometry reconstruction with the FD



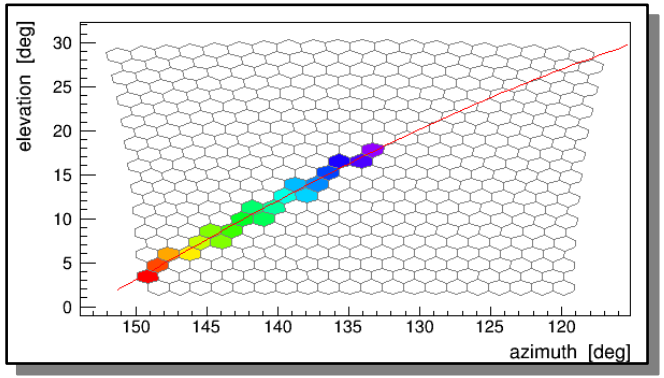


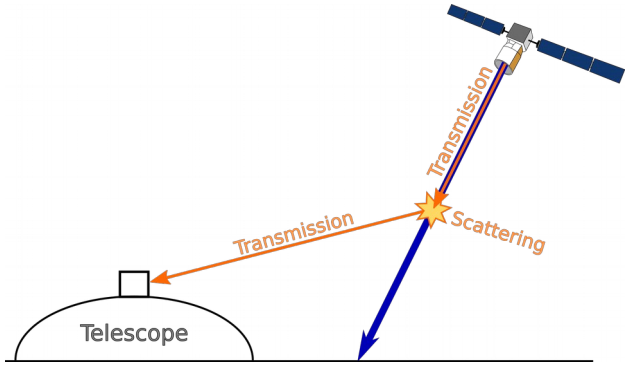


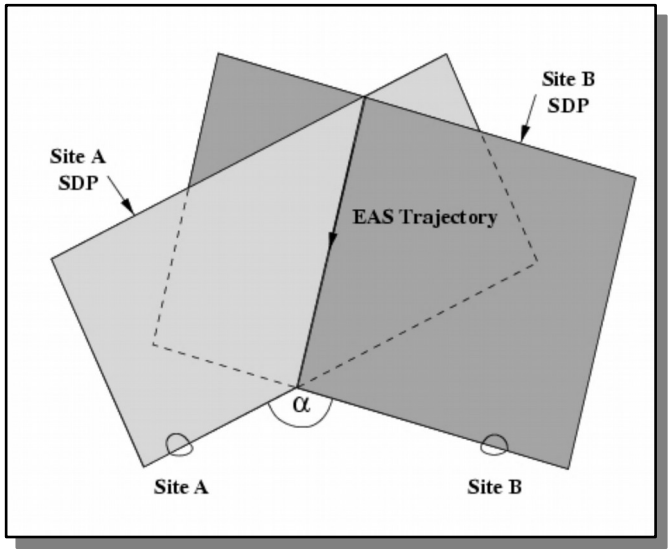


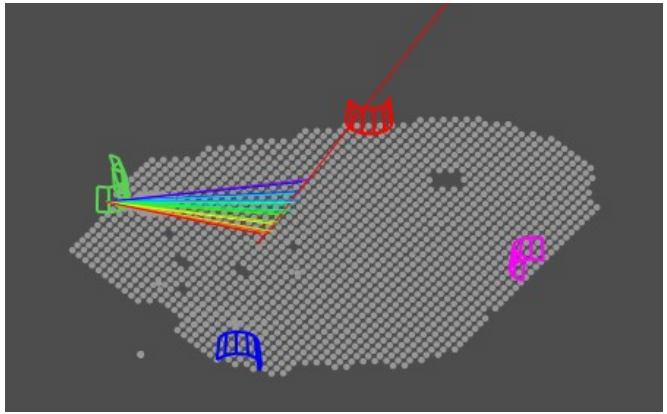
- Geometry reconstruction:
  1. Fit **S**hower **D**etector **P**lane
  2. Get remaining geometry from timing information

Laser Geometry reconstruction with the FD









- Geometry reconstruction:
  1. Fit **S**hower **D**etector **P**lane
  2. Get remaining geometry from timing information
- Improved for
  - Hybrid events (+SD) → additional time of SD (not for laser shots)
  - Stereo events (≥2 Telescopes) → intersection of 2 SDPs

Monocular reconstruction with fixed angles

high Laser frequency (~50Hz),
Detector dead time

↓

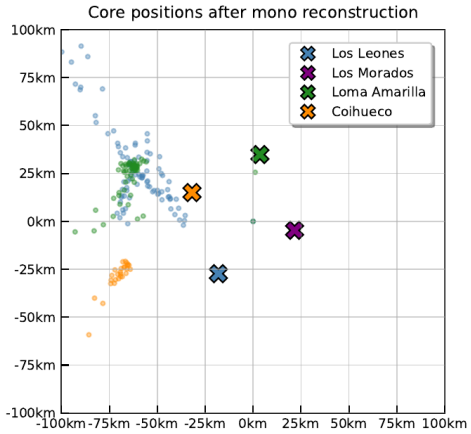
Only few stereo events

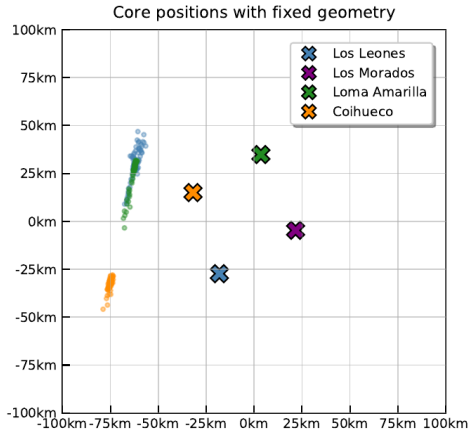
↓

Need mono events for analysis

Improvement of mono reconstruction:

