INFN
Istituto Nazionale di Fisica Nucleare

The ARCADE project

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UNIVERSITÀ DEGLI STUDI DI TORINO
ALMA UNIVERSITAS TAURINENSIS

MINISTERO DELL'ISTRUZIONE, DELL'UNIVERSITÀ E DELLA RICERCA

FUTURO IN RICERCA

CETEMPS
Integration of remote sensing techniques and modeling for the forecast of severe weather

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MINISTERO DELL'ISTRUZIONE, DELL'UNIVERSITÀ E DELLA RICERCA

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ARCADE

Atmospheric Research for Climate and Astroparticle DEtection

- Approved by the MIUR in 2011
- started in 2012 – ended in 2016
- involves people from : University / INFN of Naples and Turin, CETEMPS/DPSF L'Aquila + Colorado School of Mines, USA

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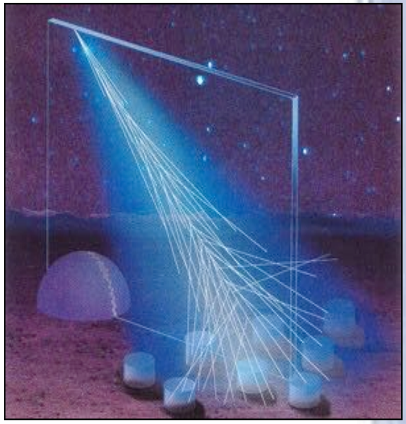
Atmosphere and UV light

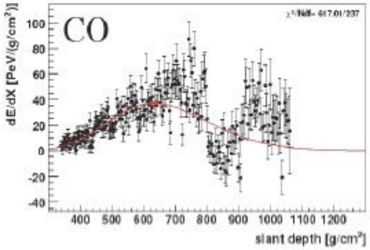


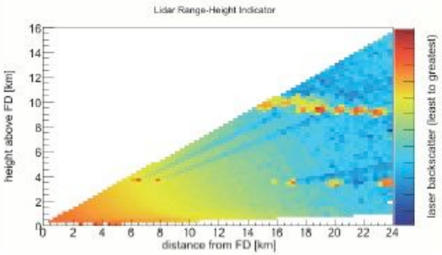
- UHE cosmic rays entering the atmosphere determine the production of showers of secondary particles (EAS) and of UV light (fluorescence / Cherenkov light)
- UV light can be detected to infer the properties of the primaries

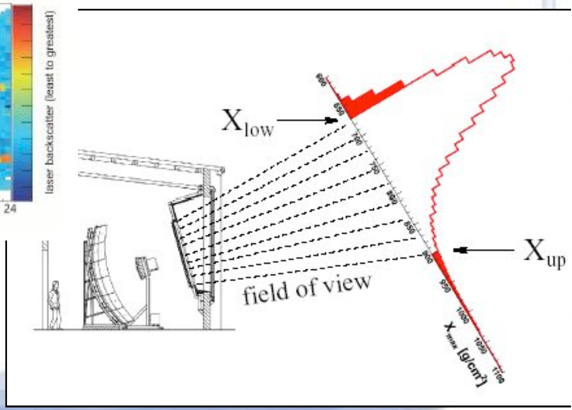
The atmosphere is responsible for both the production and attenuation of UV light

Properties of the atmosphere need to be well known : the scattering of light due to aerosols is the most significant and variable phenomenon, influencing the correct determination of the longitudinal development of the EAS in air and of its energy. Clouds distort UV light profiles (enhancing or blocking light).

aerosol layer

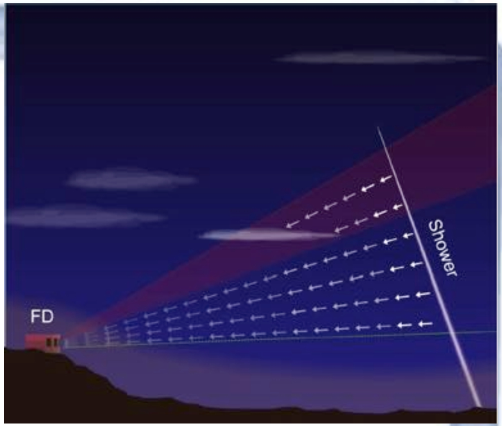






The role of the atmosphere

Atmosphere is responsible for both production
and attenuation of UV light



Molecules   Aerosols

Well known on a daily basis

Measurements of p, T at ground + profiles with height full determine the molecular density profiles.

Poorly known, and highly variable in time and space.

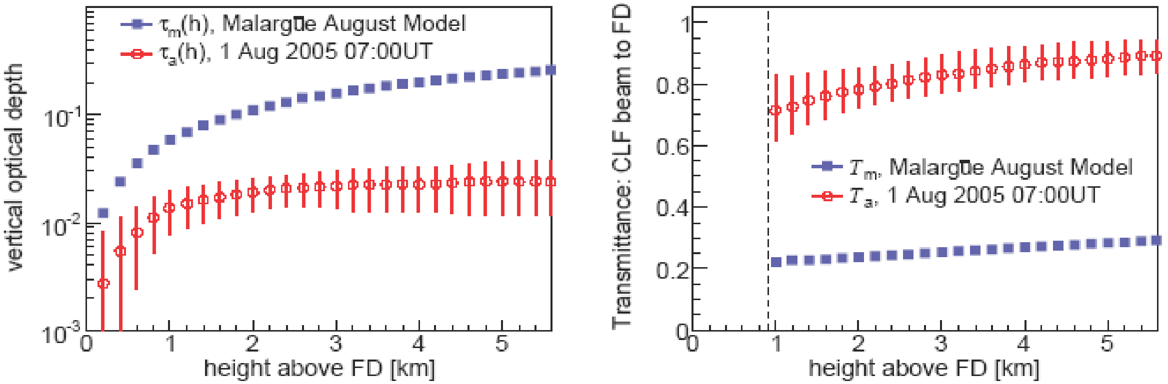
Network of instruments for a continuous monitoring needed

$$I(\lambda,s)=I_0(\lambda,s)T_{mol}(\lambda,s)T_{aer}(\lambda,s)(1+f)\frac{d\Omega}{4\pi}$$

$$\boxed{T_{aer}(\lambda,s) = \exp(-\int\alpha^{\lambda}(s)ds) = \exp(-VAOD(h)/sen\varphi)}$$

aerosol extinction

vertical aerosol optical depth

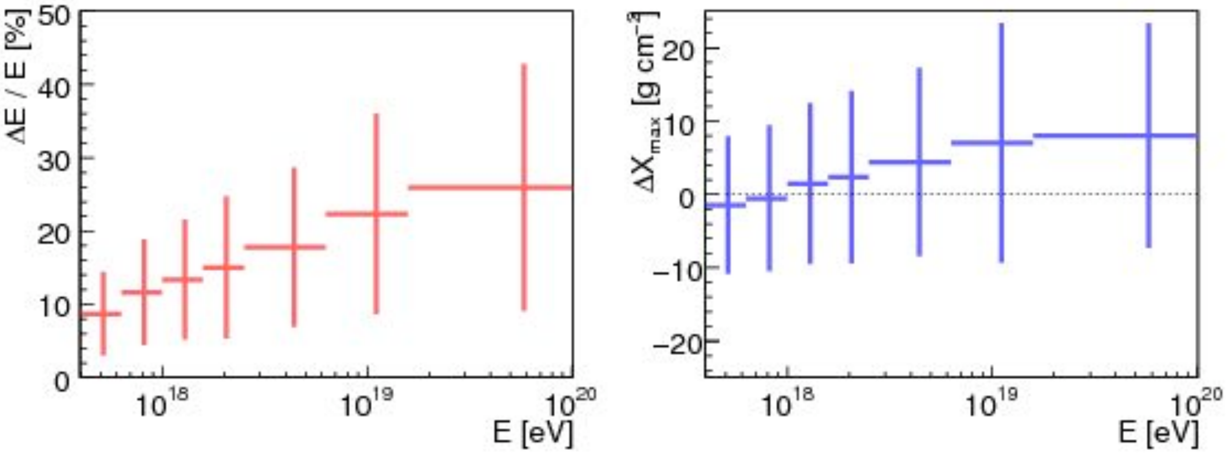


from The Pierre Auger Collaboration, Astroparticle Physics 33 (2010) 108-129

The effect of aerosol conditions on air fluorescence measurements

Neglecting the presence of aerosols causes an underestimate in energy on average from 8% (at lower energies) to 25% (at higher energies)

- 20% of showers need a >20% energy correction
- 7% of showers need a >30% energy correction
- 3% of showers need a >40% energy correction



Neglecting the presence of aerosols causes a systematic shift in Xmax from -1 g/cm^2 at lower energies to 8 g/cm^2 at higher energies

from The Pierre Auger Collaboration, Astroparticle Physics 33 (2010) 108-129

Atmospheric monitoring in the CR community

- The aerosol attenuation in CRs community is usually inferred through elastic LIDARs and / or side-scattering measurements from laser sources. Cloud layers height is measured with the same instruments.

- these measurements are based on assumptions on atmospheric properties (horizontal homogeneity, LIDAR ratio, …)

uncertainty on aerosol VAOD (h) ~ 30 %

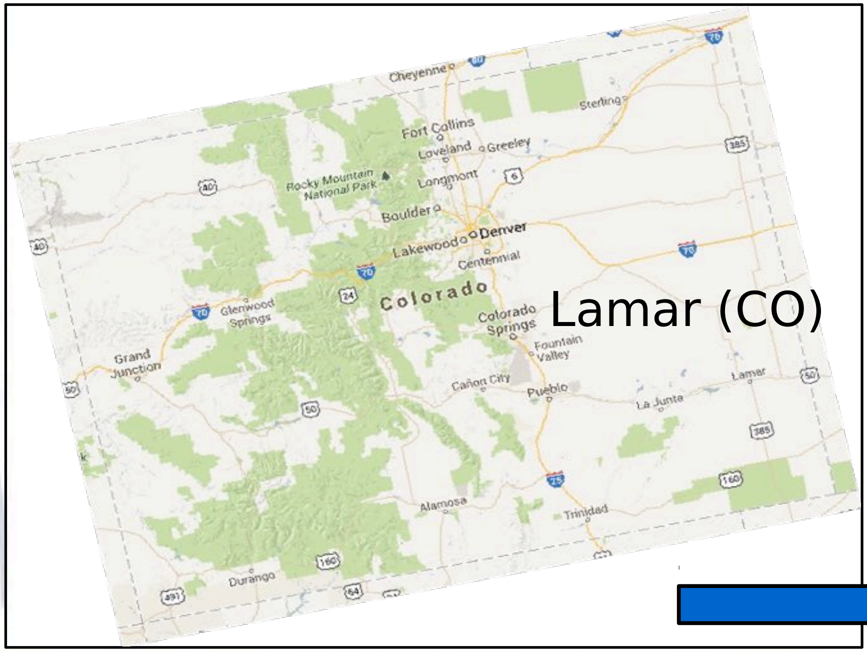
- The anelastic Raman LIDAR is the only device performing measurements not based on any assumption, but its operation in the field of view of UV light detectors is limited due to the long acquisition times needed.

↓ ARCADE

Target of the ARCADE project

Perform measurements of the aerosol attenuation profiles of UV light in atmosphere **simultaneously and on the same air mass** using the typical techniques used in cosmic ray and gamma ray observatories :

1. Side-scattering measurements using a distant laser facility and a UV light telescope
2. Back-scattering measurements using elastic and Raman lidars



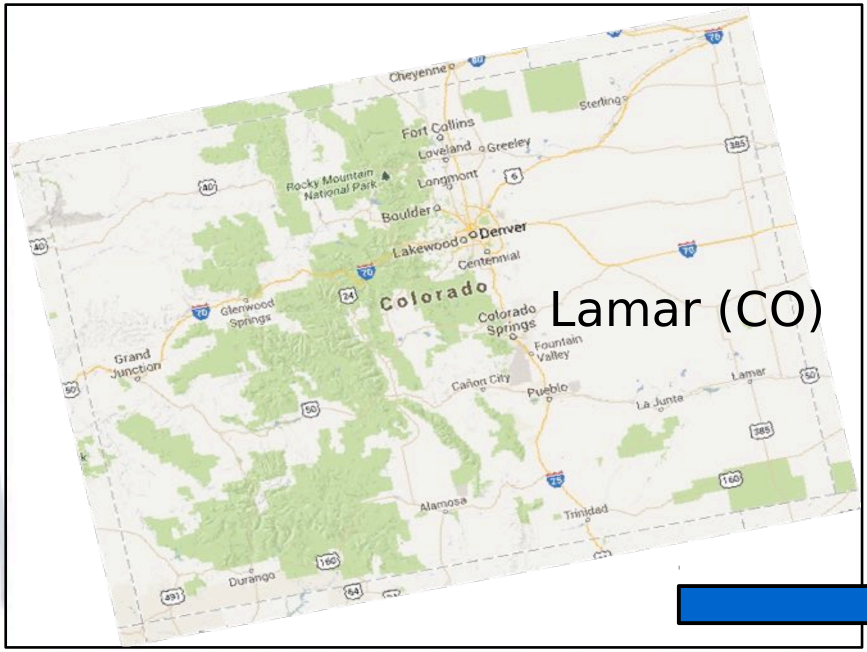
Lamar (CO)

Target of the ARCADE project

Perform measurements of the aerosol attenuation profiles of UV light in atmosphere **simultaneously and on the same air mass** using the typical techniques used in cosmic ray and gamma ray observatories

aiming to : a better understanding of the **systematics** and **limits of applicability** related to each method and **possible enhancements**

Location : desert – like environment, typical location for cosmic rays / gamma rays experiments : Lamar, Colorado (U.S.A.)

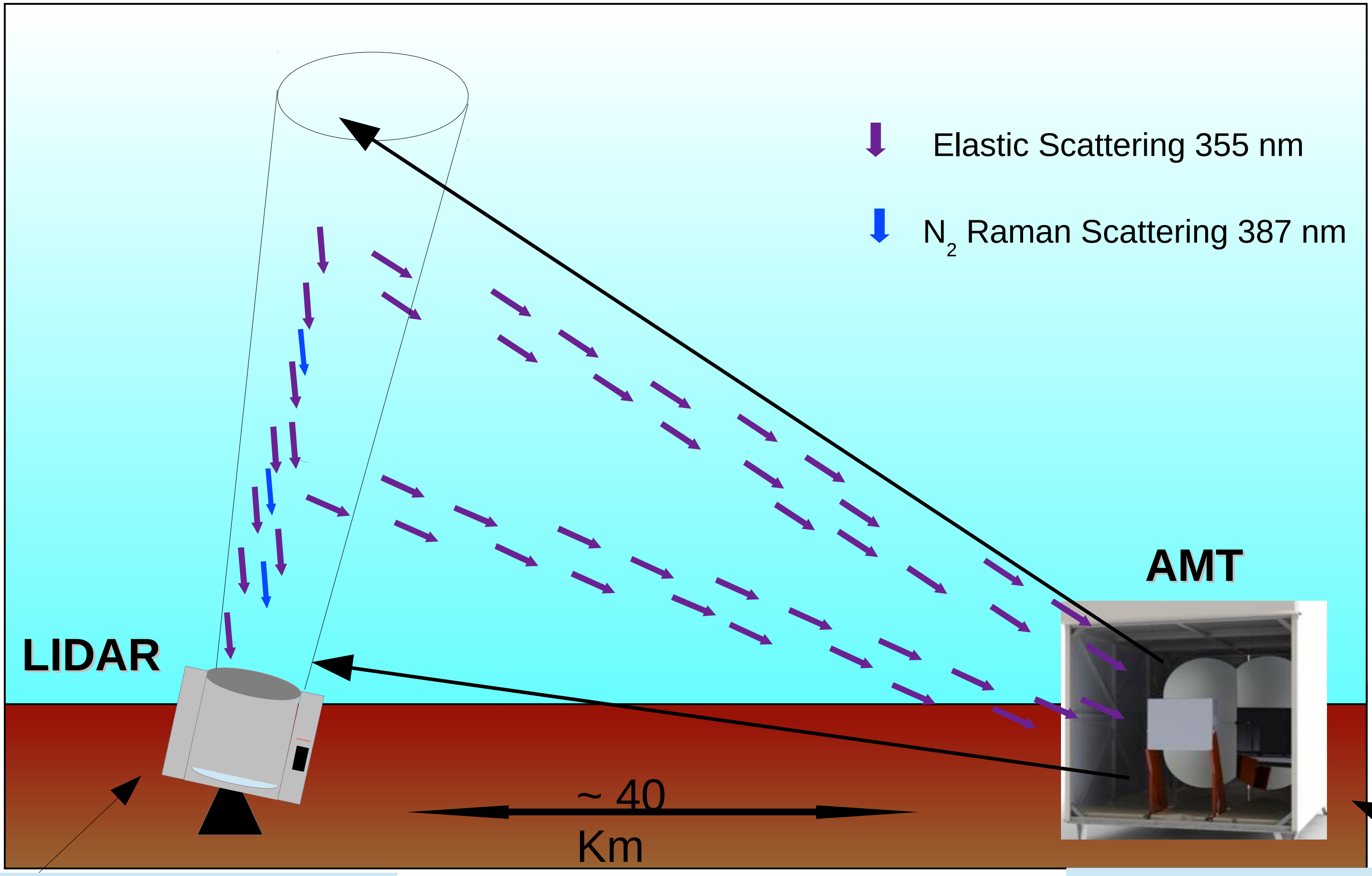


Lamar (CO)

The experimental setup

LIDAR + telescope for the detection of UV light (AMT)

No interference with any ongoing experiment : free data taking!

