The ARCADE Lidar for CTA

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The ARCADE Raman Lidar system for the Cherenkov Telescope Array

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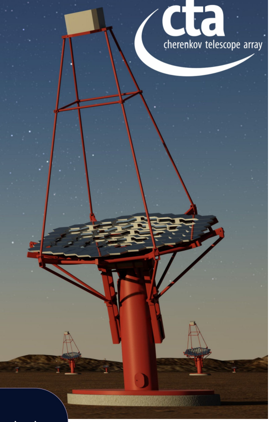
cta
cherenkov telescope array



ABSTRACT

The atmospheric calibration of the CTA telescopes is a critical task and aerosols are the most variable component in time and space. Lidars are among the most used instruments in atmospheric physics to measure the aerosol attenuation profiles of light. The ARCADE Lidar system is a compact and portable Raman Lidar system that has been built within the FIRB 2010 grant and has taken data for one year in Lamar, Colorado. The ARCADE Lidar is proposed to operate at the CTA sites to make a first survey of the aerosol conditions of the selected site and to use it as a calibrated benchmark for the other Lidars that will be installed on site. The ARCADE Lidar will be first upgraded in Italy and then tested in parallel to a Lidar of the EARLINET network in L'Aquila. Upgrades include the addition of the water vapour Raman channel to the receiver and the use of new and better performing electronics. It is proposed that the upgraded system will travel to and characterize both CTA sites, starting in 2016 from La Palma (Spain), selected for CTA-North.

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Introduction

In the CTA, to ensure high quality data for the observatory, a continuous characterization of the local optical properties of the atmosphere during data taking will be performed to correct data. Studies conducted using Monte Carlo simulations of the Magic telescopes proved the need for height-dependence aerosol attenuation measurements to correct IACT data. For this reason, the CTA will include Raman Lidars to measure the vertical aerosol optical depth profiles.

The ARCADE Raman Lidar

The ARCADE Raman Lidar will perform a first survey of the aerosol conditions on both CTA selected sites, La Palma (Spain) and Paranal (Chile), and will be used as a benchmark to the other Raman Lidar systems that are scheduled to be running on site. This lidar has been built within the FIRB 2010 grant funded by Italian MIUR and has taken data in Colorado for one year.

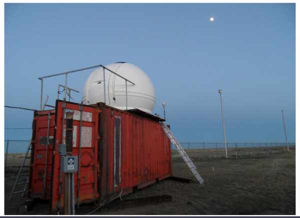

Fig. 1: the ARCADE Lidar in Lamar, Colorado

ACKNOWLEDGEMENTS

We gratefully acknowledge support from the agencies and organizations under *Funding Agencies* at www.cta-observatory.org

The laser bench and the receiver are all assembled together and move at the same time on the zenith axis from 0 to 90 degrees. This reduces possible misalignments and makes all the system easily portable. The ARCADE lidar is able to separate the elastic (355 nm) and nitrogen (387 nm) backscattered Raman components of the returning signal and to process them separately. Analysis methods that can be performed with the present configuration are the multi-angle analysis applied to the elastic traces and the Raman analysis.

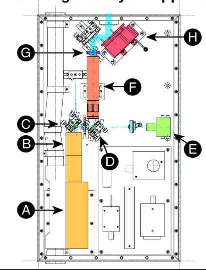

Fig. 2: the laser bench A : the laser; B,C : dichroics; D : 95/5 beam splitter; E : probe; F : 10X beam expander; G : depolarizer; H : motorized mirror.

The planned upgrade

The list of improvements, decided after one year of operation in difficult conditions, will include :

- **new photomultipliers;**
- **a new more efficient HV control system;**
- **a better insulation for the Lidar box;**
- **adding the water vapour Raman channel to the receiver. This includes the modification of the receiver to host a third photomultiplier and the related filters.**

The addition of a second Raman channel at 407 nm will improve the precision of the measurements and will allow to obtain the water vapour profiles in atmosphere.

The future in CTA

The target of the ARCADE campaign in the CTA is to characterize the aerosol content in the atmosphere over the site. ARCADE can measure the aerosol extinction α(h) and volume backscatter β(h) coefficients profiles, as well as the water vapour mixing ratio up to an altitude of 10 km. α (h) and β (h) can fully describe the optical properties of the aerosols. The water vapour profiles, measured simultaneously to the aerosol attenuation profiles, can help to define the physical properties of the aerosol particles. In addition also horizontal homogeneity can be sampled.