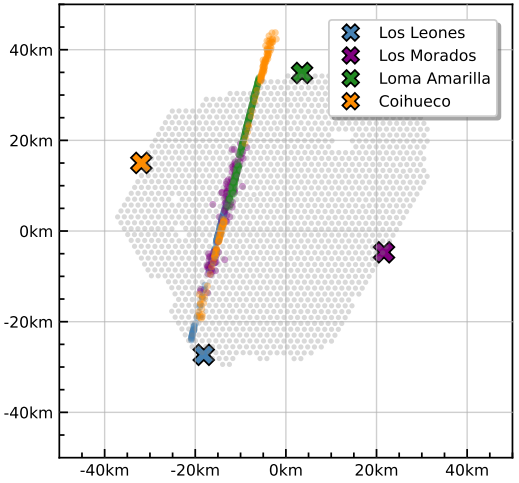
- Take all stereo events
- Reconstruct arrival direction from stereo events
- Fix arrival direction in mono reconstruction

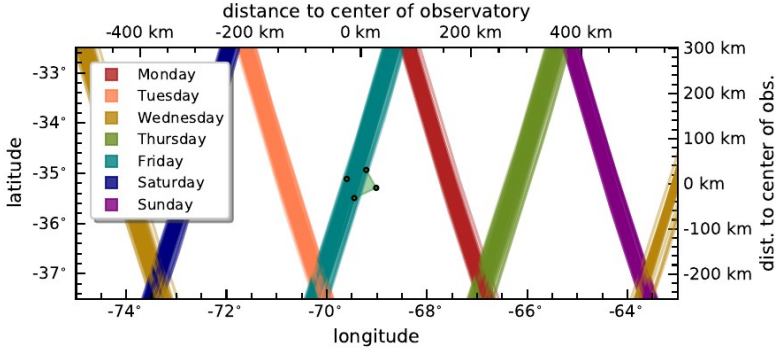




Reconstructed impact points of one transition

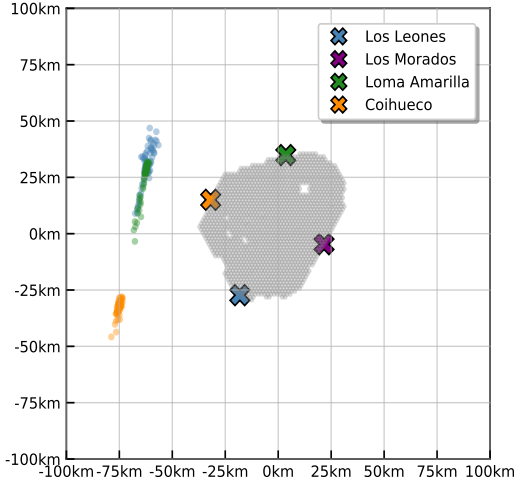
Secondary Beam

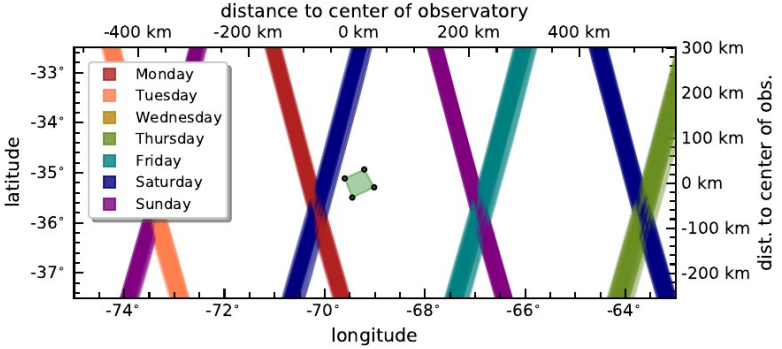




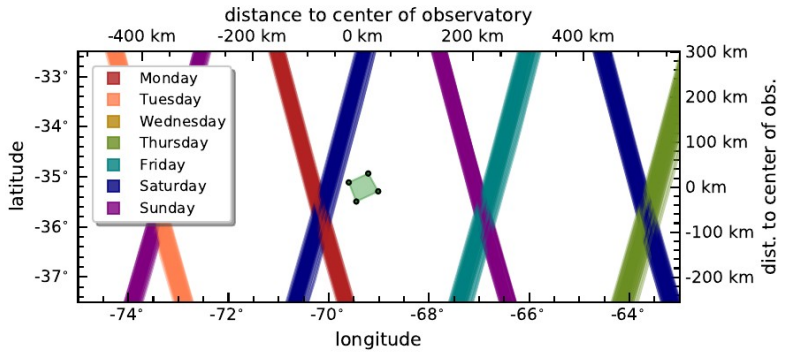