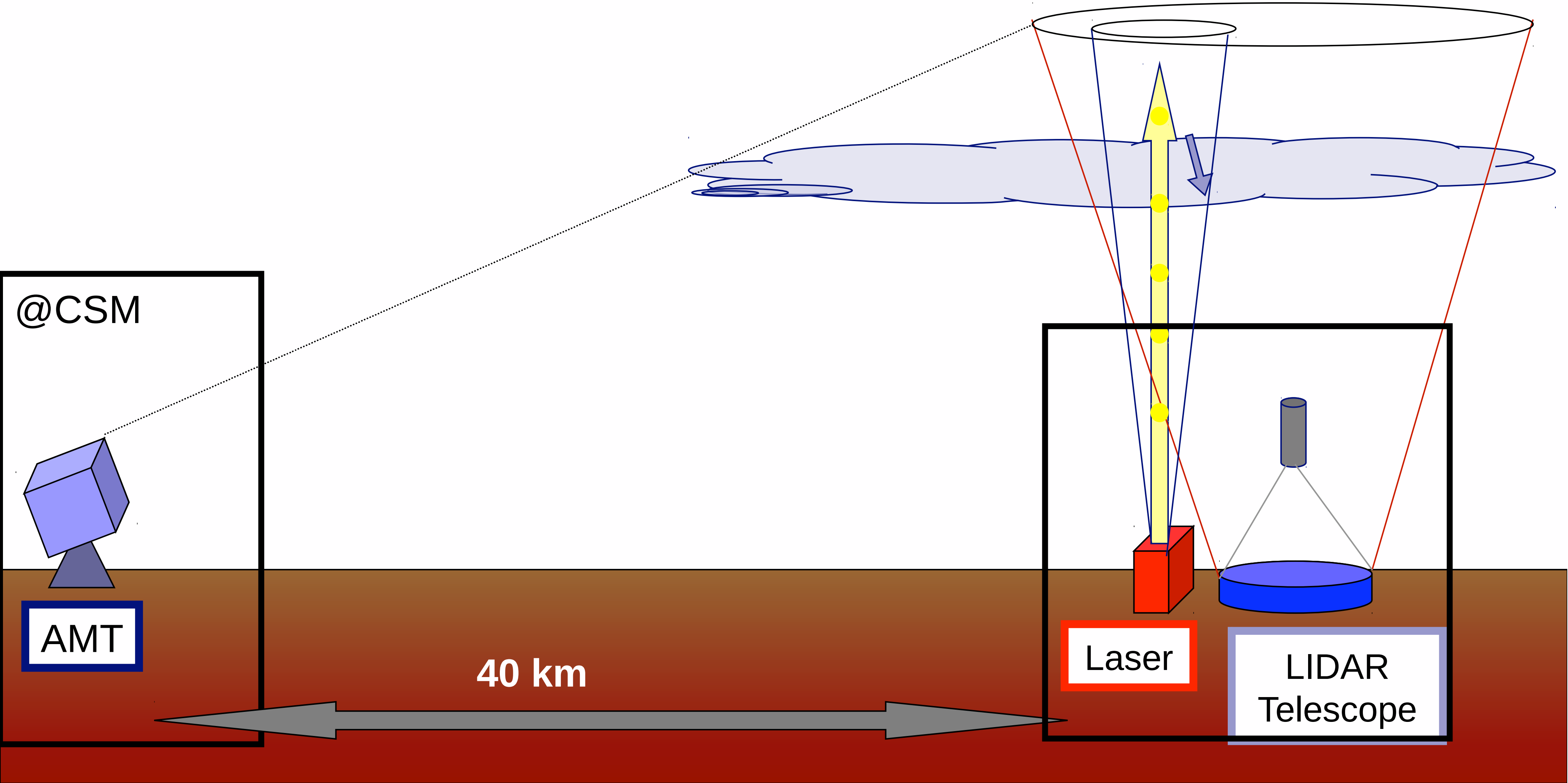


designed and realized within this project at the Turin INFN mechanical workshop

owned by the Colorado School of Mines, reassembled and improved for this project

Instrumentation

LIDAR (elastic + Raman) and telescope for side-scattering measurements (Atmospheric Monitoring Telescope). The laser source is common.



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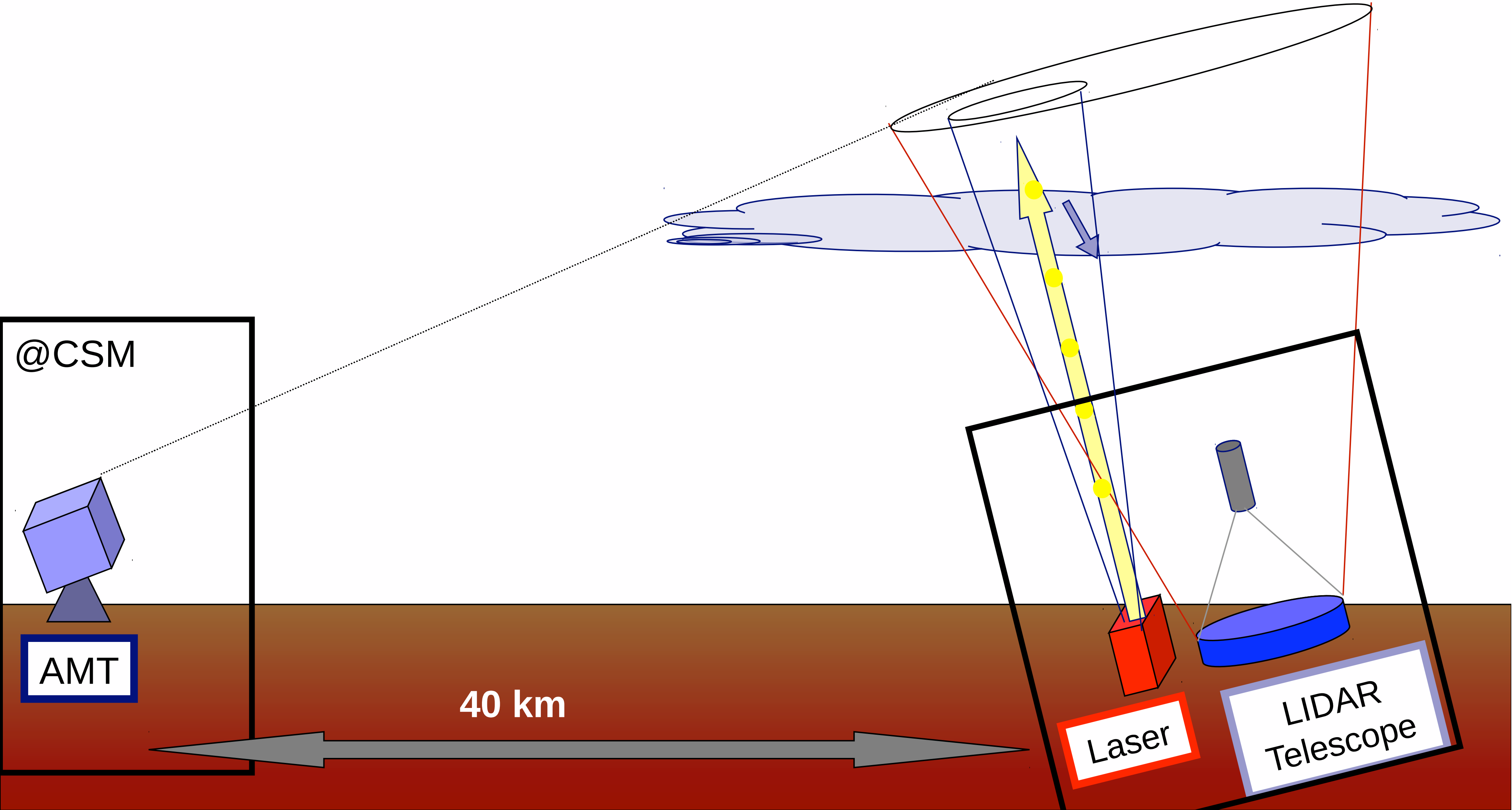

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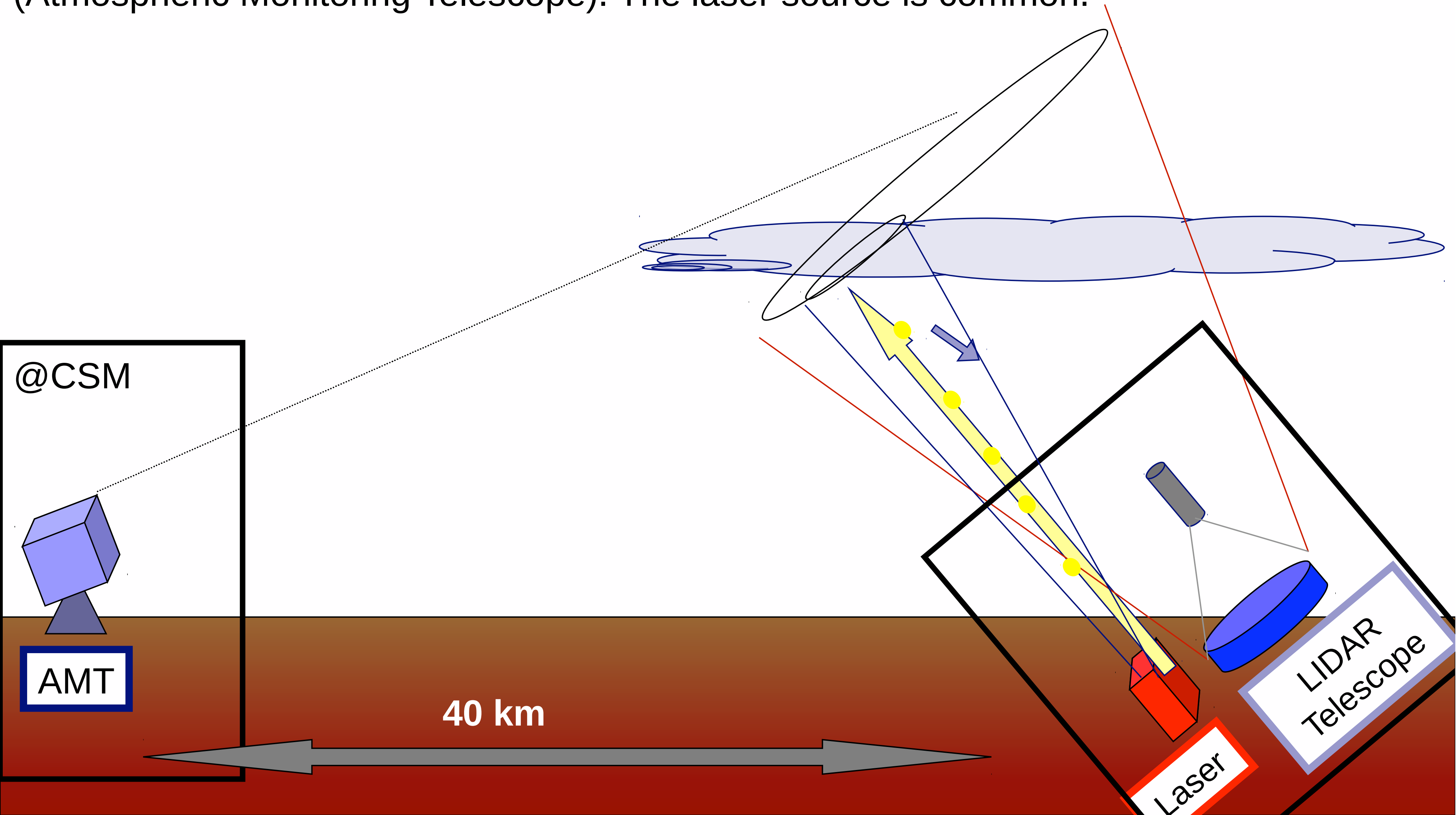

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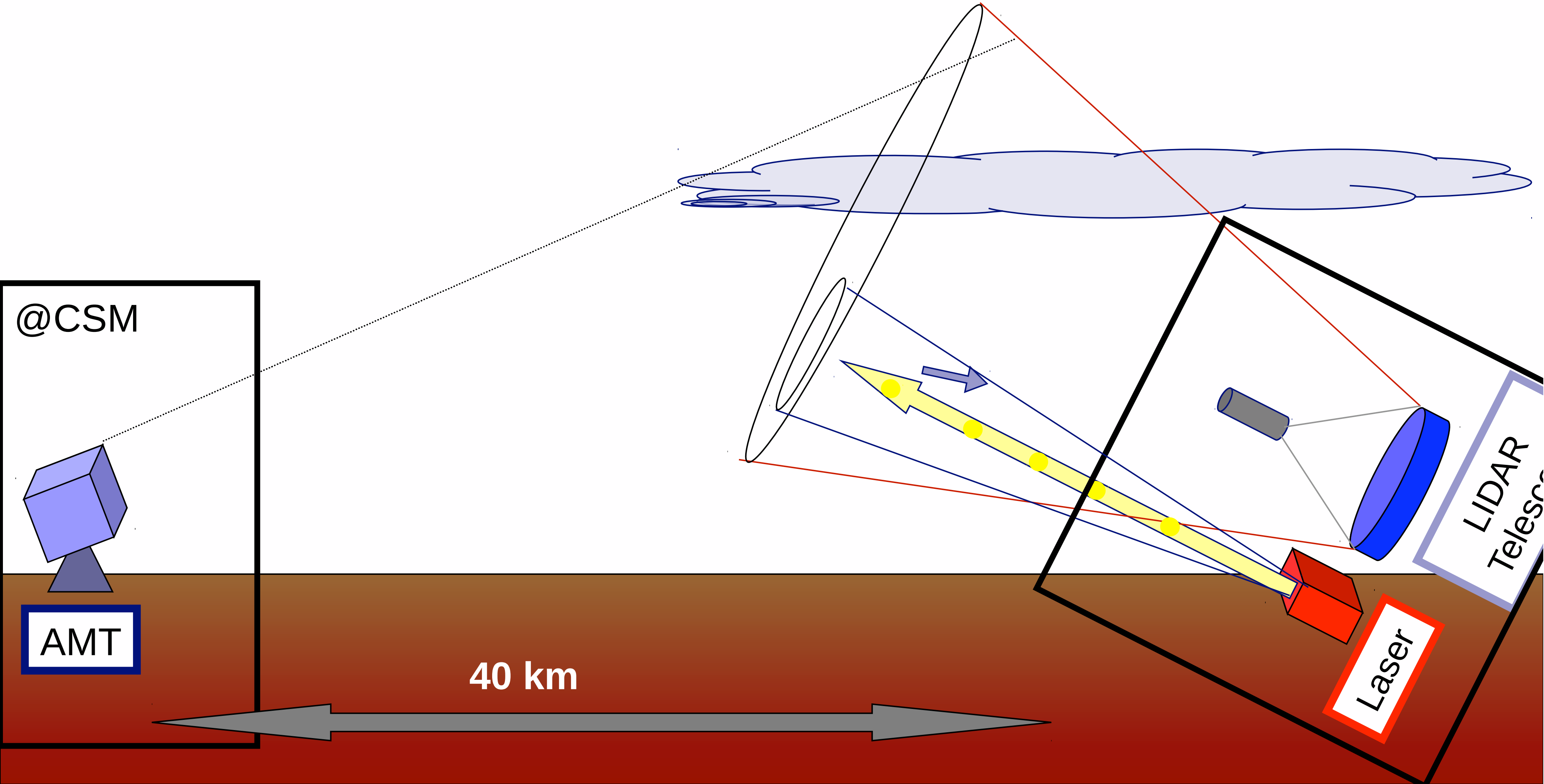