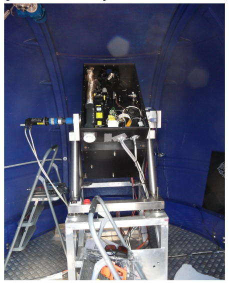

Fig. 3: a picture of the lidar mounted on the steering mechanism

Target of ARCADE in CTA

The ARCADE Lidar is proposed to operate at the CTA sites with the goal of making a first survey of the aerosol conditions of the selected site and to use it as a calibrated benchmark for the other Lidars that will be installed on site.

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Upgrades include the addition of the water vapour Raman channel to the receiver and the use of new and better performing electronics.

The upgraded system will be installed at both CTA sites, starting from XXX? in 2016

It will measure the aerosol extinction $\alpha(h)$ and backscattering coefficient $\beta(h)$ profiles as well as the water vapour mixing ratio : all information will help to characterize the optical properties of aerosols on site.

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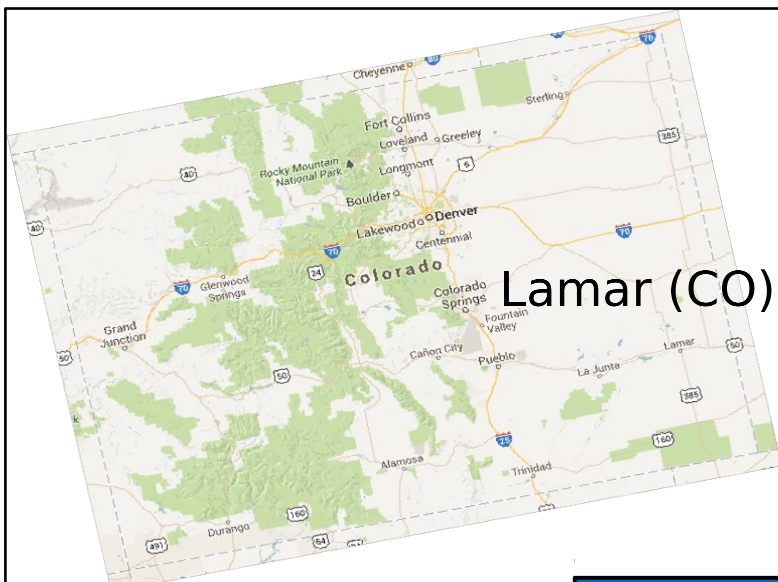
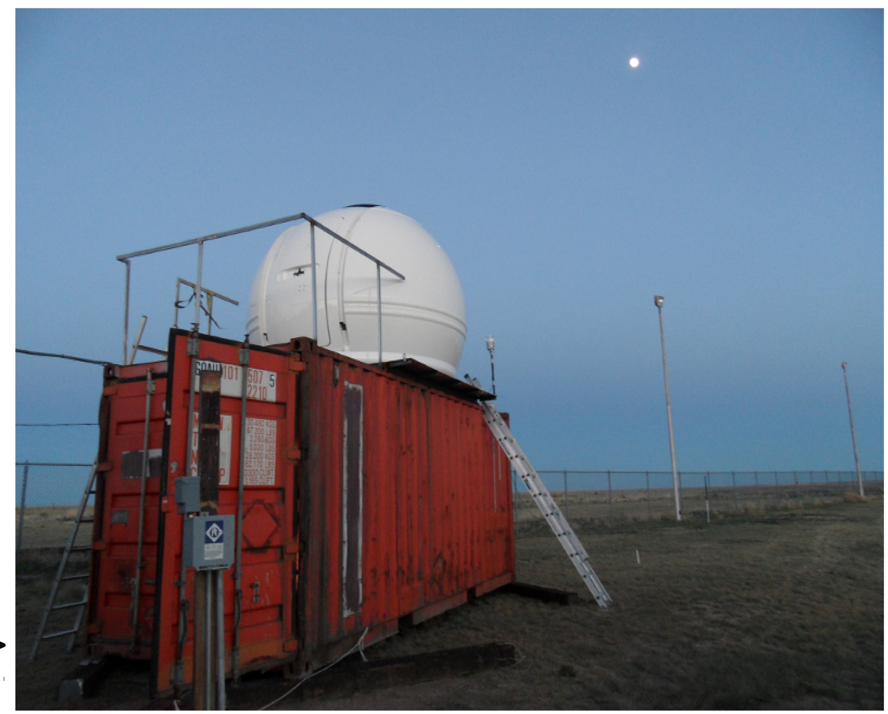
Target of the former ARCADE project