~100 shots per transition, within ~10s

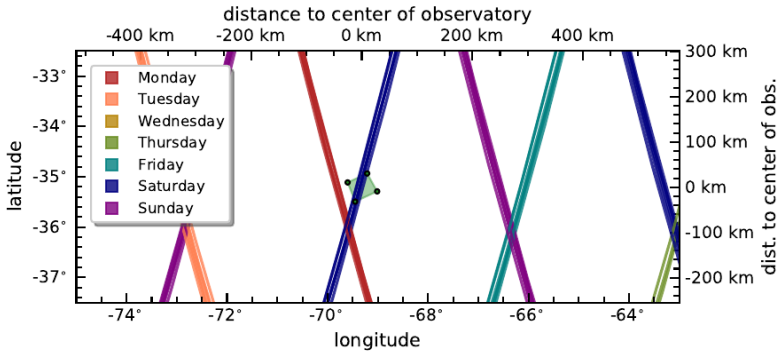
Main Beam



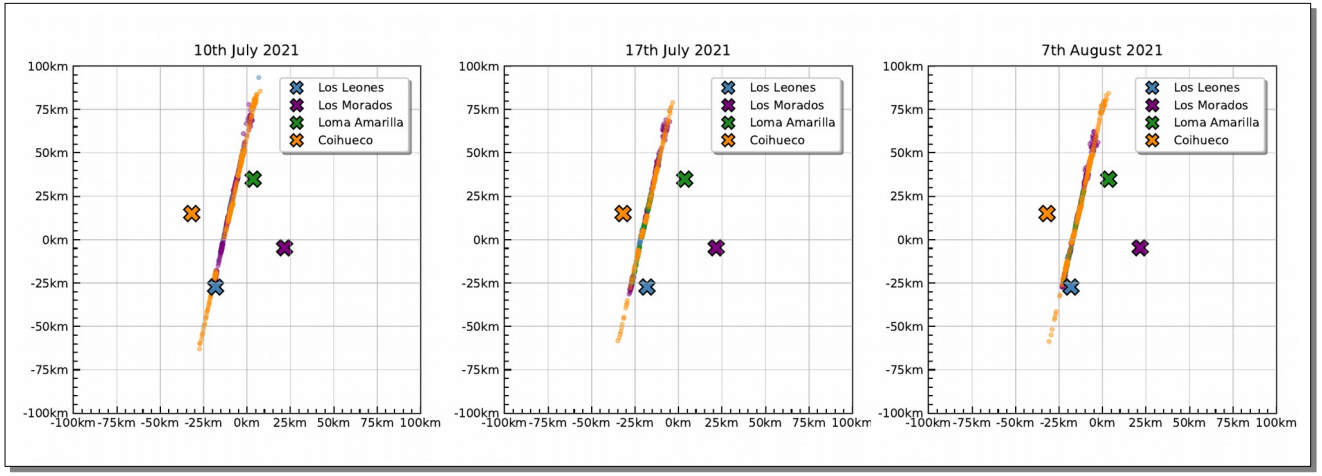


New position of the Main Beam track after July 2021

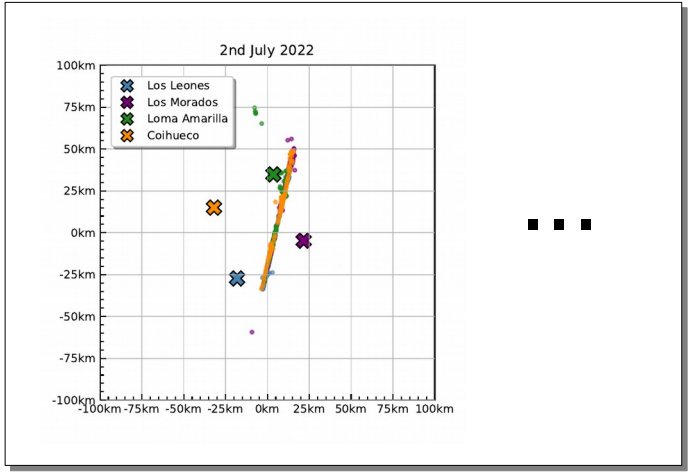




2021



2022



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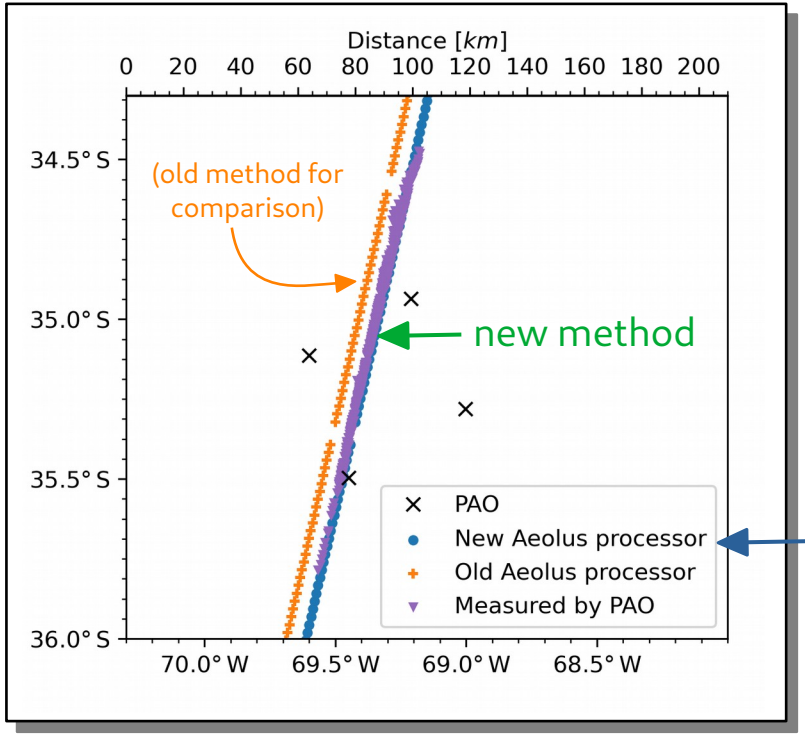
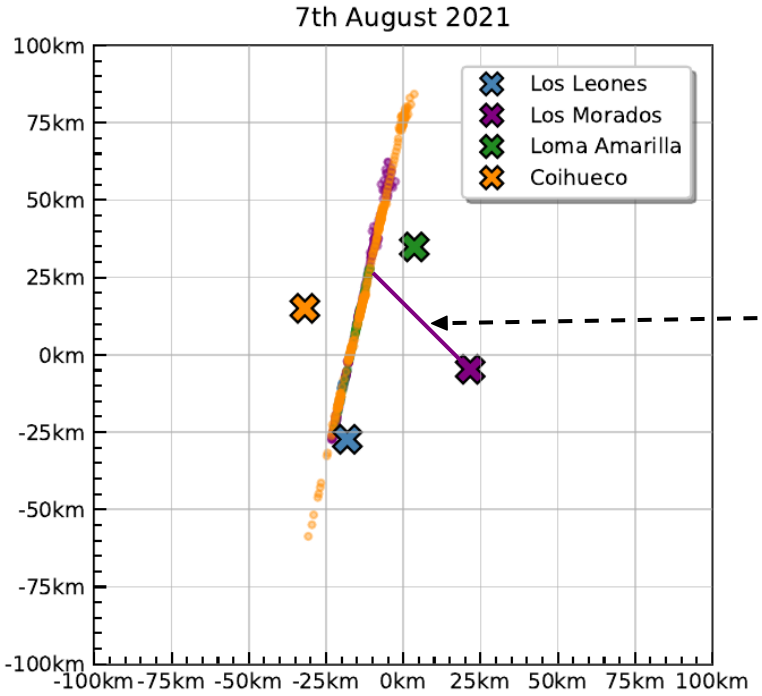
Laser Position – Aeolus vs. Auger