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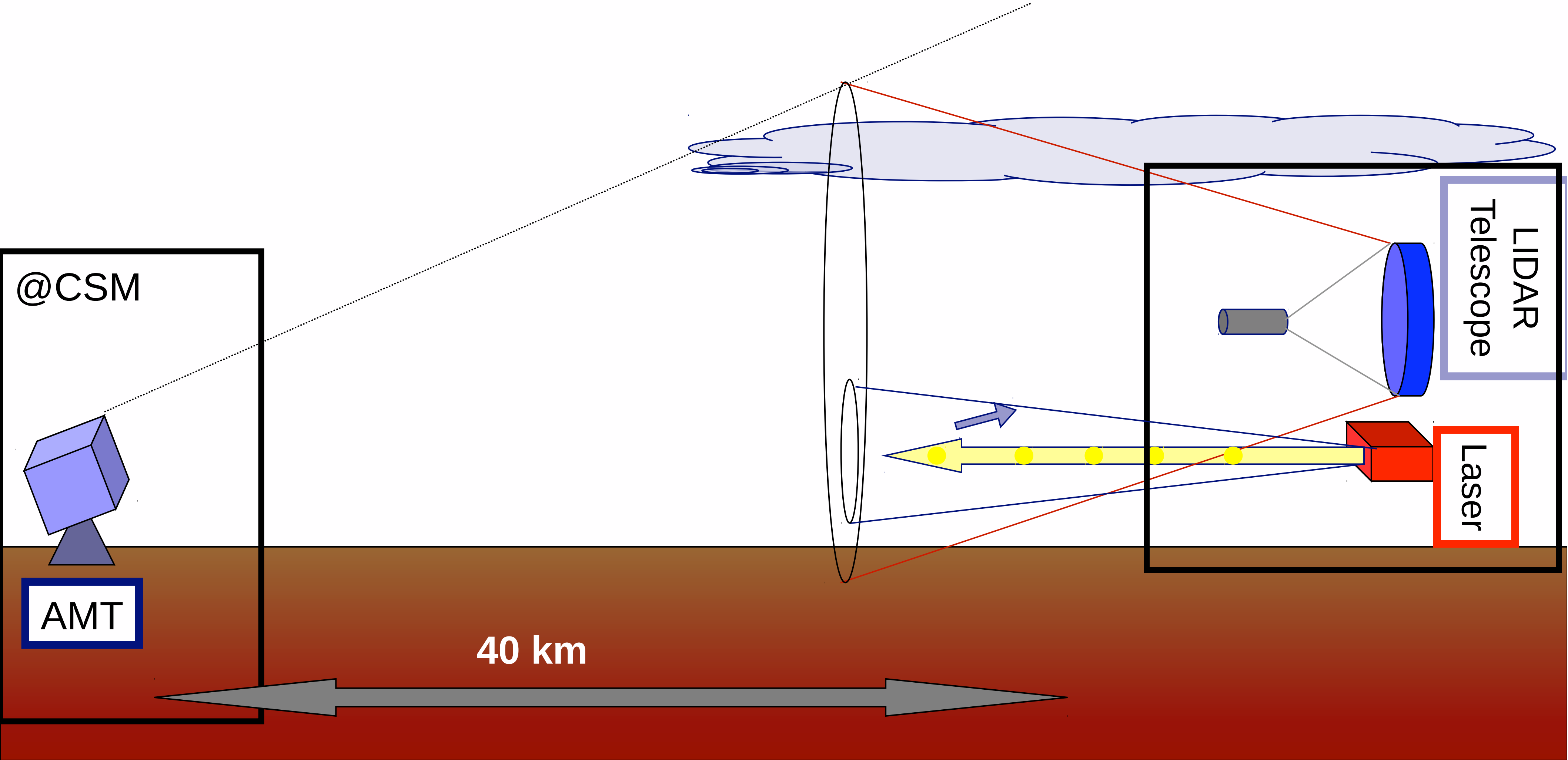


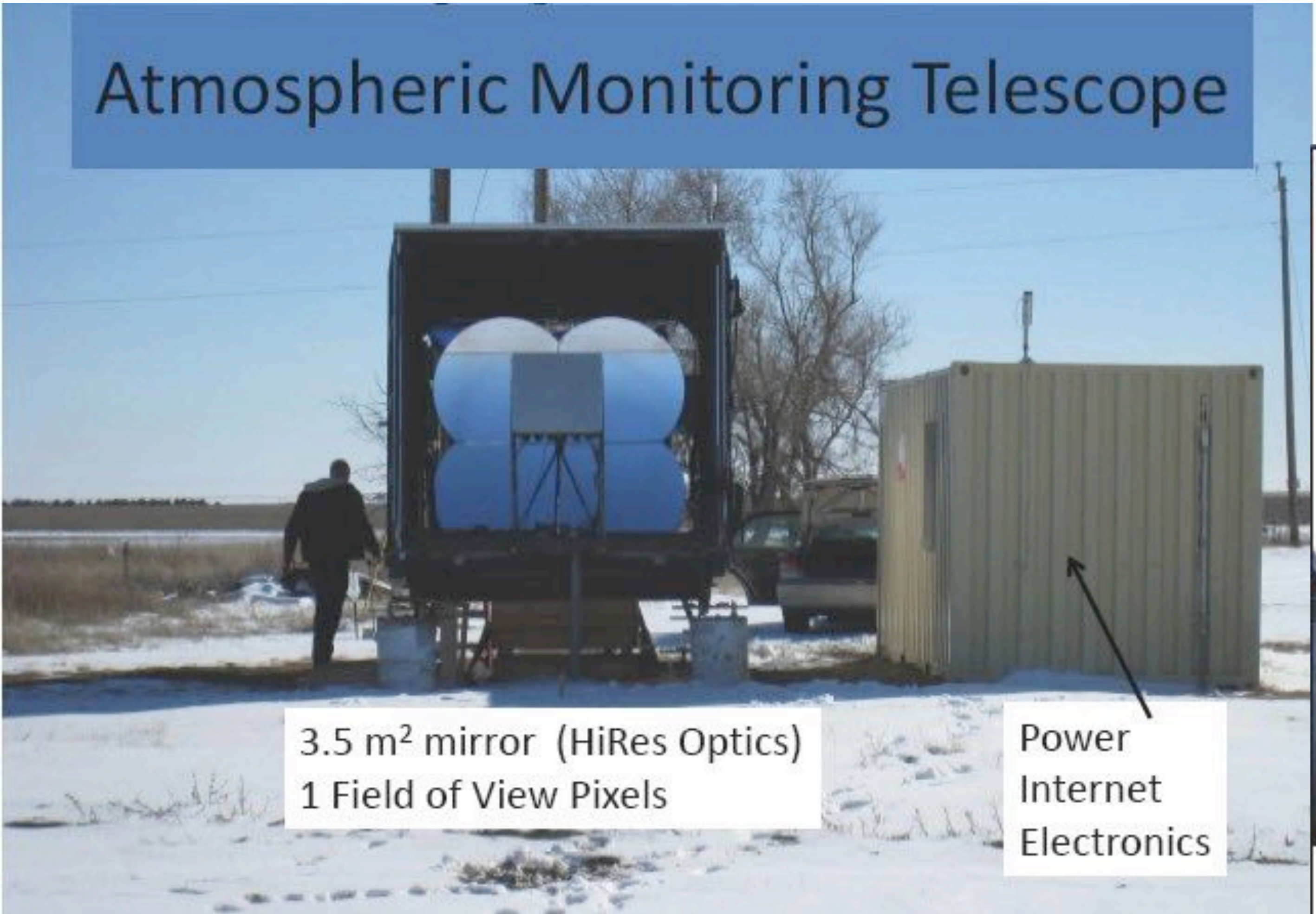
Lidars and side scattering

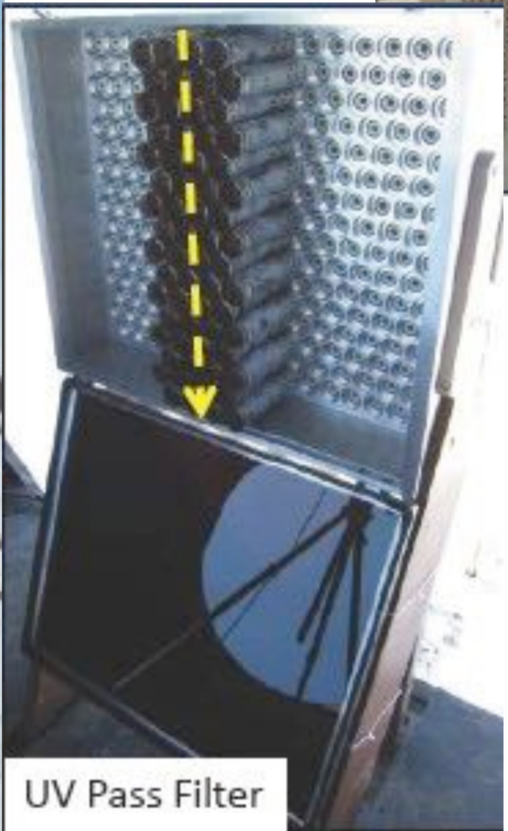
- **LIDARs :** remote sensing technology that measures aerosol attenuation profiles by firing a laser beam through the atmosphere and analyzing the back-scattered light.
  - Elastic Lidars measure the backscattered light on molecules and aerosols (needs for some assumption)
  - Raman Lidars measure the backscattered light on specific molecules (N2, H2O, …)
- **Side Scattering Measurements** : a telescope for the detection of UV light is positioned far from a UV laser light source. The laser light is scattered and attenuated exactly as the UV light produced during the development of an EAS → the study of the laser light that reaches the telescope is used to infer the aerosol attenuation properties

Atmospheric Monitoring Telescope

Colorado School of Mines

Put in operation after 2 years of incativity. Tested and reassembled in the lab in Golden. Improved DAQ and calibration. Back to operation in the field in June 2014.

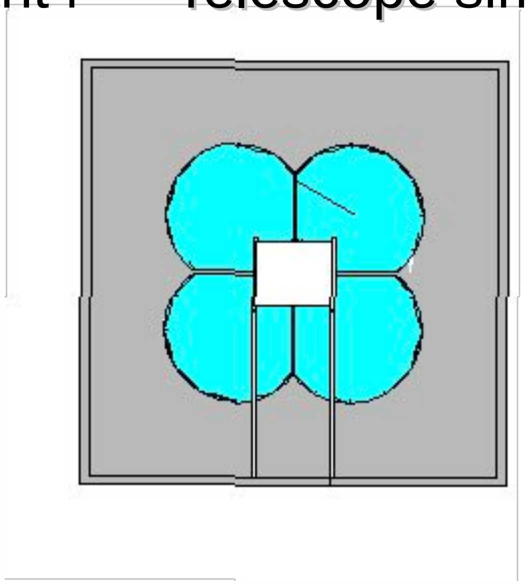


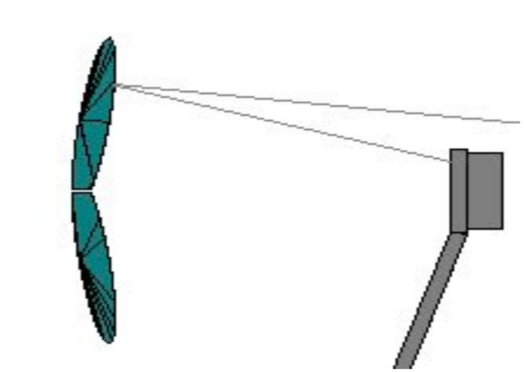


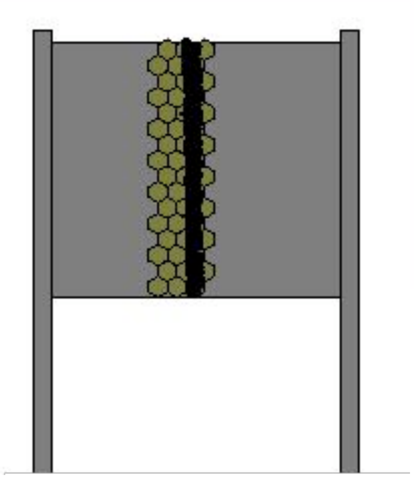
AMT -> Laser Simulation

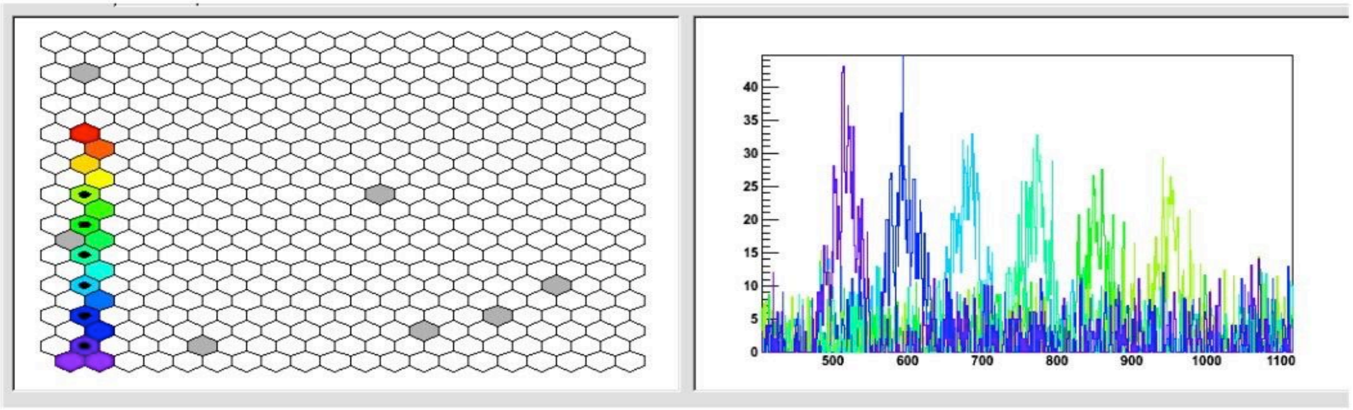
AugerOffline software → Simulation of laser light emission, transportation and attenuation towards the telescope

Geant4 → Telescope simulation





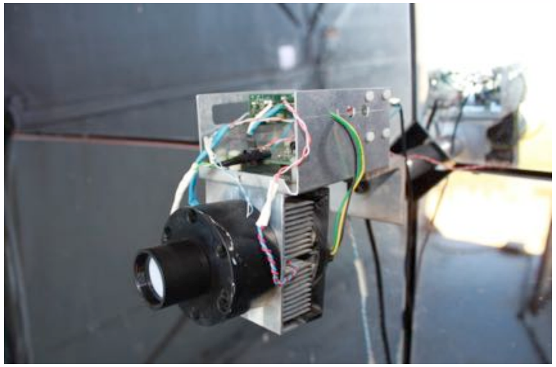




LED Calibration

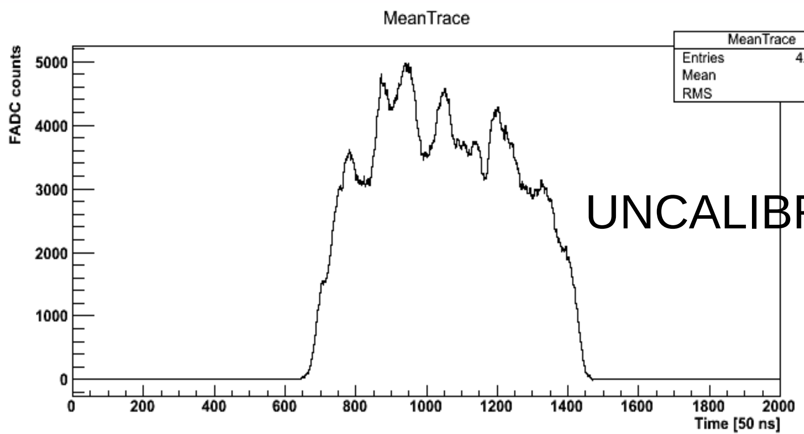
Each pixel of the telescope respond in a different way to the same amount of light

Relative calibration needed to make it uniform--> FLAT FIELDING CORRECTION

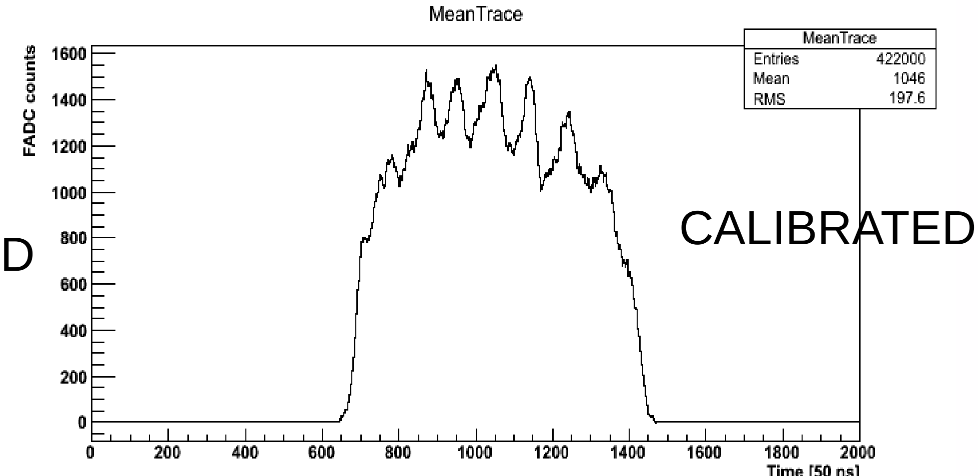


An uniforme and stable LED source
is placed in the center of the 4-petals
mirror of the AMT and illuminate uniformly
the whole camera.