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

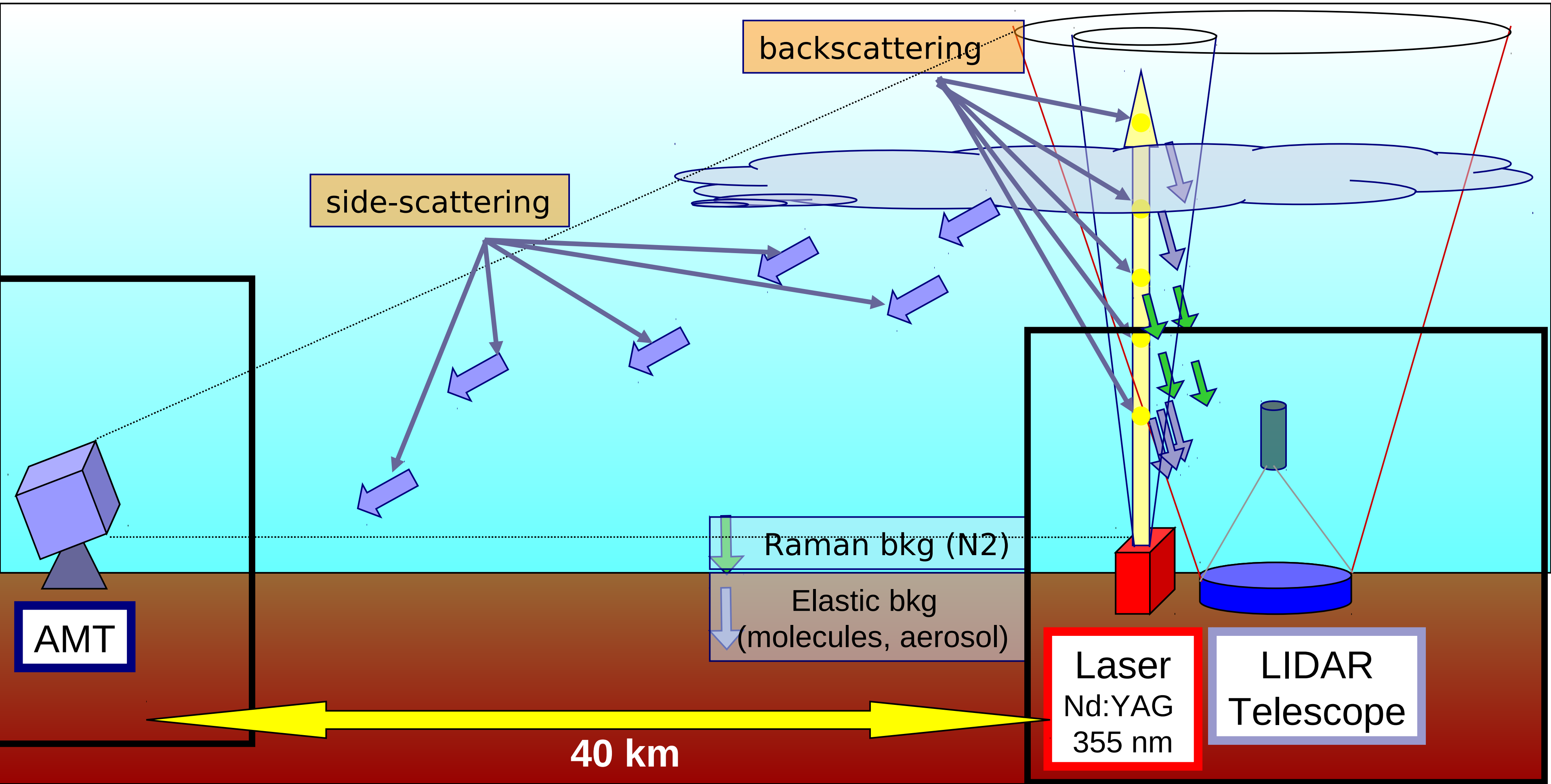
1. Side-scattering measurements using a distant laser facility and a UV light telescope
2. Back-scattering measurements using elastic and Raman lidars