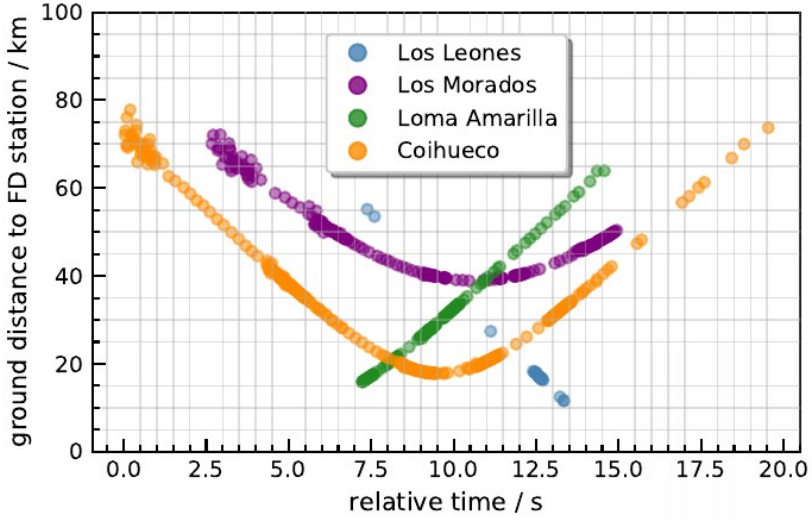


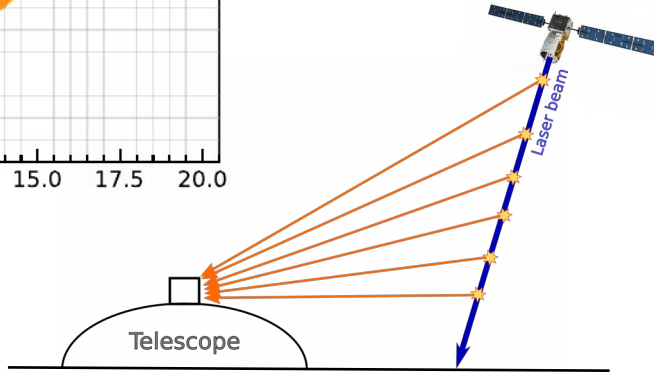
bug fix of the Aeolus processor

Plot by Isabell Krisch (DLR)

Laser-Telescope-Distance



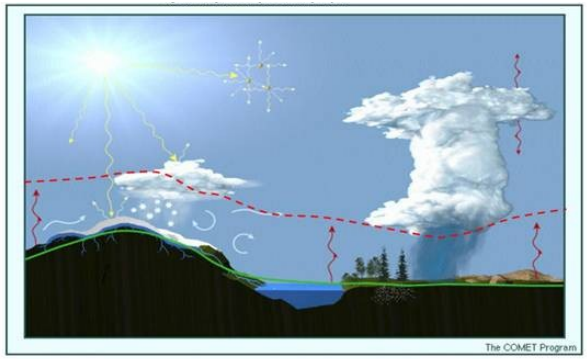




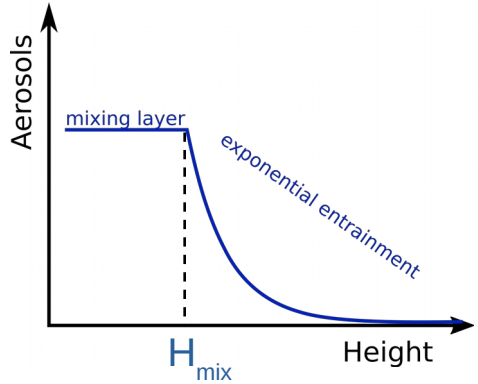
→ **use measurement of the same laser from many different distances for aerosol determination**

Parametric Aerosol Model

- Express aerosol content with model
  - Constant concentration within mixing layer
  - Exponential decay above mixing layer
- Model is described by three parameters
  - Attenuation length at ground level L
  - Height of mixing layer H_{mix}
  - Scale Height S of exponential decay above mixing layer