LED calibrations → before and after each night of data taking



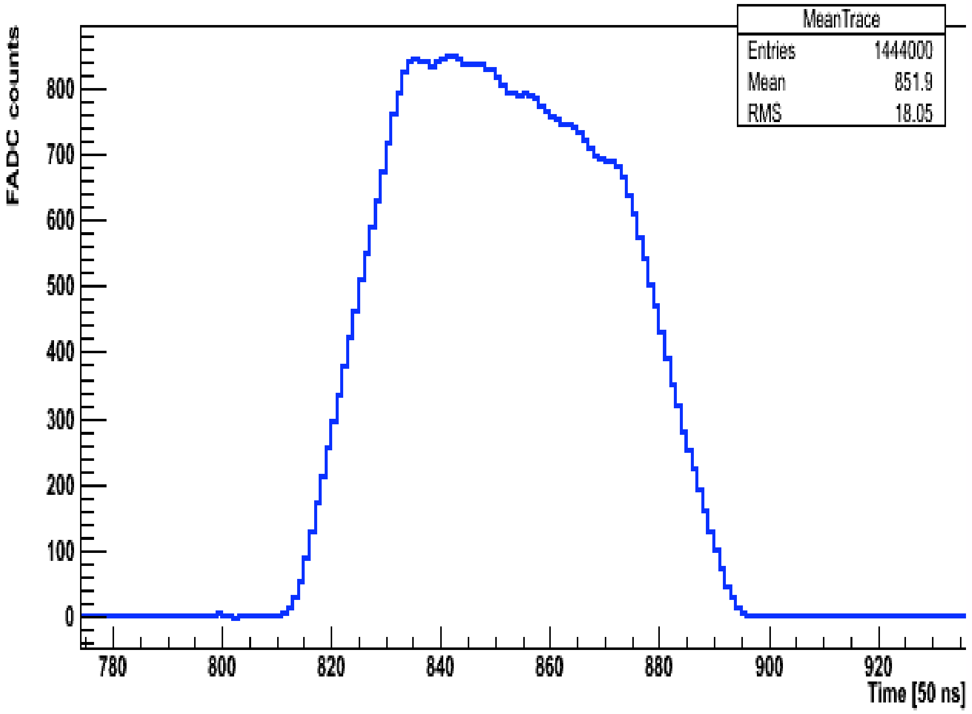
UNCALIBRATED



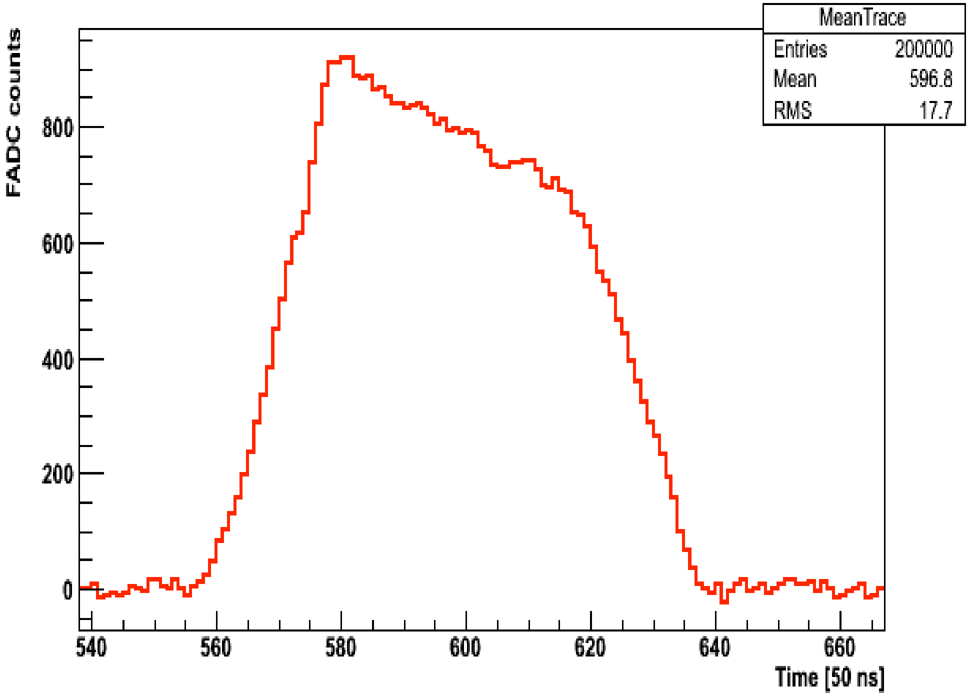
CALIBRATED

Nearby Laser Calibration

A roving laser placed at 3km far from the AMT was used to obtain an absolute normalization of the simulation to the real data
The effects of atmosphere on simulation are negligible at this distance

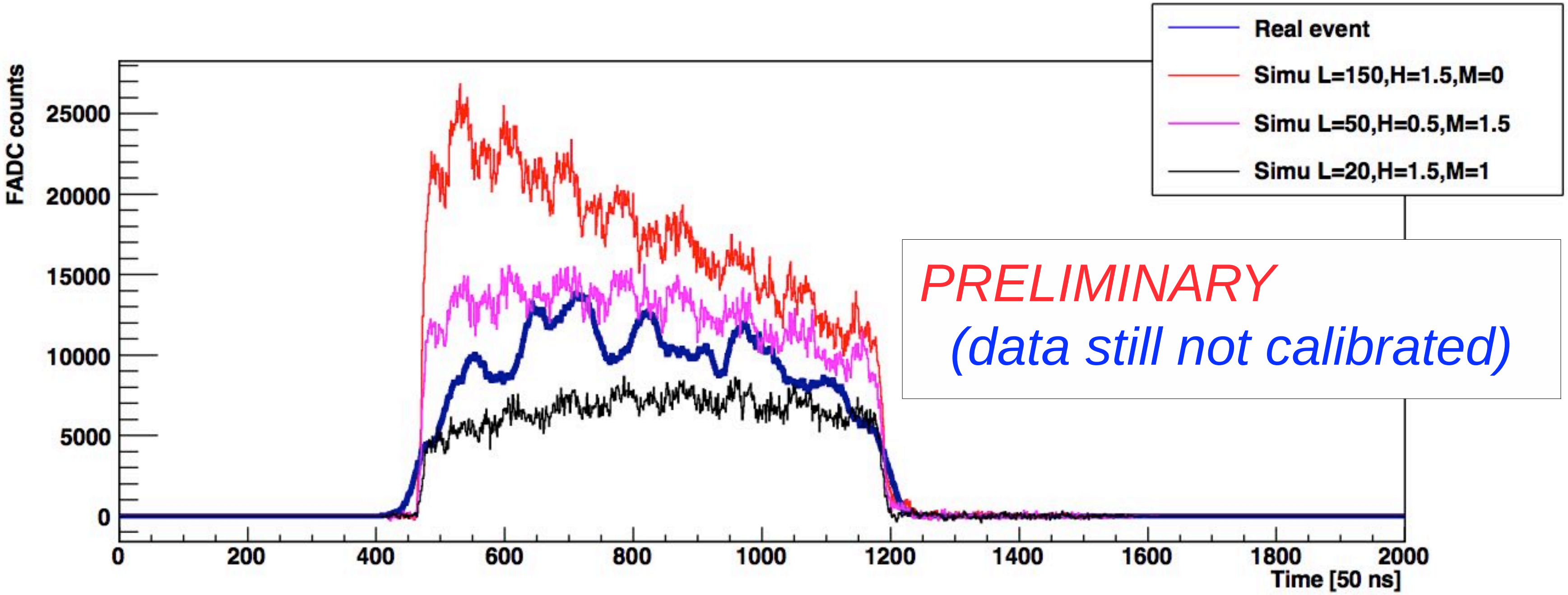


REAL PROFILE



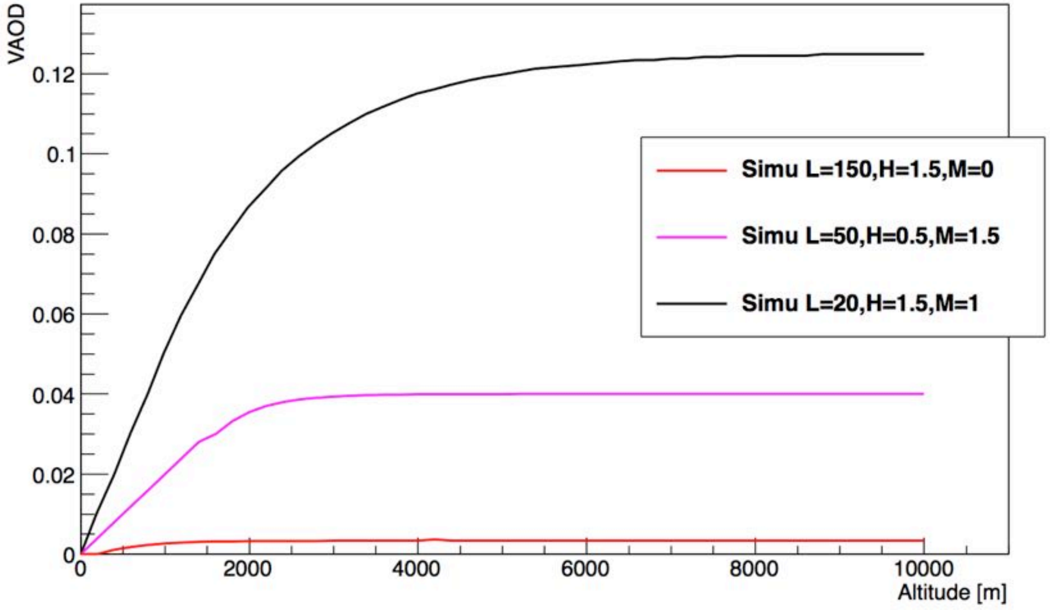
SIMULATION NORMALIZED PROFILE

Sum of 250 side scattering laser events *compared to different simulated e*

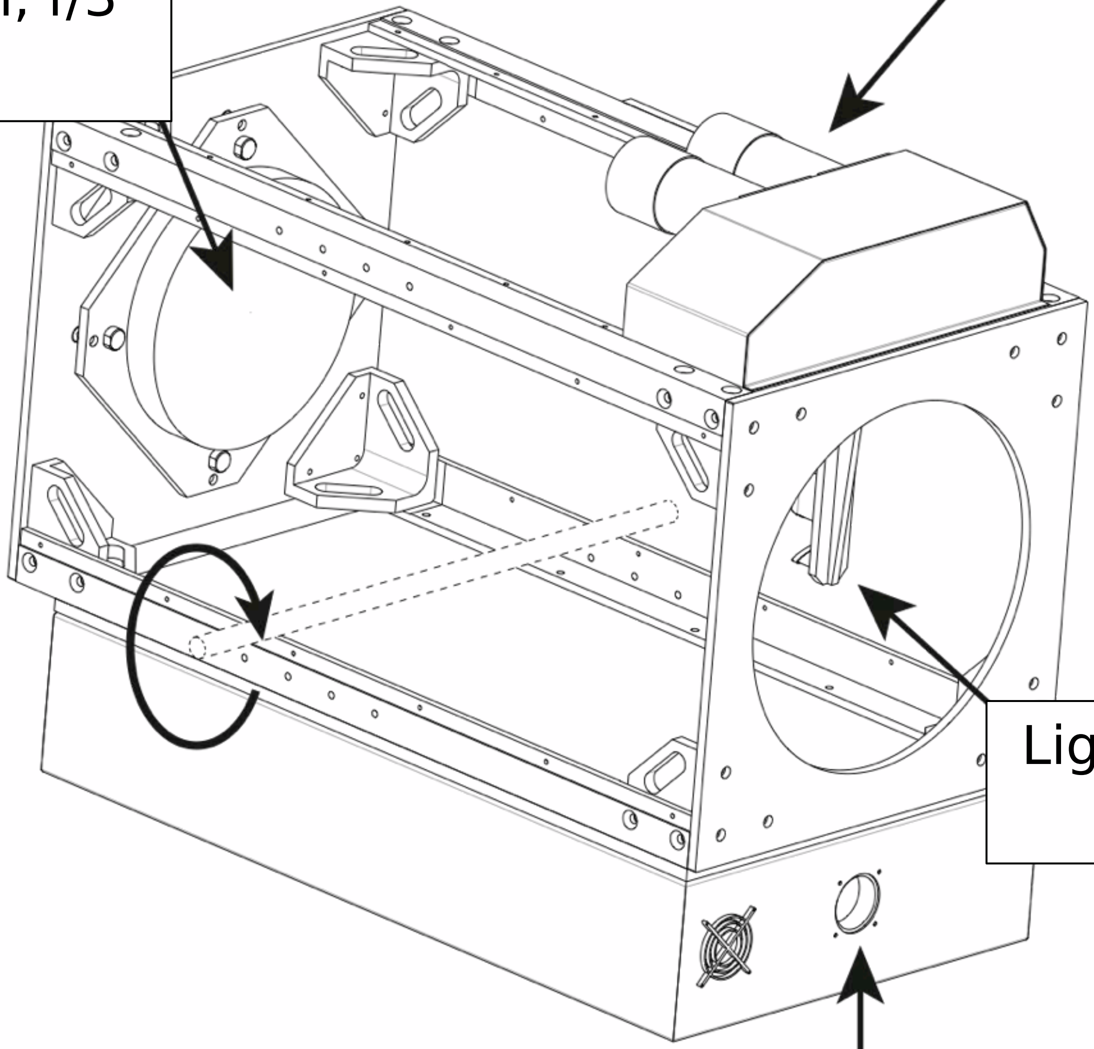


PRELIMINARY

(data still not calibrated)