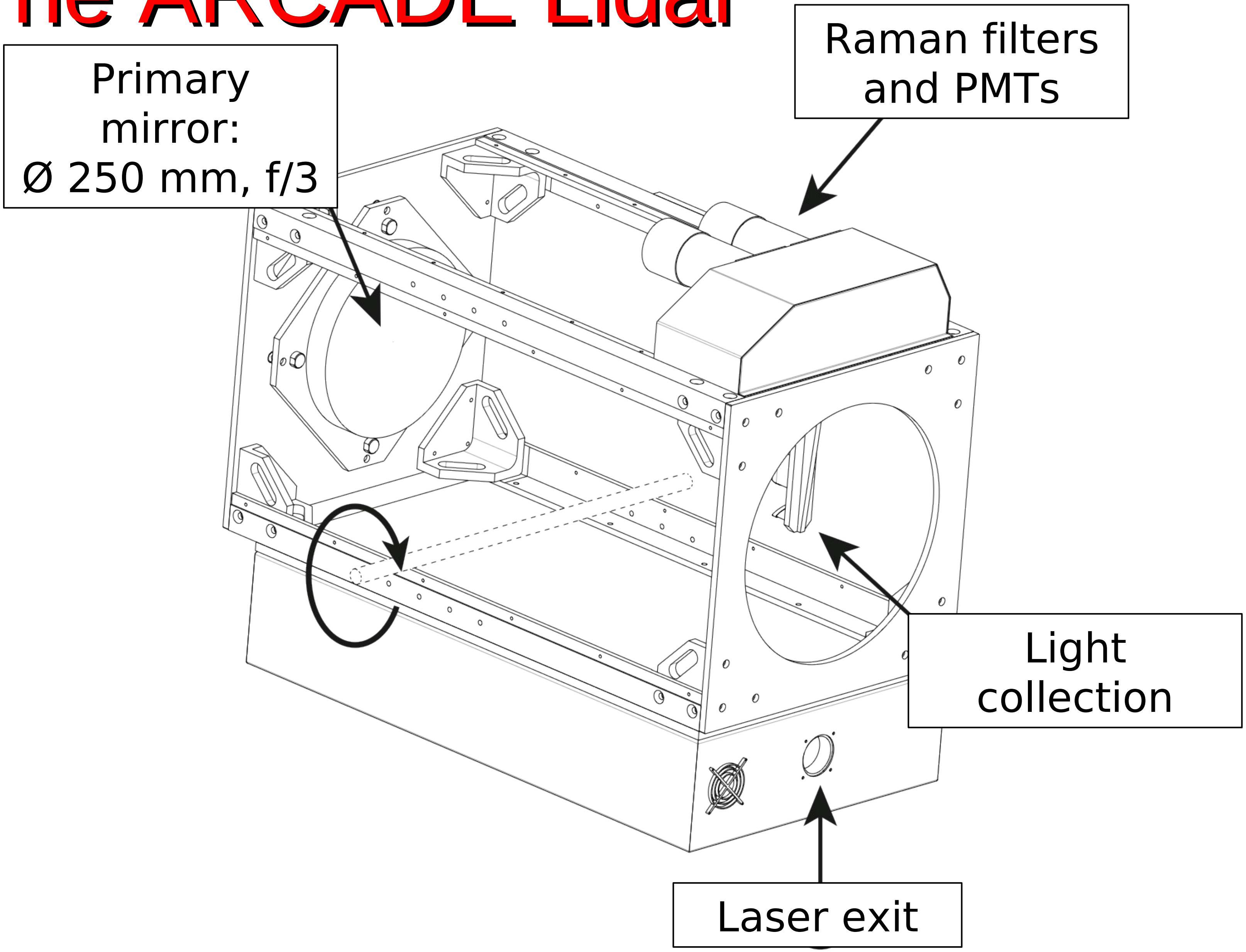


The ARCADE system setup