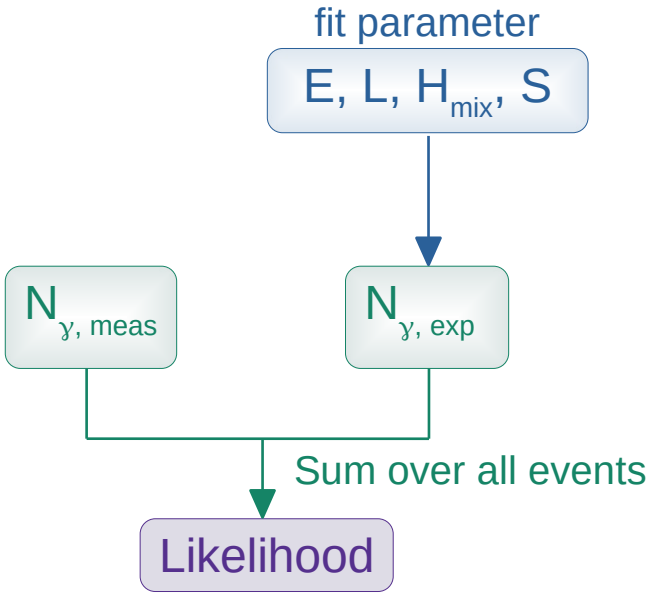


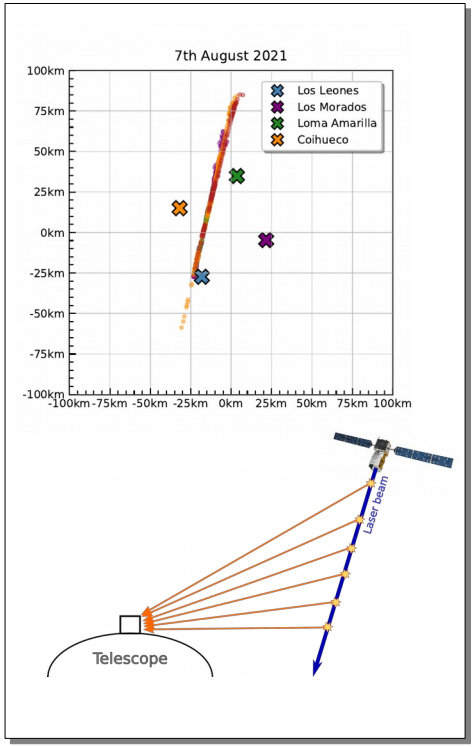
https://en.wikipedia.org/wiki/Planetary_boundary_layer



Likelihood fit of aerosol parameters

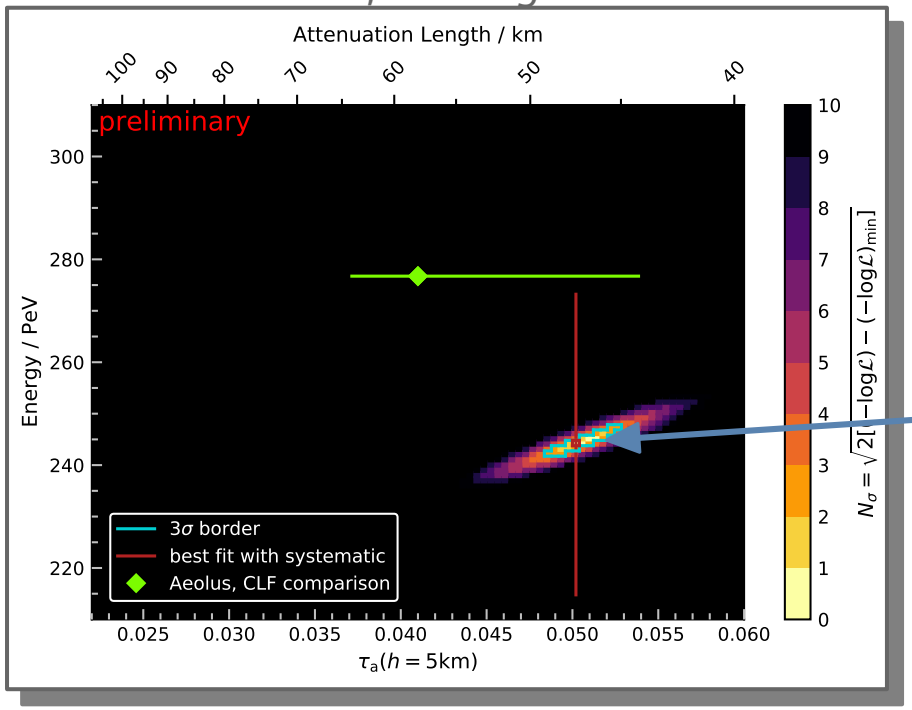
- Energy and L, H_{mix}, S as free parameters in likelihood fit
- With known geometry: calculate expected photons at telescope for E, L, H_{mix}, S
- Comparison with measurement
- Sum over all events gives one Likelihood for whole transition





Scan in two dimensions

Main beam, 3rd August 2019

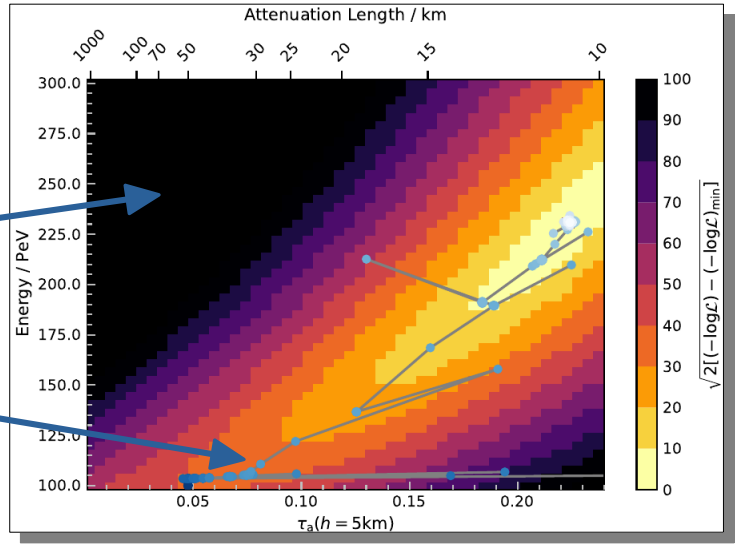


- Here: only E and L free, other two parameters fixed
- Likelihood calculated for every combination of E and L
- Maximum Likelihood gives best fit E, L

Next step: minimization algorithm

- Desired: Scan with all parameters instead of only two
- e.g. 4-dimensional scan with 50 values each:
  N(E) x N(L) x N(H_{mix}) x N(S) x 800 Events = $5 \cdot 10^9$ calculations of Likelihood
  → inefficient
- Instead: search for maximum Likelihood with Minuit