The ARCADE Lidar



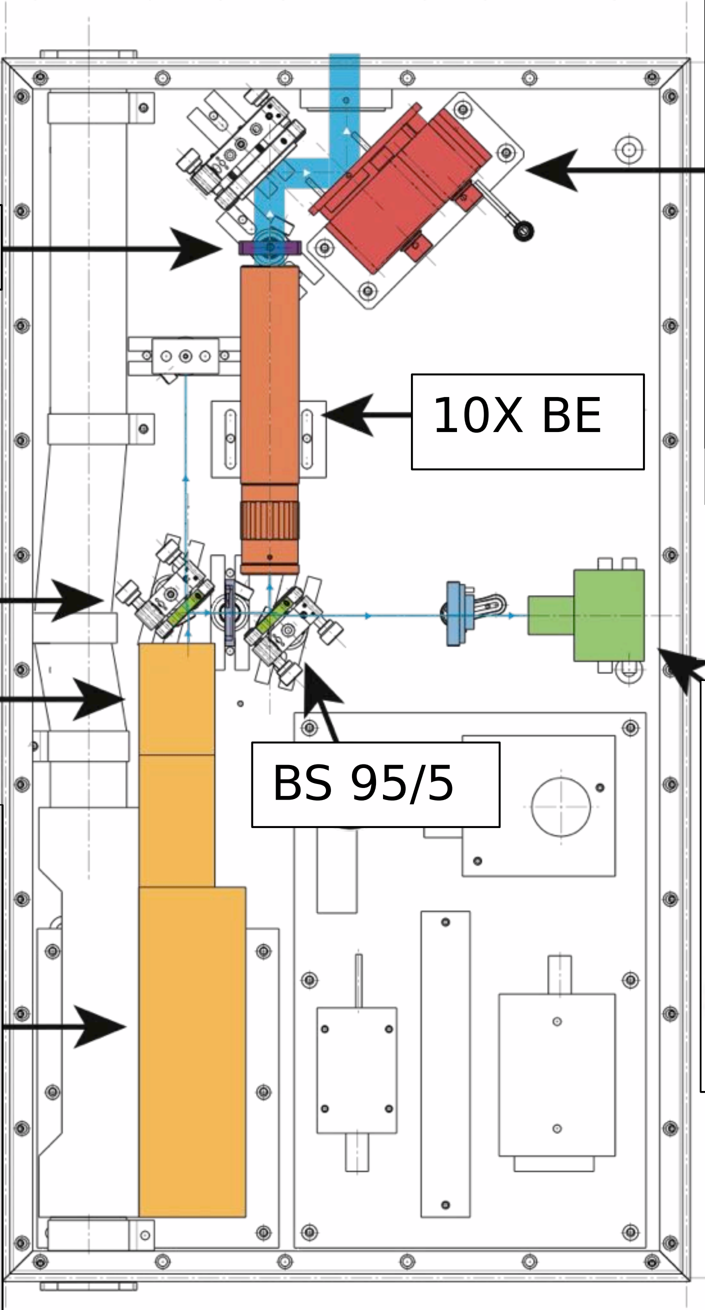
Primary mirror:
Ø 250 mm, f/3

Raman filters
and PMTs

Light collection

Laser exit

The laser bench



Depolarizer

10X BE

5 dichroic mirrors for ultra-pure 355nm laser line

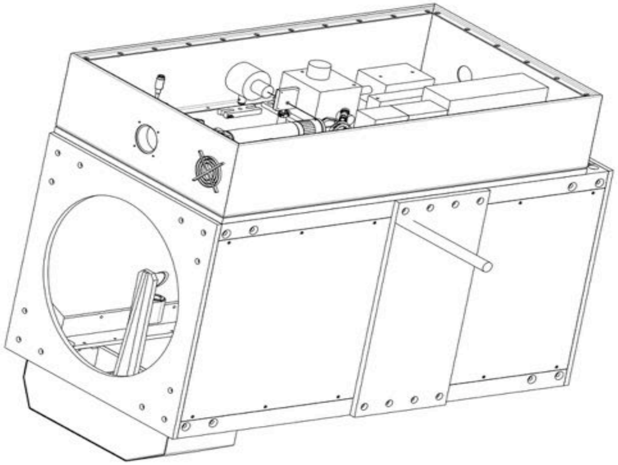
BS 95/5

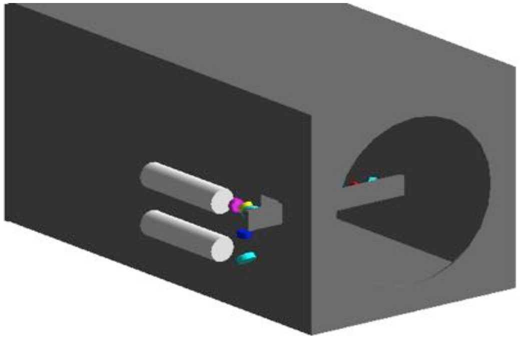
Zaber motorized mirror mount: remotely computer controlled fine alignment

Laser probe RjP-445

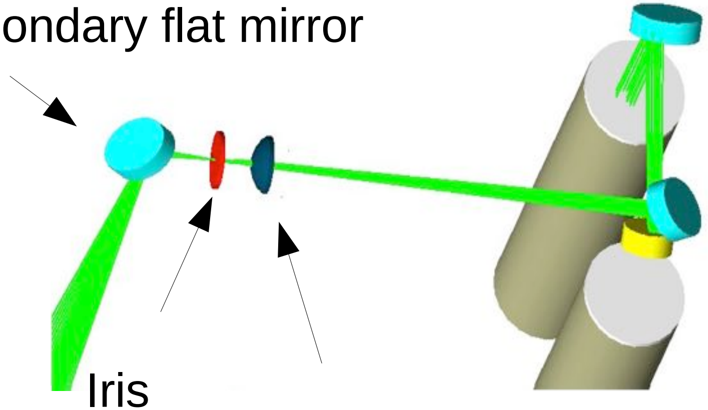
Quantel Centurion Nd:YAG laser

Geant4 simulation of the Lidar



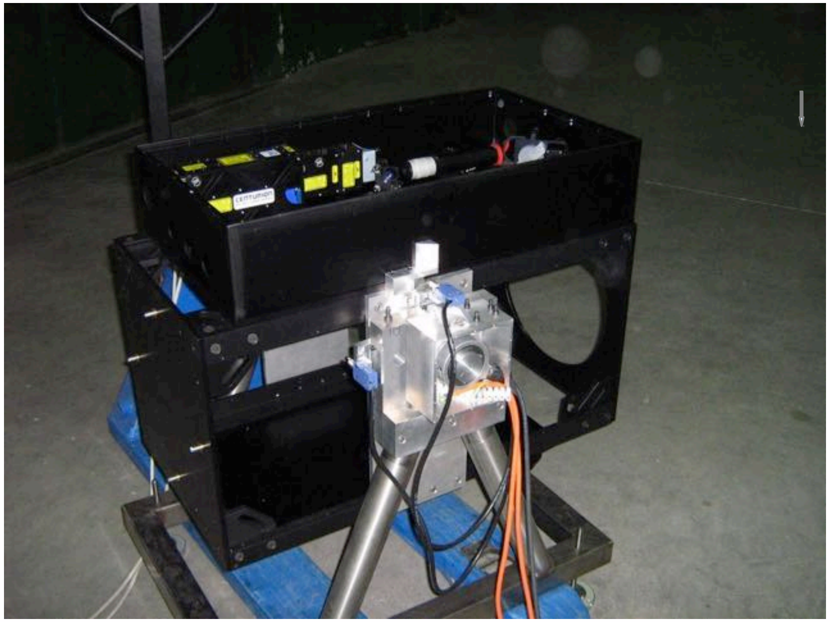


LIDAR box and optics



The laser bench realized

The lidar is mounted on a steering mechanism ...

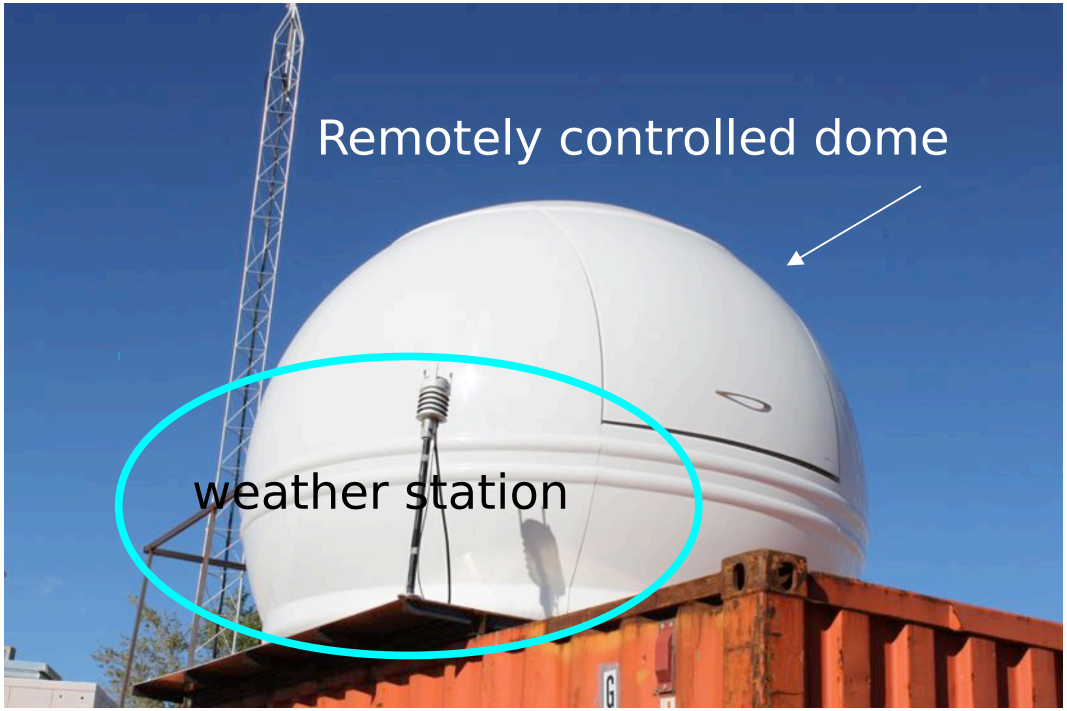


… is housed within an astronomical dome ...

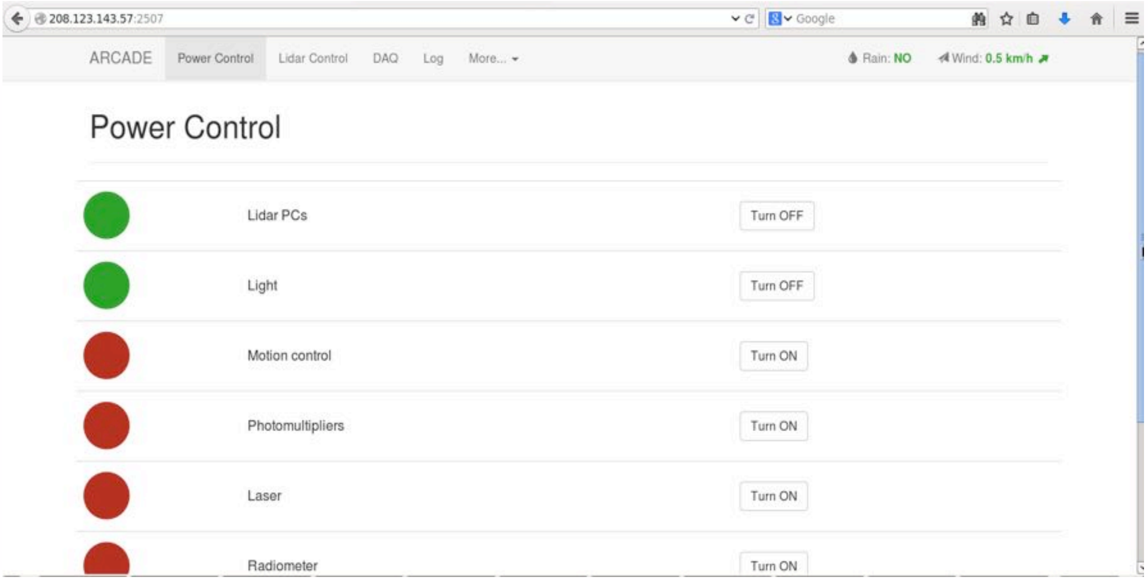
… and is hosted on top of a 20 ft shipping container

Built for remote operation

Needs only power and internet connection



Remote Control



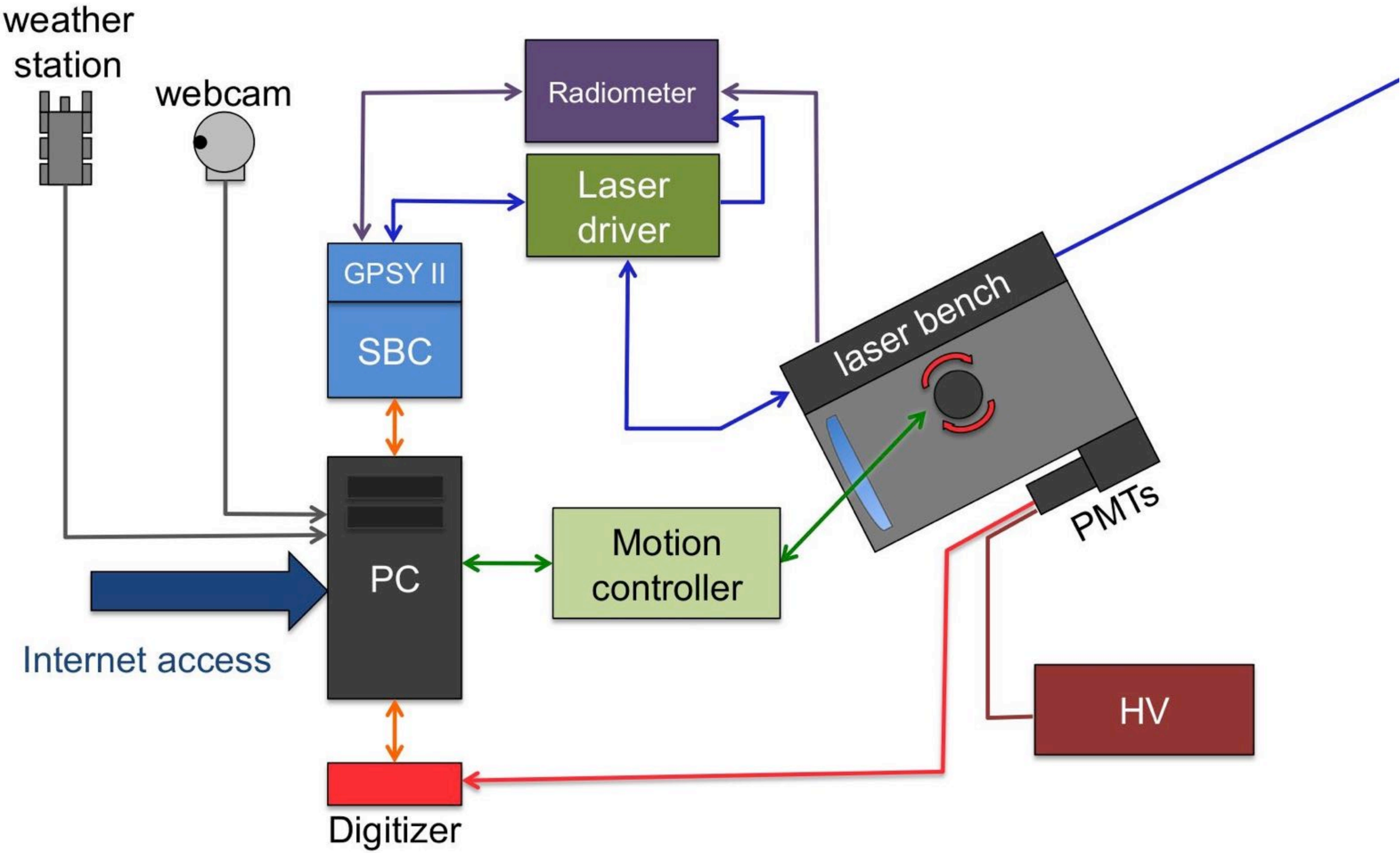
Power Control

🟢	Lidar PCs	Turn OFF
🟢	Light	Turn OFF
🔴	Motion control	Turn ON
🔴	Photomultipliers	Turn ON
🔴	Laser	Turn ON
🔴	Radiometer	Turn ON