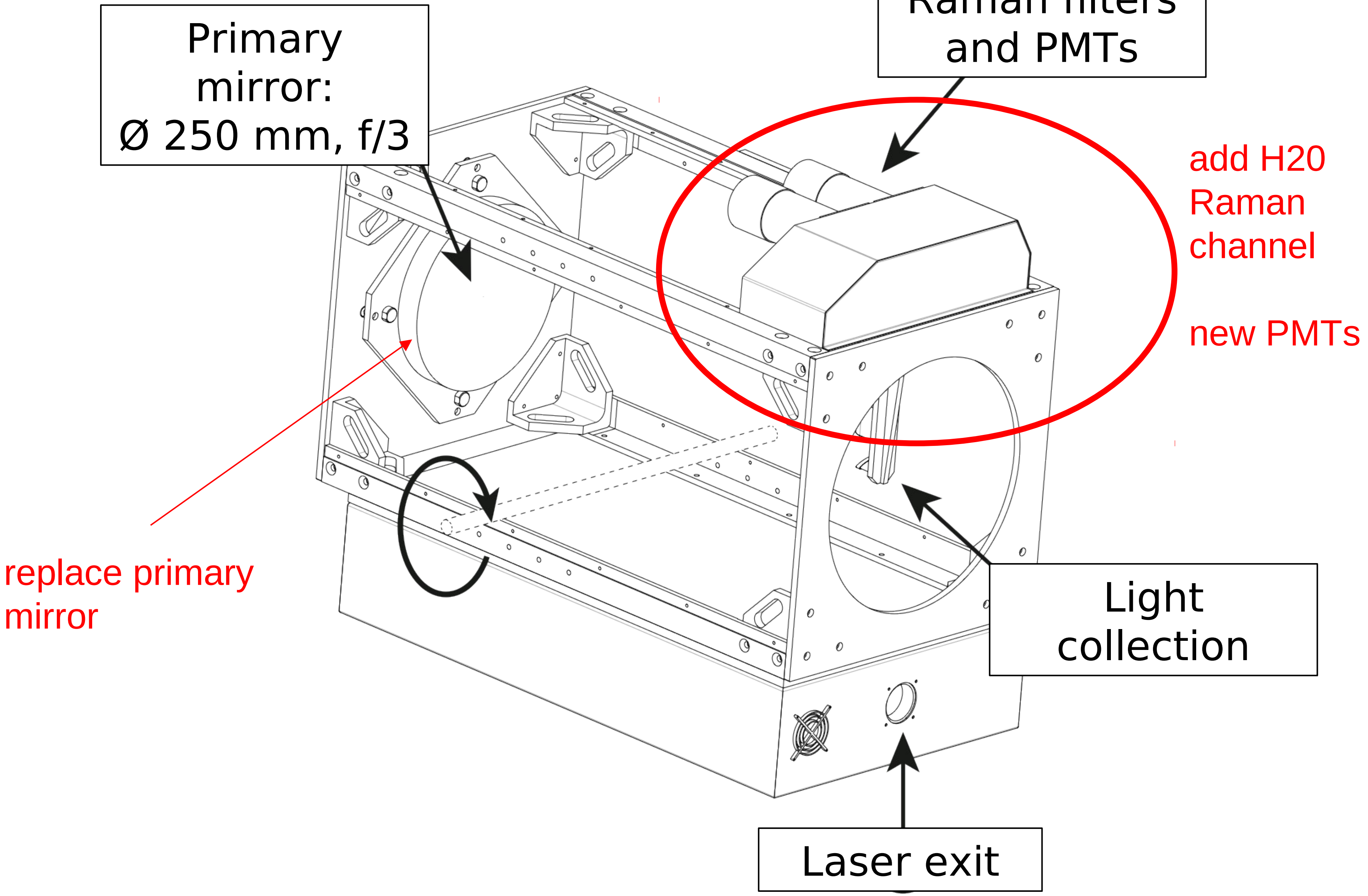
elastic + Raman lidar & the AMT telescope