Test in two dimensions

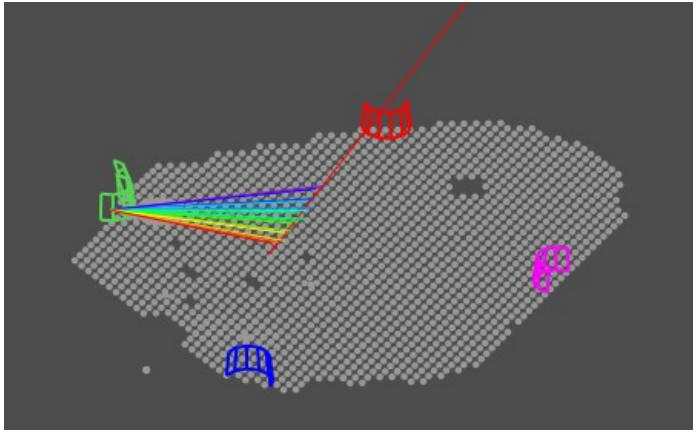


background: scan with previous method (here only one event)

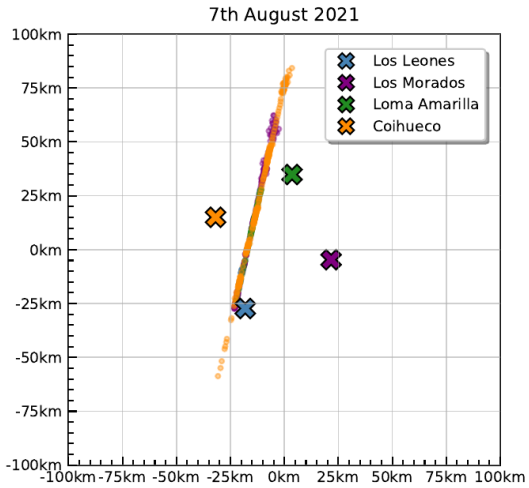
path: minimization steps

Summary

- Aeolus: satellite emitting UV laser shots, visible in FD for few nights per year
- Geometry of laser shots can be reconstructed from the FD data



Summary



- Aeolus: satellite emitting UV laser shots, visible in FD for few nights per year
- Geometry of laser shots can be reconstructed from the FD data
- Laser is seen from many distances within few seconds → leverage on aerosol content of atmosphere
- Energy and aerosol parameters are obtained by likelihood fit to one complete laser transition

Outlook

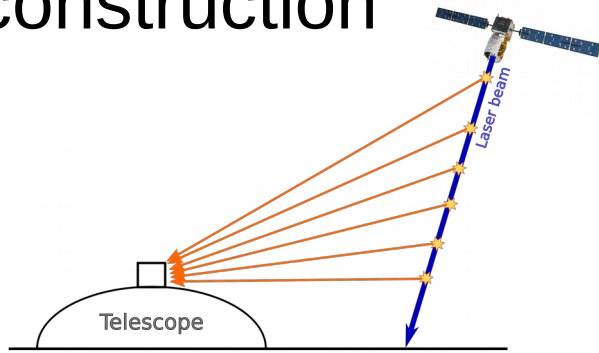
- Perform Likelihood fit in four dimensions with Minuit
- Test fit algorithm with simulations
  - Simulate laser transition with certain E, L, H_{mix}, S
  - How well are these parameters fitted?
- Comparison of fitted aerosol parameters to CLF-measurement
  → systematic cross check with different method
- Other uses of laser data:
  - test of horizontal uniformity
  - test of relative calibration of telescopes
- Launch of EarthCARE satellite in 2023(?) with similar lidar instrument

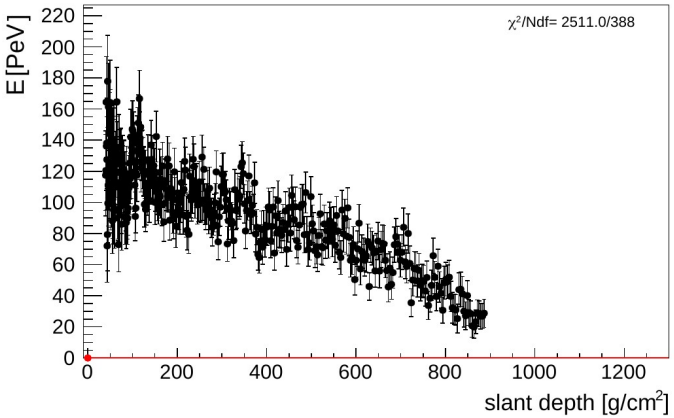
Backup Slides

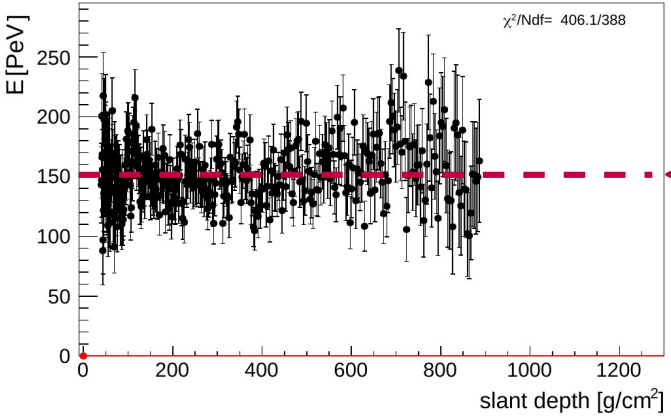
Example: effect of aerosols on laser reconstruction