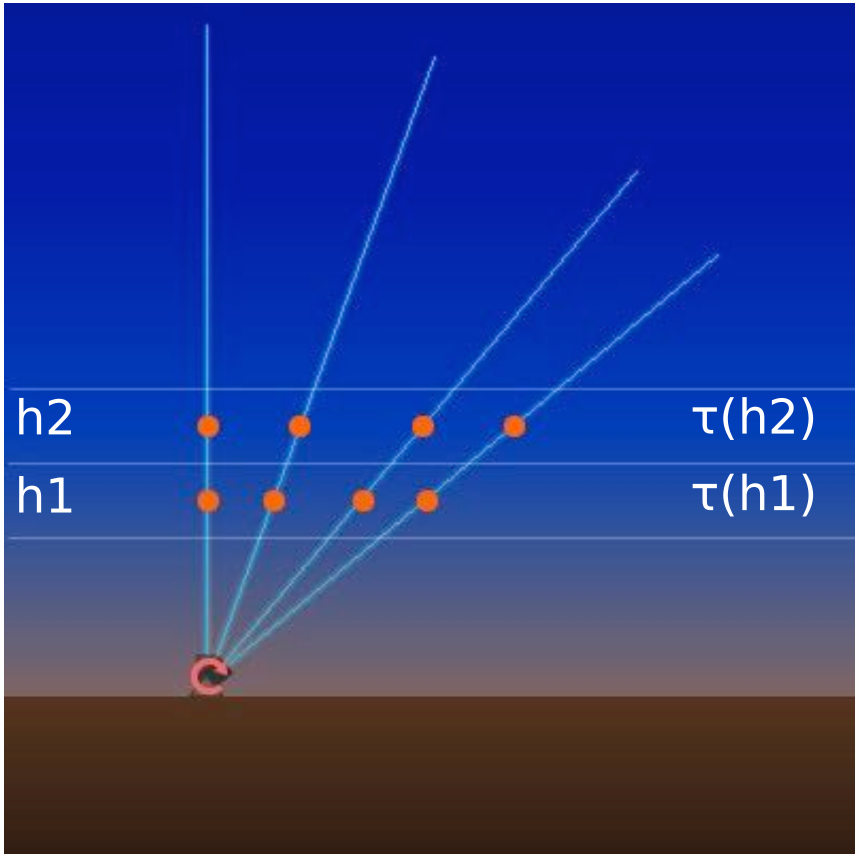
All the devices are remotly controlled :

- Dome Open/Close
- High Voltage of PMTs
- Radiometer
- Laser
- Steering
- Weather Stations
- Beam Mirror Alignment

Lidar system

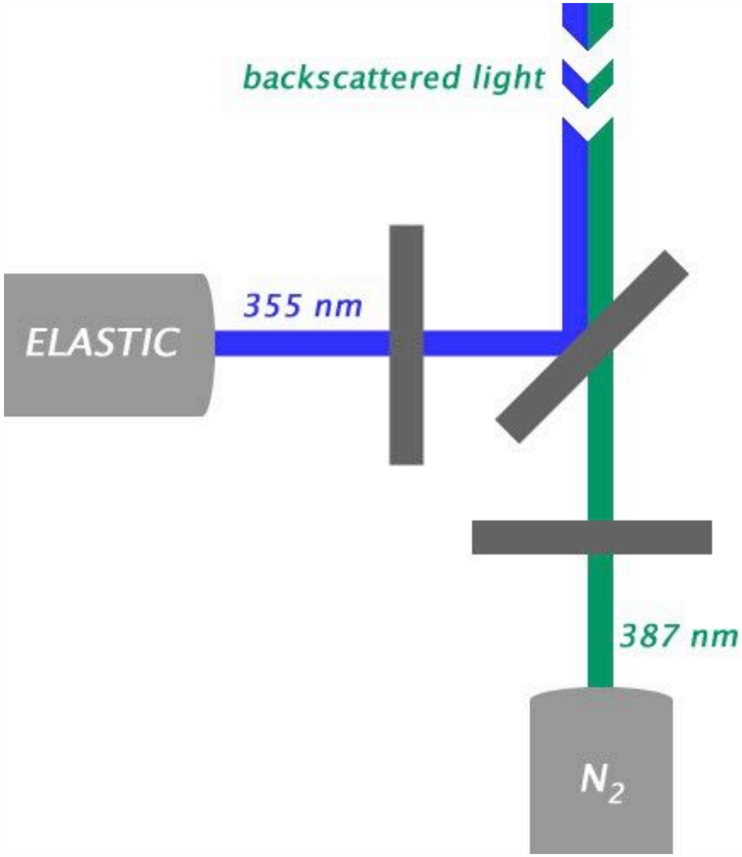


ELASTIC LIDAR
Multi-angle analysis



Hp: horizontally homogeneous atmosphere

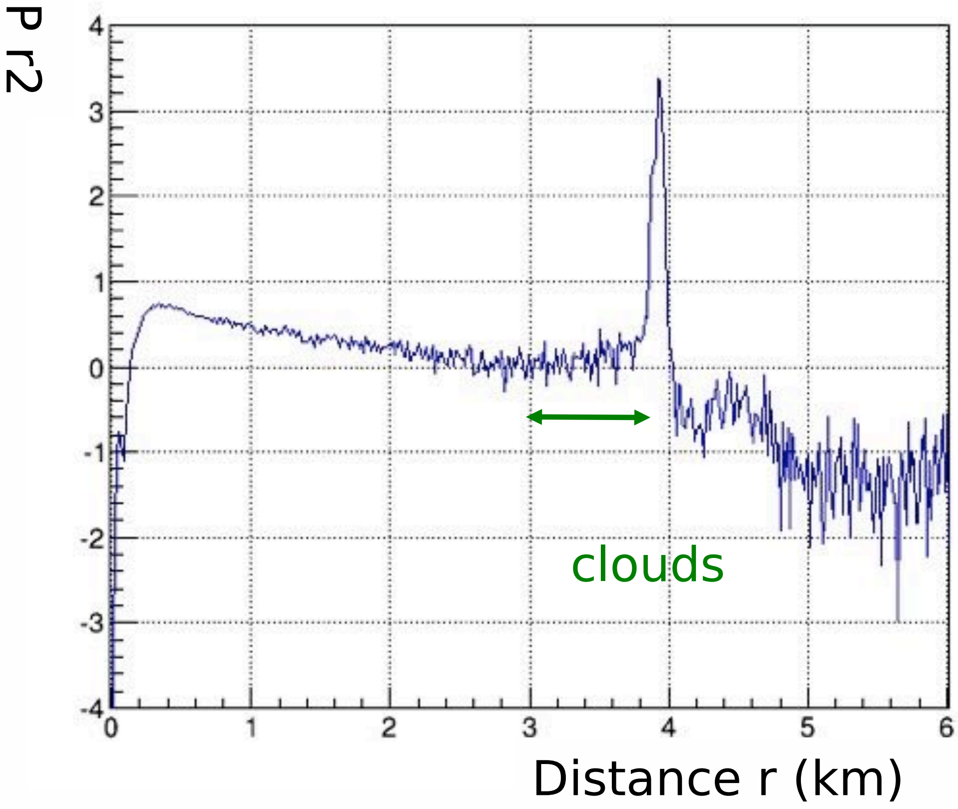
RAMAN LIDAR
Vertical and inclined shots



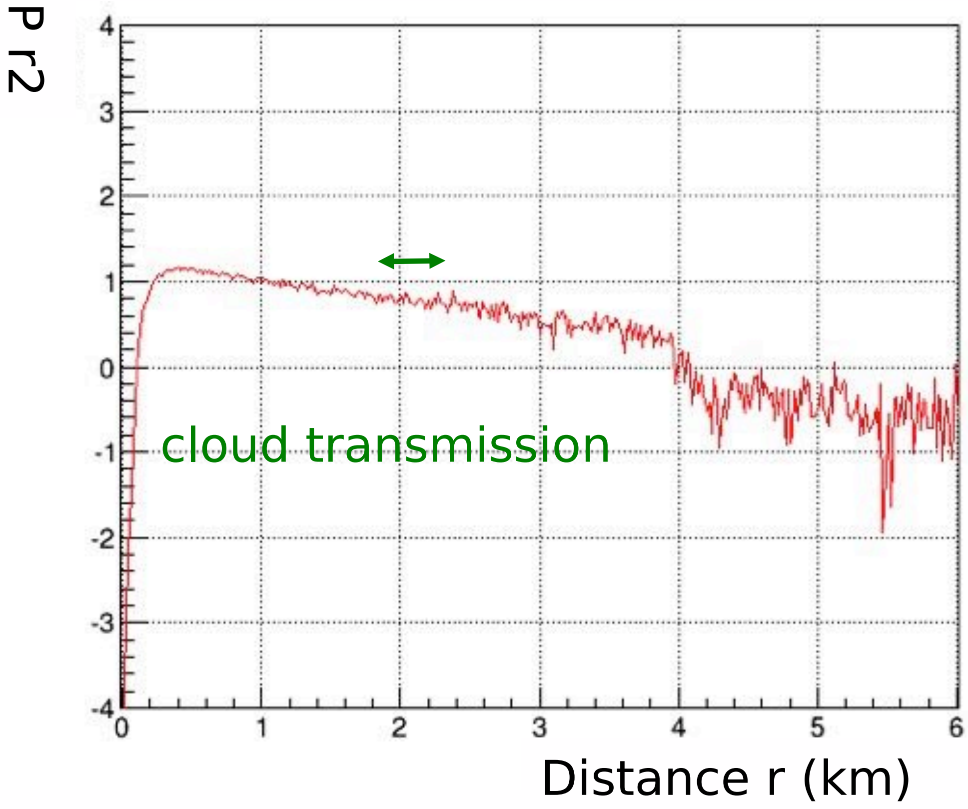
2 equations for two unknowns

An example of the ARCADE lidar data

ELASTIC CHANNEL



N2 RAMAN CHANNEL



LIDAR -> Raman Analysis

In collaboration with
atmospheric group
of CETEMPS - L'Aquila

$$P(\lambda_{N_R}, R) = \frac{K(\lambda_R)}{R^2} \cdot \beta(\lambda_R, R) \cdot e^{-\int \alpha(\lambda_0, R) + \alpha(\lambda_R, R) dR}$$

Aerosol extinction coefficient

$$\alpha_{aer}(R, \lambda_0) = \frac{\frac{d}{dR} \ln \frac{N_R(R)}{S(R, \lambda_R)} - \alpha_{mol}(R, \lambda_0) - \alpha_{mol}(R, \lambda_R)}{1 + \left(\frac{\lambda_0}{\lambda_R}\right)^{a(R)}}$$

$$\Longrightarrow$$

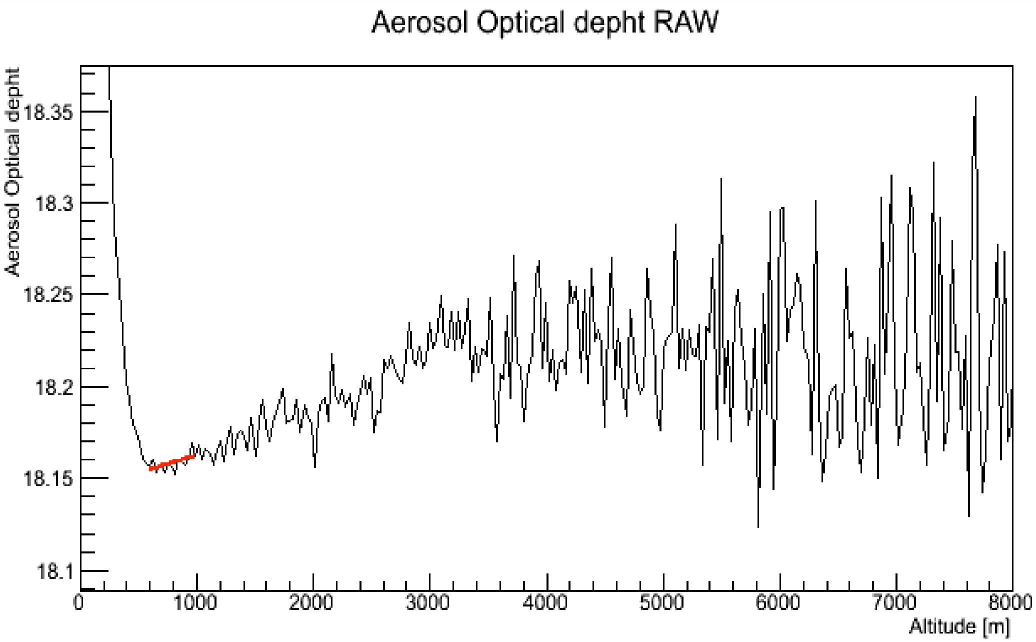
Aerosol Optical Depth

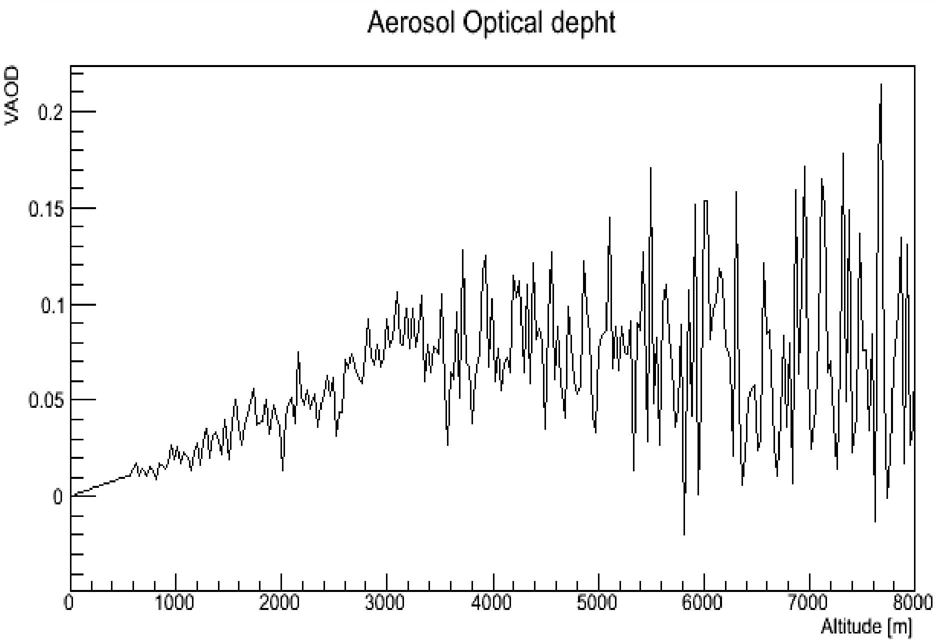
$$\tau_{aer}(R) = \frac{-\log\left(\frac{S(\lambda_{N_R}, R)}{T_{mol}(\lambda_R, R) \cdot T_{mol}(\lambda_{0,} R) \cdot N_R(R)}\right)}{1 + \left(\frac{\lambda_0}{\lambda_R}\right)^{a(R)}} \boxed{+C}$$

The constant "C" is determined imposing that $\tau_{aer}(R)$ is a linear function between the ground level and a certain altitude R_1