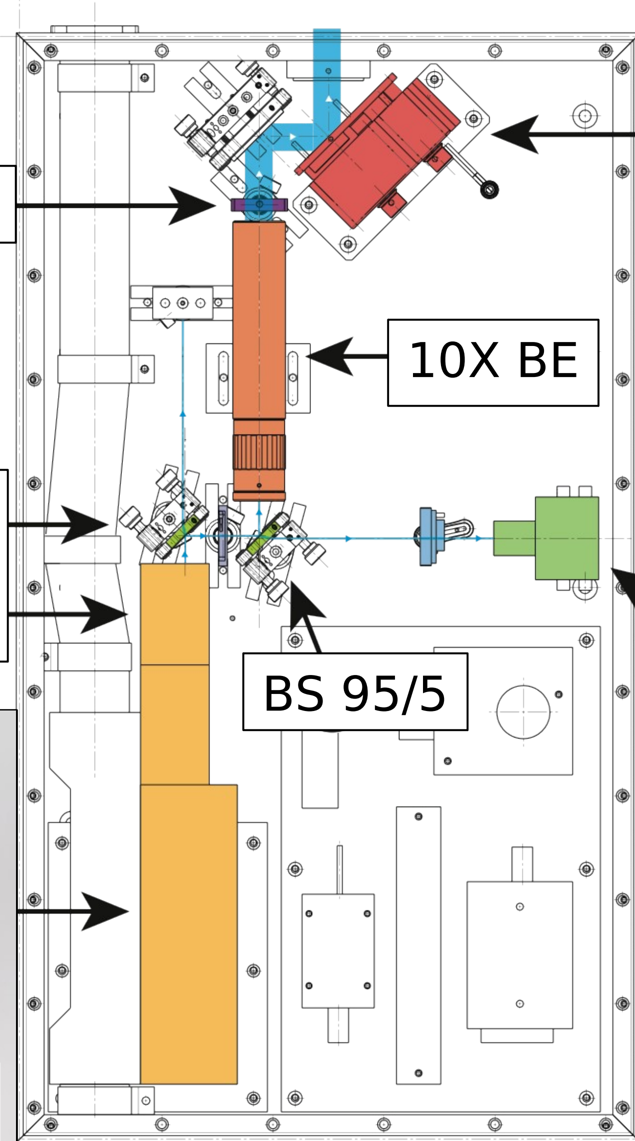
The ARCADE Lidar

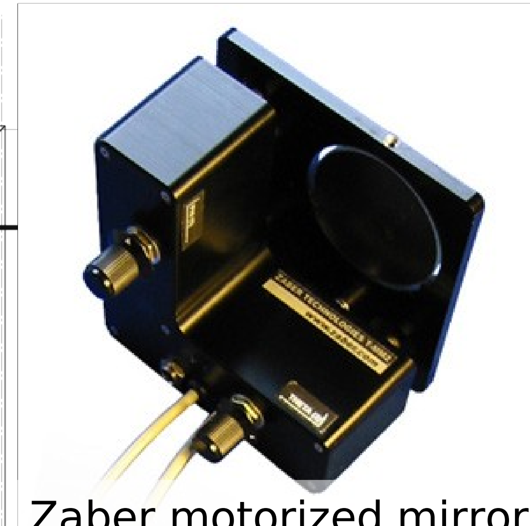


The ARCADE Lidar



The laser bench





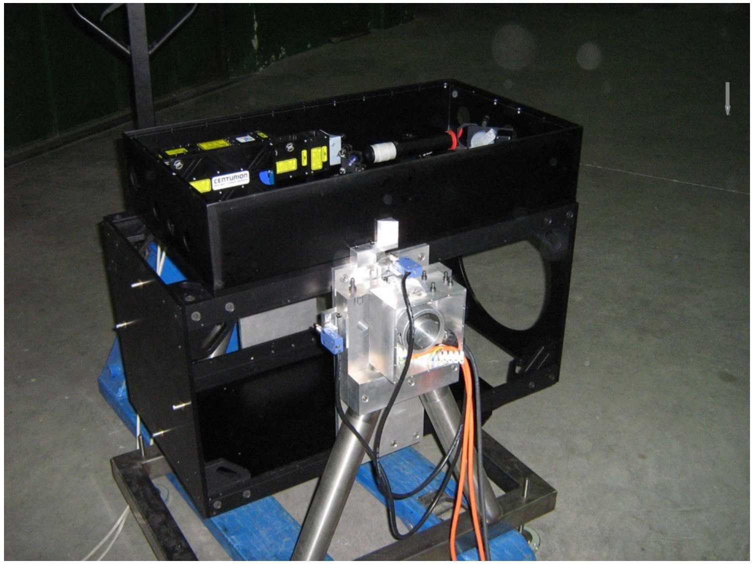
Zaber motorized mirror mount: remotely computer controlled fine alignment

Laser probe RjP-445

Quantel Centurion Nd:YAG laser

The laser bench realized

The lidar is mounted on a steering mechanism ...



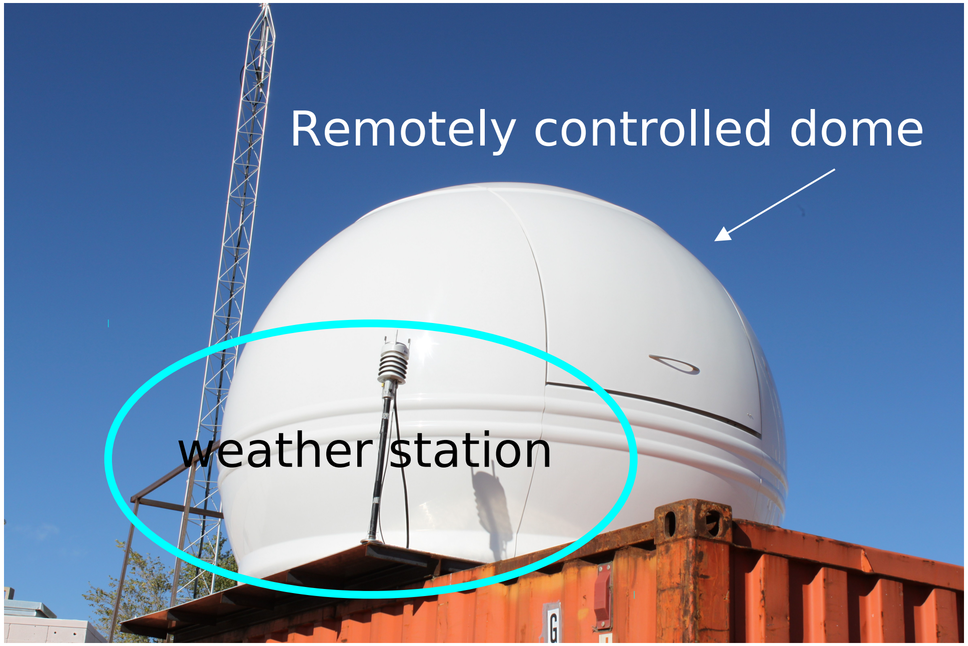
… is housed within an astronomical dome ...