Average values:
L = 52645m
H_{mix} = 0m
S = 2889m

L, H_{mix} and S fitted:
L = 9758m
H_{mix} = 507m
S = 1070m





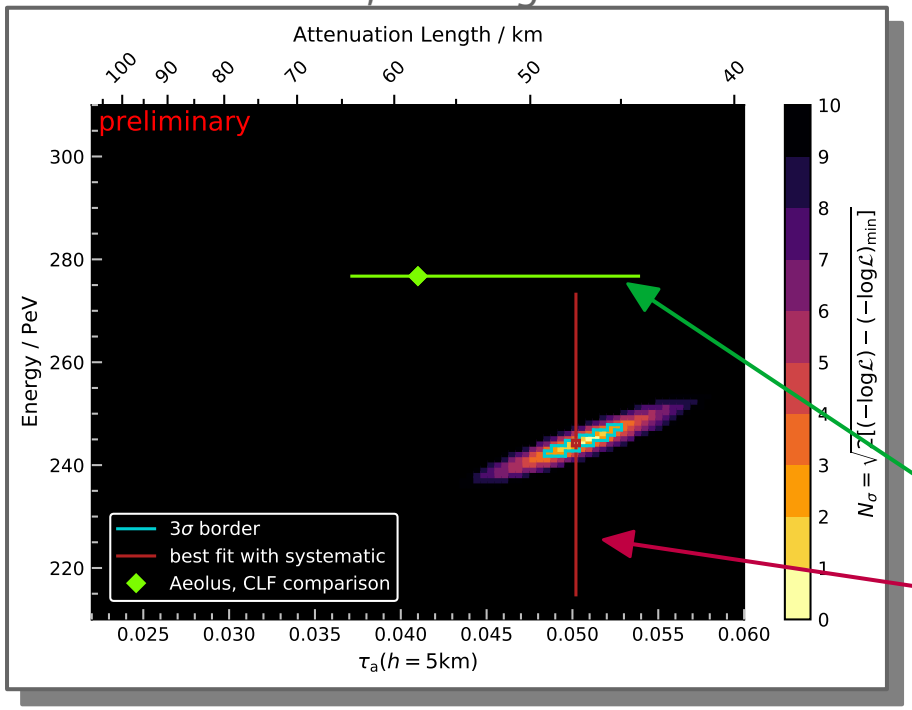


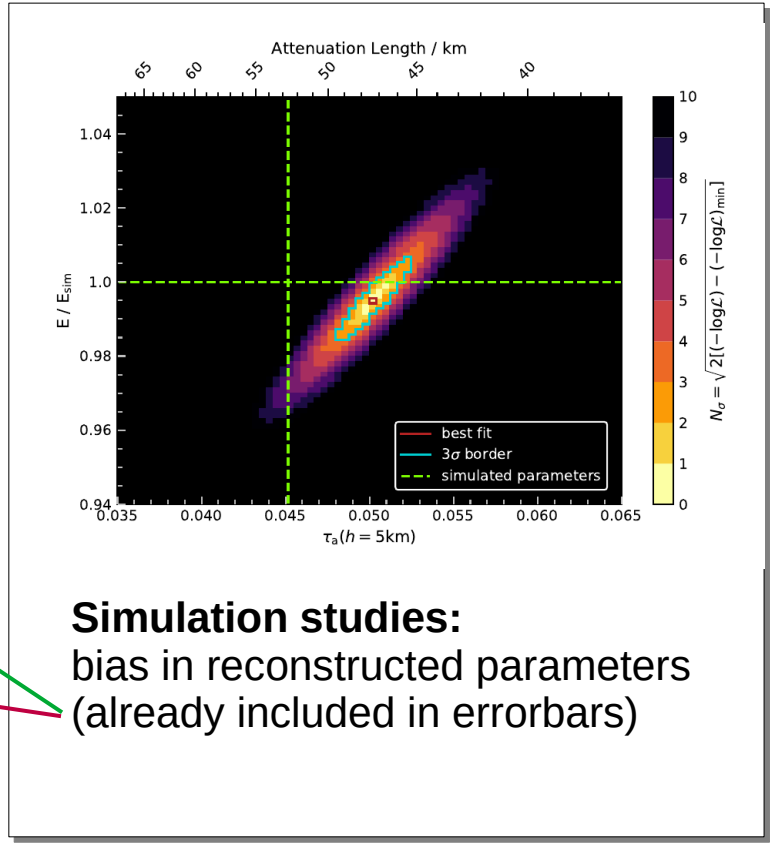
ideally:
constant energy

Here also only one event

Likelihood fit bias in simulation studies

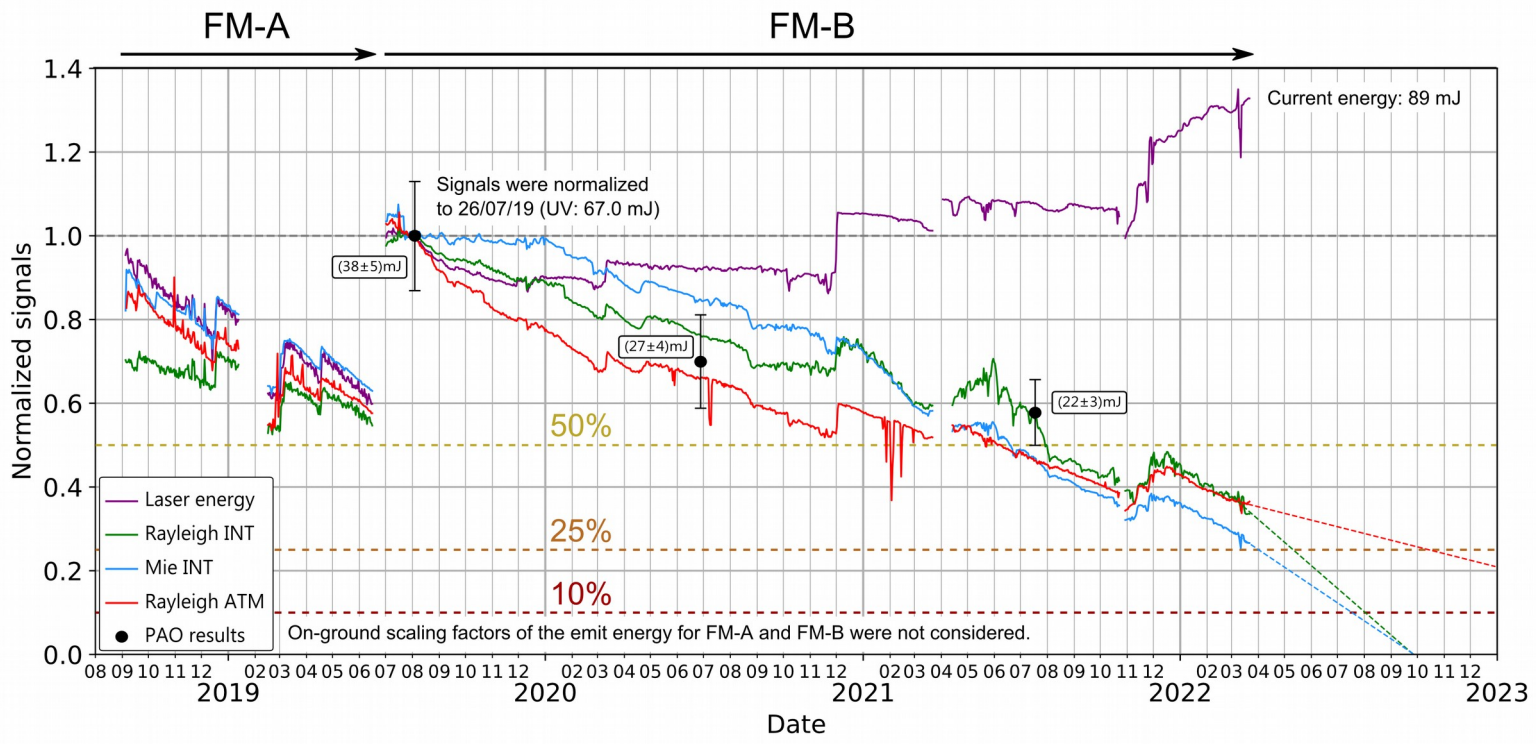
Main beam, 3rd August 2019