LIDAR -> Raman Analysis

$$\tau_{aer}(R > R_1) = \alpha(R_1) \cdot R_1 + \tau(R_{1,} R)$$





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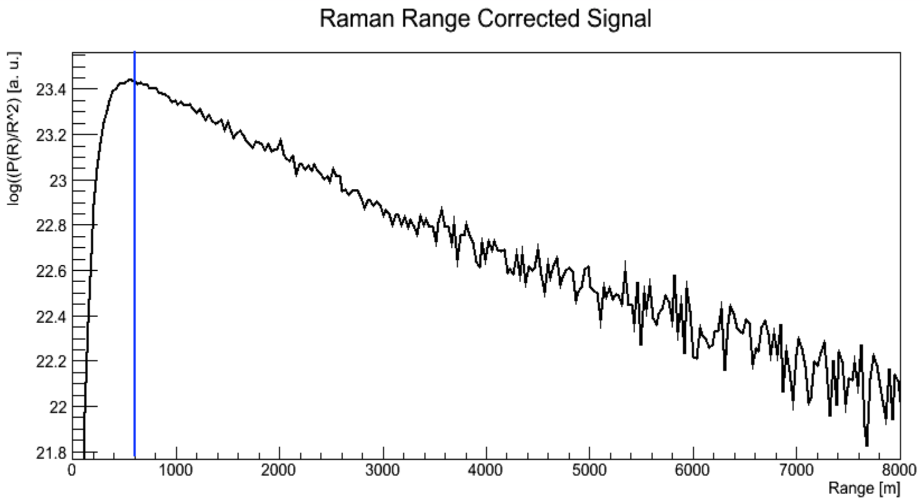
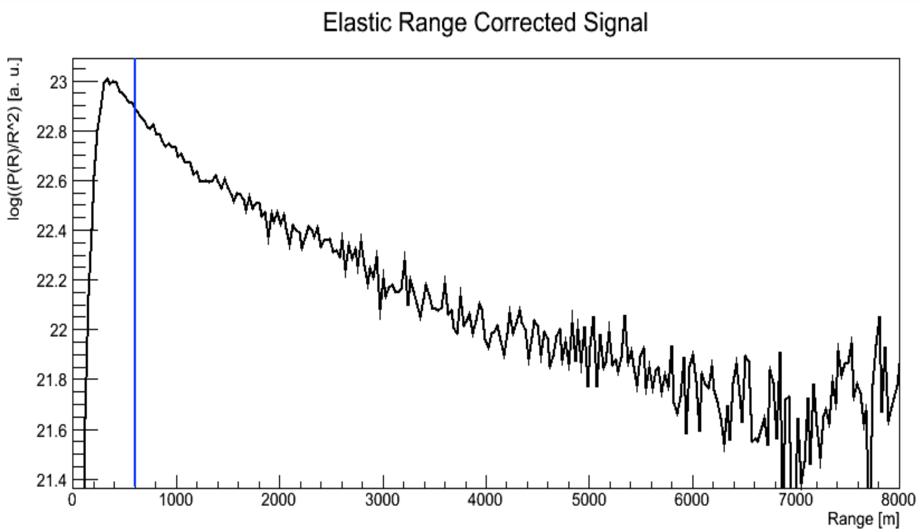
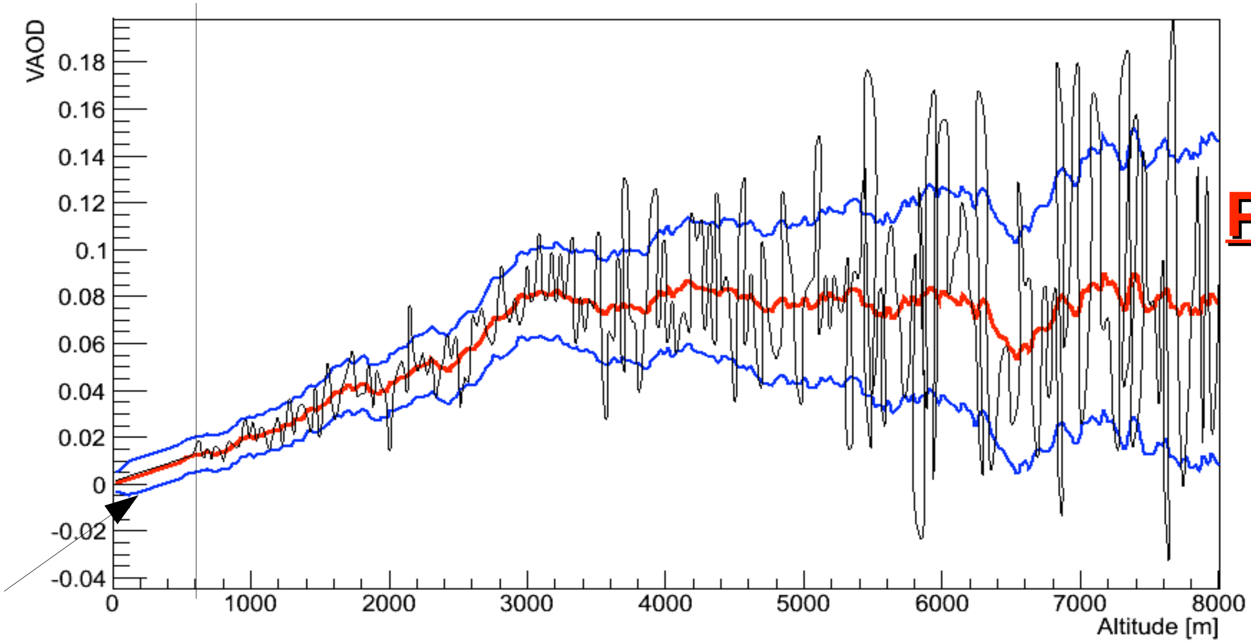
Preliminary aerosol profiles with the ARCADE Raman Lidar





Original Signal
resolution 30m

Averaged Signal
Resolution:
600m - 1km = 200m
1km – 3km = 300m
3km – 8km = 600m

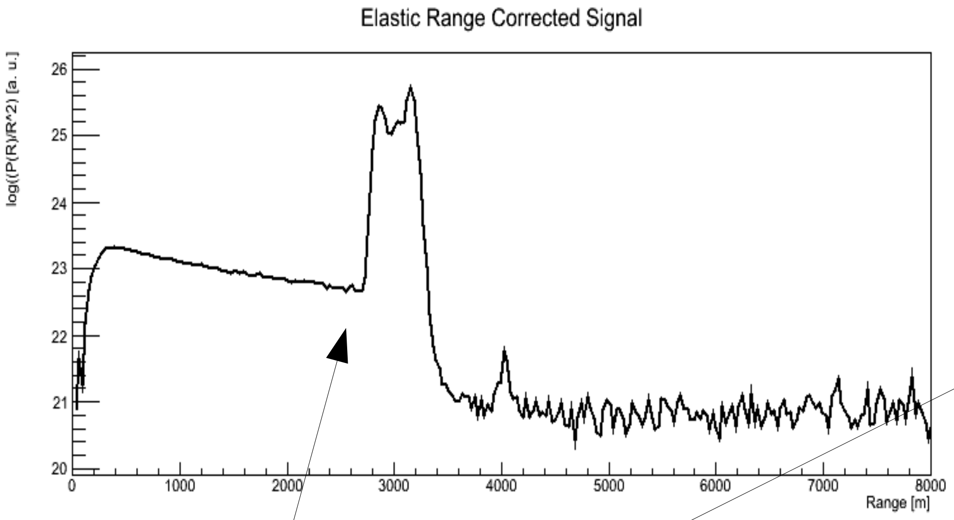


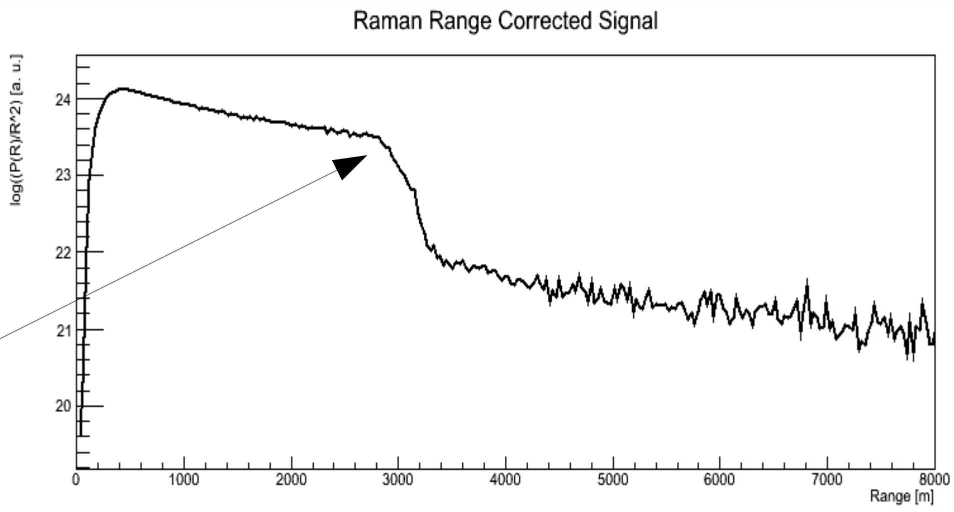
extrapolation

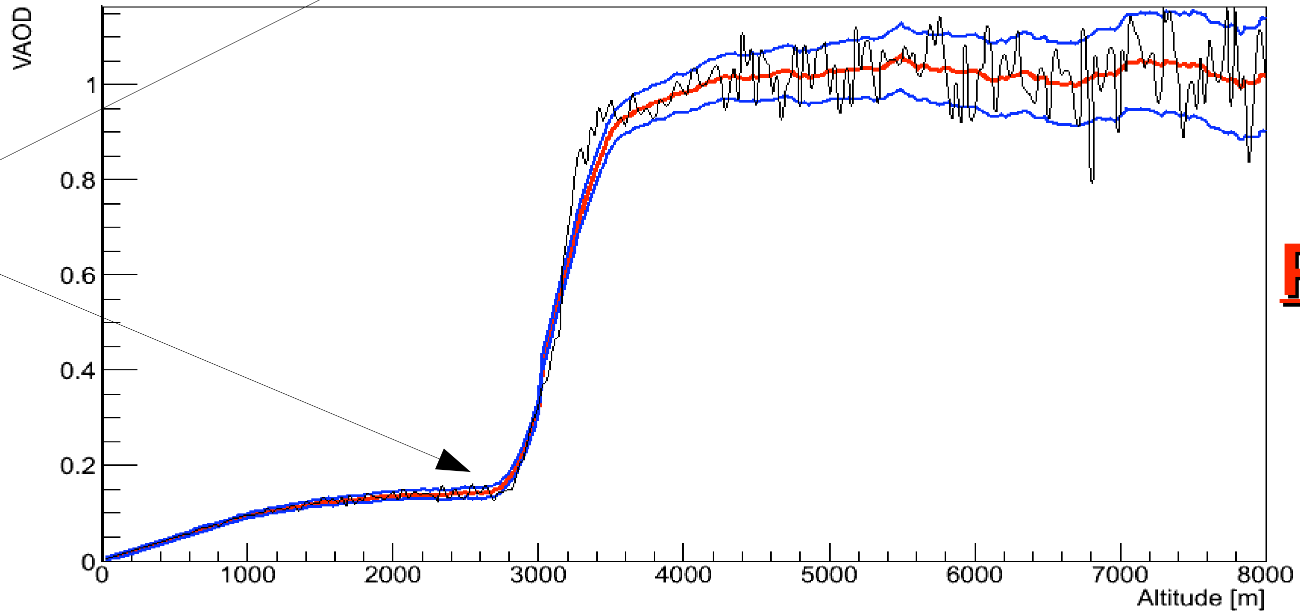
Preliminary

Preliminary aerosol profiles with the ARCADE Raman Lidar

CLOUDY DAY





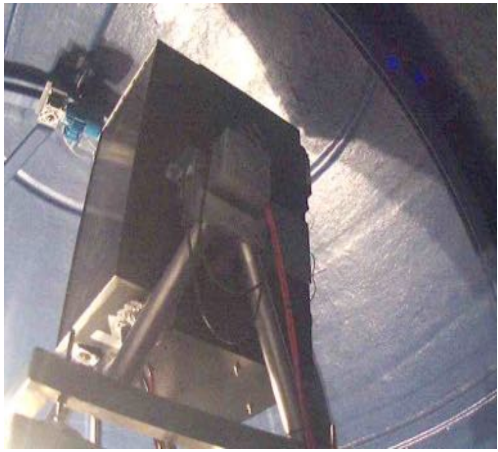


CLOUD
@ 2.8 km

Preliminary

Data taking & problems

1 year – June 2014 to June 2015



remote shifts from Italy, 1 shifter

- 20 minutes vertical (0°) Raman acquisition @ 100Hz, full power (6 mJ)
- 5 minutes @ 100Hz for each of the 5 positions (0°, 30°, 40°, 46°, 51°)
- 10 minutes @ 90° to test the horizontal homogeneity of the atmosphere

- a few problems during data taking ...

1. Temperatures too low (long periods T<-10°C) – laser heating failing when T < -5°C
2. hardware failures needed to be fixed
3. network very unstable on site
4. weather rapidly changing and extremely dusty ...

July 2015 – umounting the lidar

… very bad weather in June (tornado @ less than 1 mile from the Lidar) broke the electrical panel and the lidar was stuck open under the bad weather for a few hours ...

the ARCADE Lidar is now back in Italy being upgraded to become part of the CTA

Conclusions

The target of ARCADE is the measurement of the aerosol attenuation profiles of UV light in atmosphere using different techniques on the same air mass, at the same time, to understand the limits of applicability and the systematics of each technique.

We took data for one year with the ARCADE Raman Lidar and the AMT in Lamar, Colorado.

Simulations of the Lidar and AMT + calibration campaignes of the AMT have been performed. First aerosol profiles using the Raman Lidar have been measured, while the AMT data analysis is in progress.

Thanks for your attention!

BACKUP

An example of the ARCADE lidar data

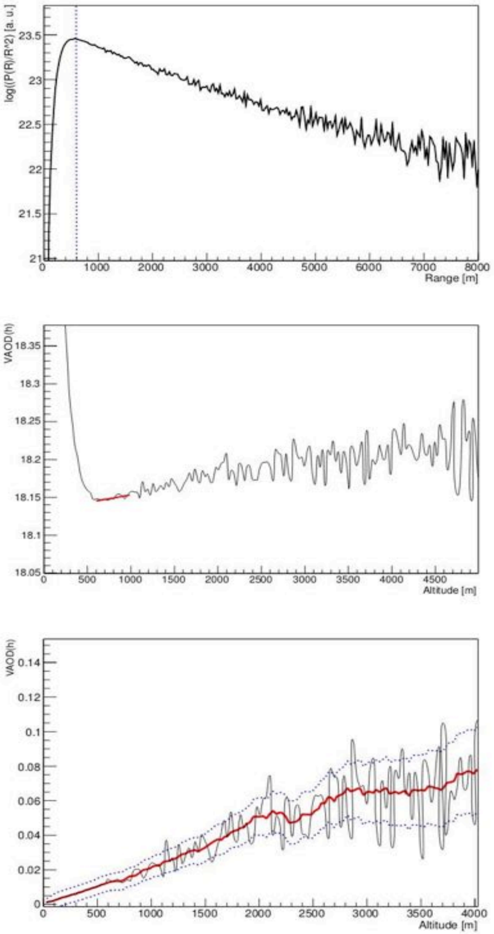


Fig. 5.7: Top: an example of a Raman signal resulting from the sum of 30000 laser shots. The dashed blue line indicate the altitude from where the analysis is performed. Middle: VAOD profile resulting from the analysis of the Raman signal before the evaluation of the integration constant. Bottom: corrected VAOD profile; continous red line is a smoothing obtained using a central running average, dashed blue lines are obtained shifting the smoothed profile by the associated uncertainty.