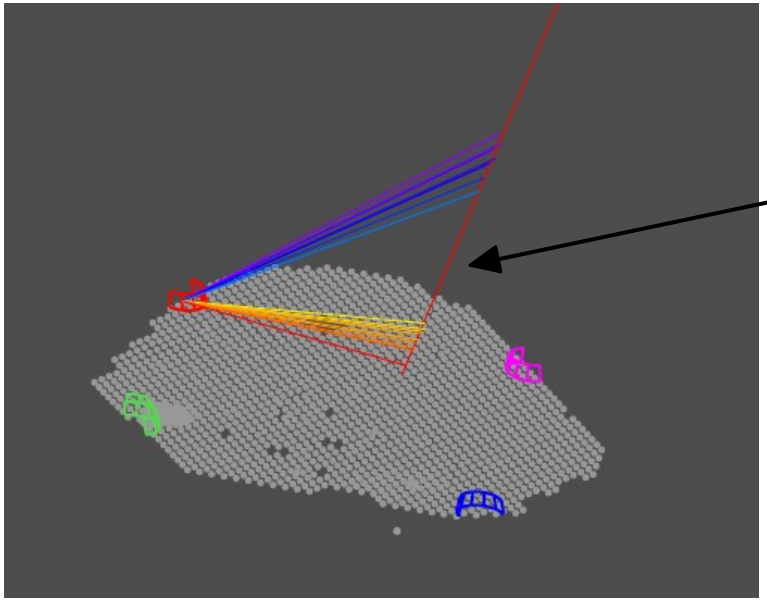
Simulation studies:
bias in reconstructed parameters
(already included in errorbars)

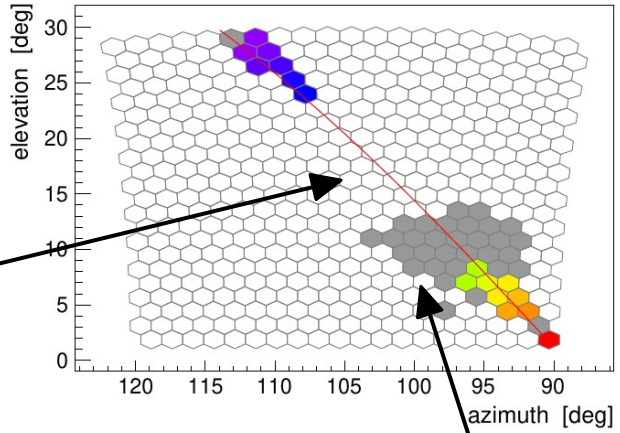
Laser energy over time



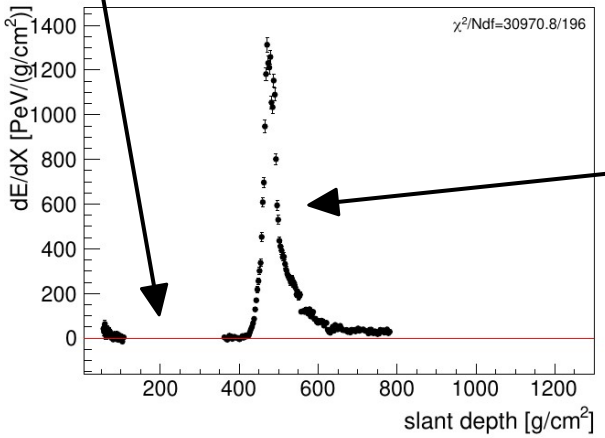
Plot by Oliver Lux (DLR)

Example: measured event with cloud





Gap in visibility of laser beam



"blob" of light from scattering in cloud