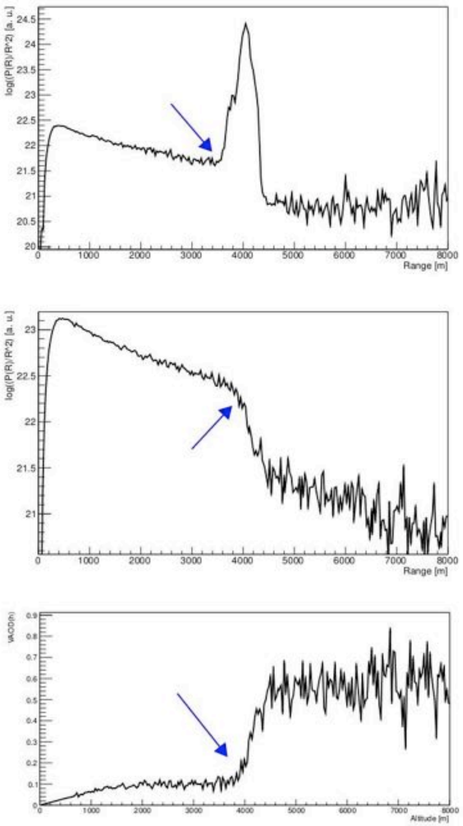
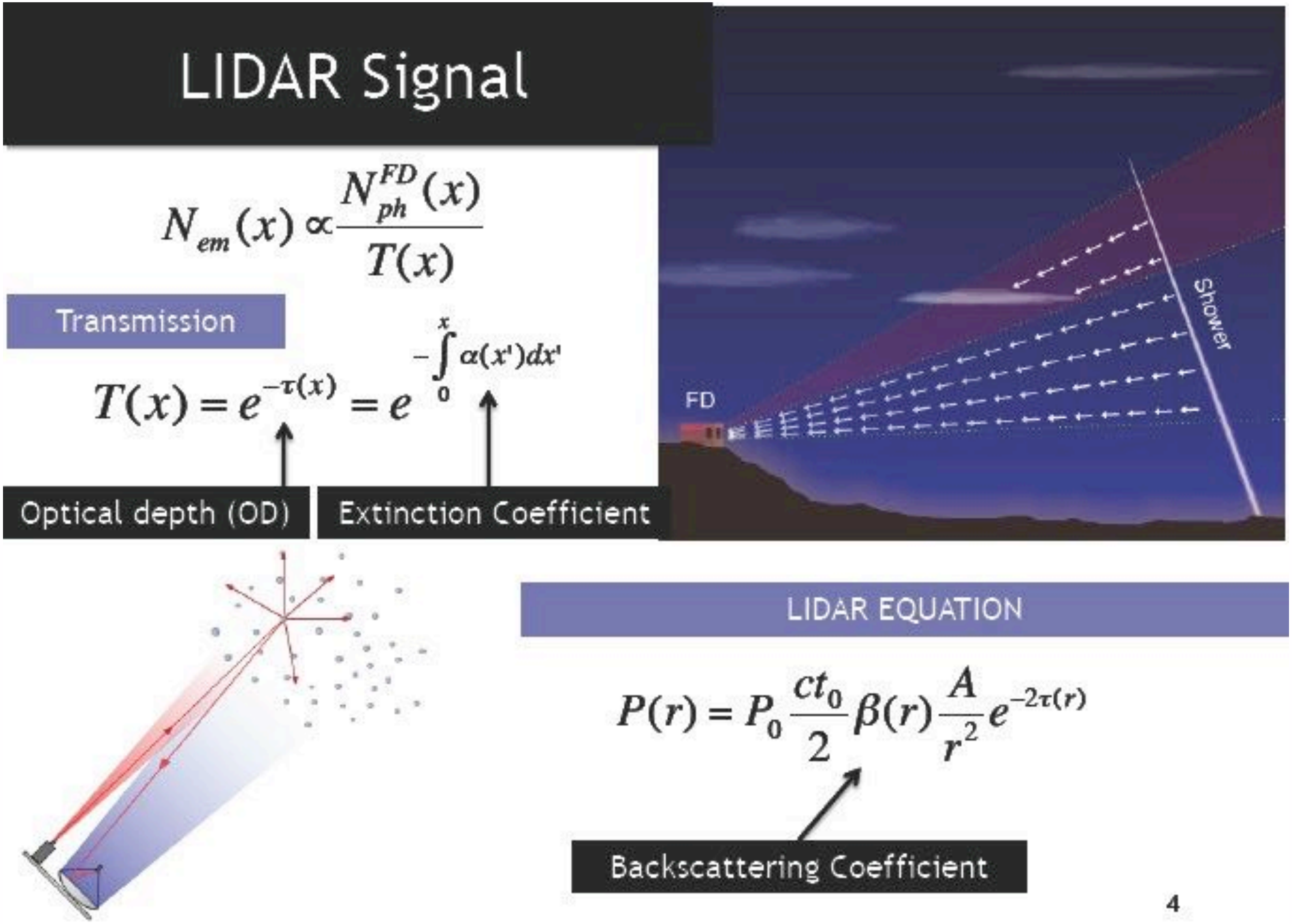


Fig. 5.8: A cloud is present above the lidar: it appears as a bump in the elastic signal (top) and as a depression in the Raman one (middle). The value of the VAOD increases at the altitude correspondig to the cloud base (bottom)

Receiver alignment

The LIDAR signal



LIDAR Signal

$$N_{em}(x) \propto \frac{N_{ph}^{FD}(x)}{T(x)}$$

Transmission

$$T(x) = e^{-\tau(x)} = e^{-\int_{0}^{x} \alpha(x')dx'}$$

Optical depth (OD)

Extinction Coefficient

LIDAR EQUATION

$$P(r) = P_0 \frac{ct_0}{2}\beta(r)\frac{A}{r^2}e^{-2\tau(r)}$$

Backscattering Coefficient

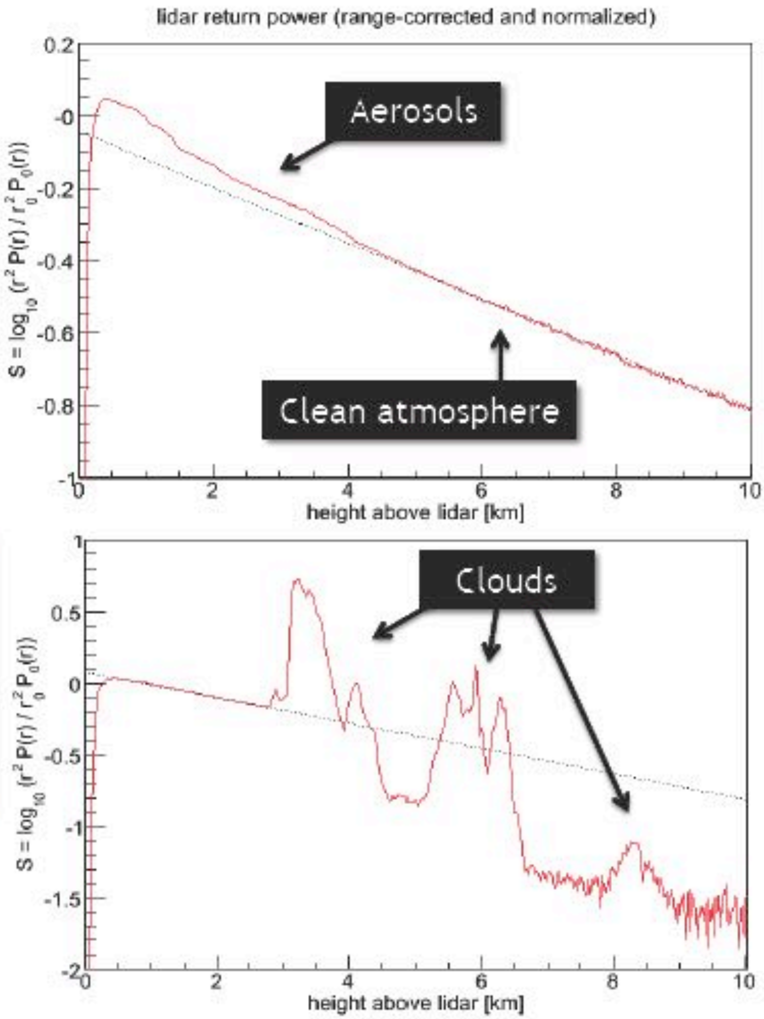
LIDAR data analysis: VAOD(h)

LIDARs provide a VAOD(h) estimate using the multiangle analysis

What we want to measure

$$P(r) = P_0 \frac{ct_0}{2} \beta(r) \frac{A}{r^2} e^{-2\tau(r)}$$

$$S(r) = \ln \frac{P(r) r^2}{P(r_n) r_n^2} = \ln \frac{\beta(r)}{\beta(r_n)} - 2\tau(r;r_n)$$



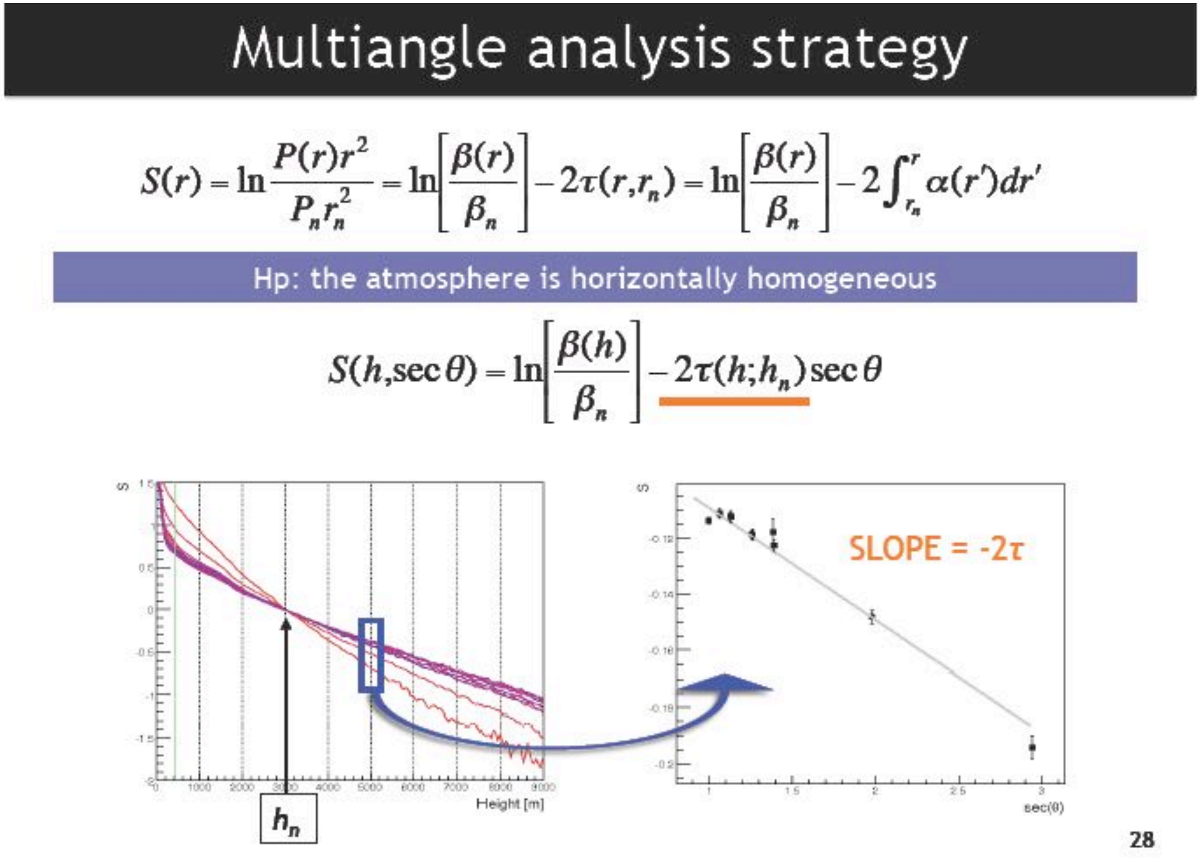
NIM A574:171-184, 2007
&
AstroparticlePhysics 18 (2003)

Auxiliary function S(r) which is the ratio between the Lidar signal at distance r and r_n

Multiangle analysis

A.Filipcic et al., AstroparticlePhysics 18 (2003)

based on the assumption of a horizontally uniform atmosphere : **r = h/cosθ**

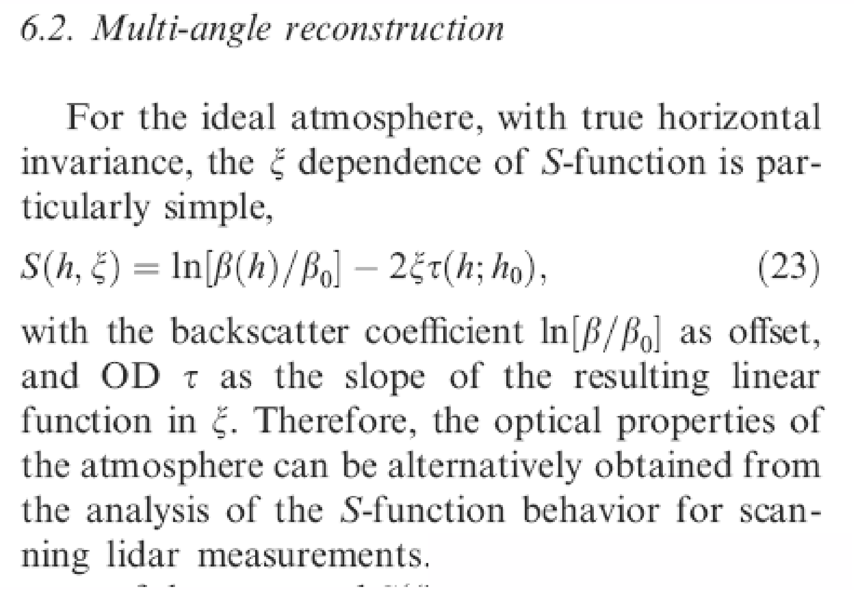


Multiangle analysis strategy

$$S(r) = \ln \frac{P(r)r^2}{P_n r_n^2} = \ln\left[\frac{\beta(r)}{\beta_n}\right] - 2\tau(r,r_n) = \ln\left[\frac{\beta(r)}{\beta_n}\right] - 2\int_{r_n}^{r} \alpha(r')dr'$$

Hp: the atmosphere is horizontally homogeneous

$$S(h,\sec\theta) = \ln\left[\frac{\beta(h)}{\beta_n}\right] \underline{-2\tau(h;h_n)\sec\theta}$$



6.2. Multi-angle reconstruction

For the ideal atmosphere, with true horizontal invariance, the ξ dependence of S-function is particularly simple,

$$S(h,\xi) = \ln[\beta(h)/\beta_0] - 2\xi\tau(h;h_0), \qquad (23)$$

with the backscatter coefficient $\ln[\beta/\beta_0]$ as offset, and OD τ as the slope of the resulting linear function in ξ. Therefore, the optical properties of the atmosphere can be alternatively obtained from the analysis of the S-function behavior for scanning lidar measurements.

The Elastic Lidar

Elastic scattering on both molecules and aerosols

$$L^{\lambda 0}(s) = L^{\lambda 0}_{0} O(r) \bullet$$

$$T^{\lambda 0}_{mol}(s)\, T^{\lambda 0}_{aer}(s)\, T^{\lambda 0}_{abs}(s) \bullet$$

$$[\sigma^{\lambda 0}_{mol}(\pi)\, n_{mol}(s) + \beta^{\lambda 0}_{aer}]\, d\Omega/4\pi \bullet$$

$$T^{\lambda 0}_{mol}(s)\, T^{\lambda 0}_{aer}(s)\, T^{\lambda 0}_{abs}(s)$$

Emitting laser intensity

Attenuation (ongoing path)

Backscattering volume

Attenuation (backscattered light)

Assumption needed on atmospheric properties: Lidar Ratio = $\alpha^{\lambda 0}_{aer} / \beta^{\lambda 0}_{aer}$

$$\boxed{T^{\lambda}_{aer}(s) = \exp(- \int \alpha^{\lambda}_{aer}(s)(ds)}$$

The Raman Lidar

Raman Scattering : anelastic collision on N2, O2, H_2O
producing a frequency shift of the backscattered photons

$$\begin{aligned} L^{\lambda i=\lambda 0+\Delta\lambda i}(s) = L^{\lambda 0}_{0}\, O(r) \bullet \\ T^{\lambda 0}_{mol}(s)\, T^{\lambda 0}_{aer}(s)\, T^{\lambda 0}_{abs}(s) \bullet \\ [\sigma^{\lambda i}_{Raman}(\pi)\, n_i(s)]\, d\Omega/4\pi \quad \bullet \\ T^{\lambda i}_{mol}(s)\, T^{\lambda i}_{aer}(s)\, T^{\lambda i}_{abs}(s) \end{aligned}$$

No more $\beta^{\lambda 0}_{aer}$ → no need to make assumptions on the Lidar Ratio, but T^{λ}_{aer} appears at 2 different wavelengths

$(\alpha^{\lambda 0}_{aer} / \alpha^{\lambda i}_{aer}) = (\lambda_0/\lambda_i)^k$: 2 Raman channels are used to extrapolate k

Uncertainty on aerosol extinction is lower than with the elastic lidar BUT Raman cross section is 3 orders of magnitude lower than elastic → longer acquisition time !