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

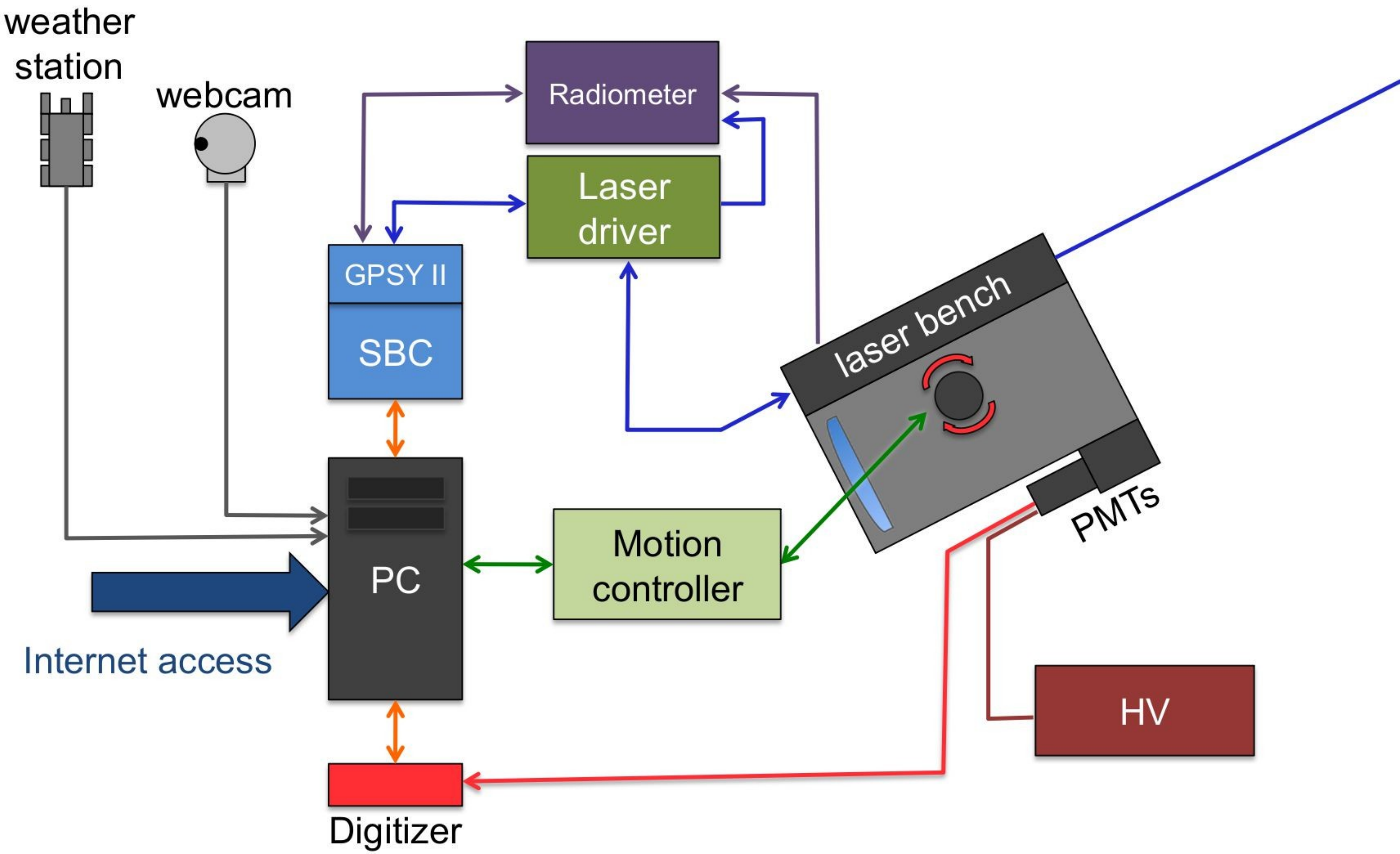
Built for remote operation

Needs power and internet connection

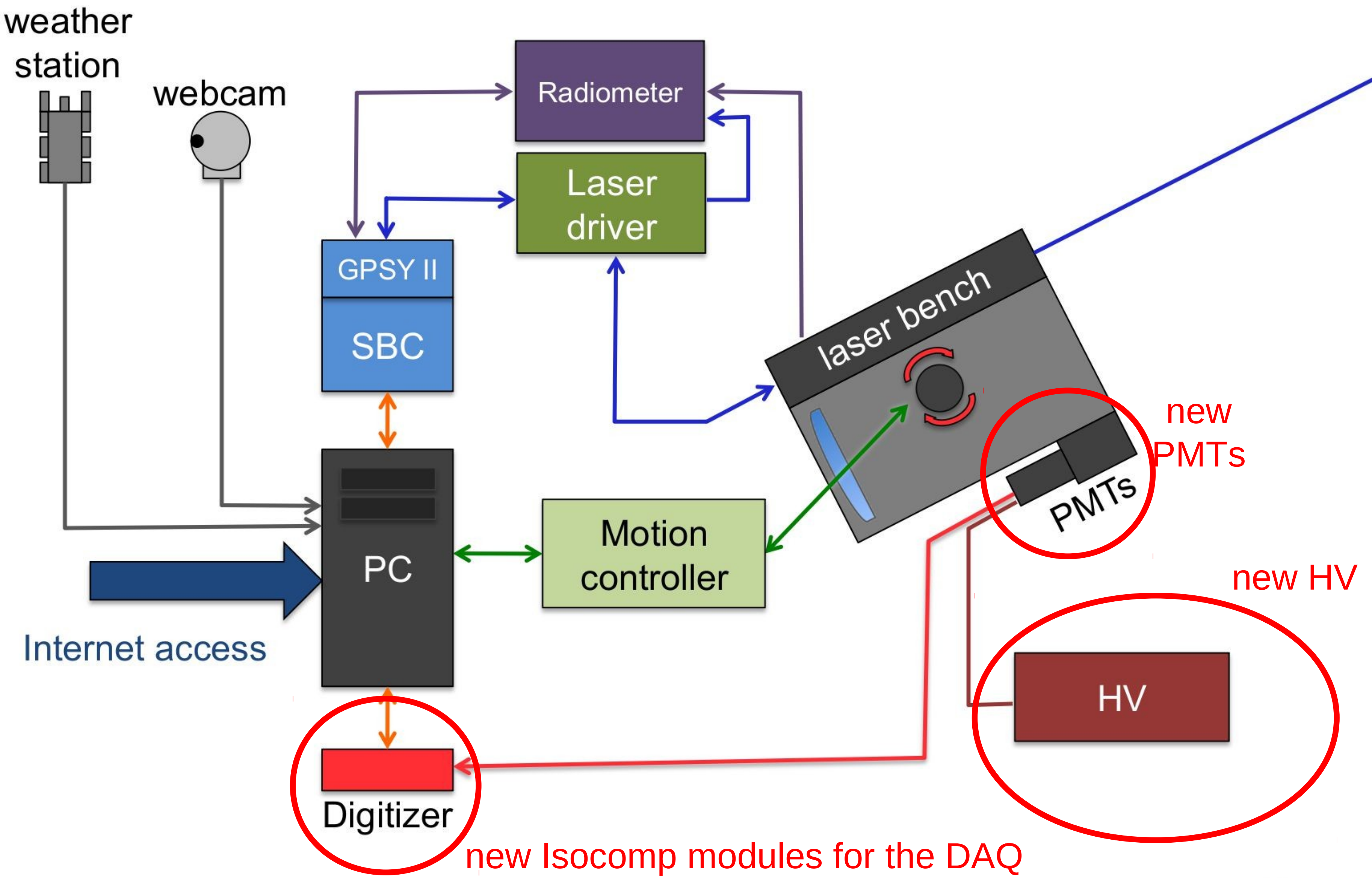
A 20 ft standard shipping container will be used to ship the Lidar to the first of the two CTA selected sites and it will host the DAQ inside. A concrete pad is needed as basement. A building to store the materials during the installation is needed too.
The astronomical dome on top has been working also in very difficult weather conditions during this year !



Lidar system

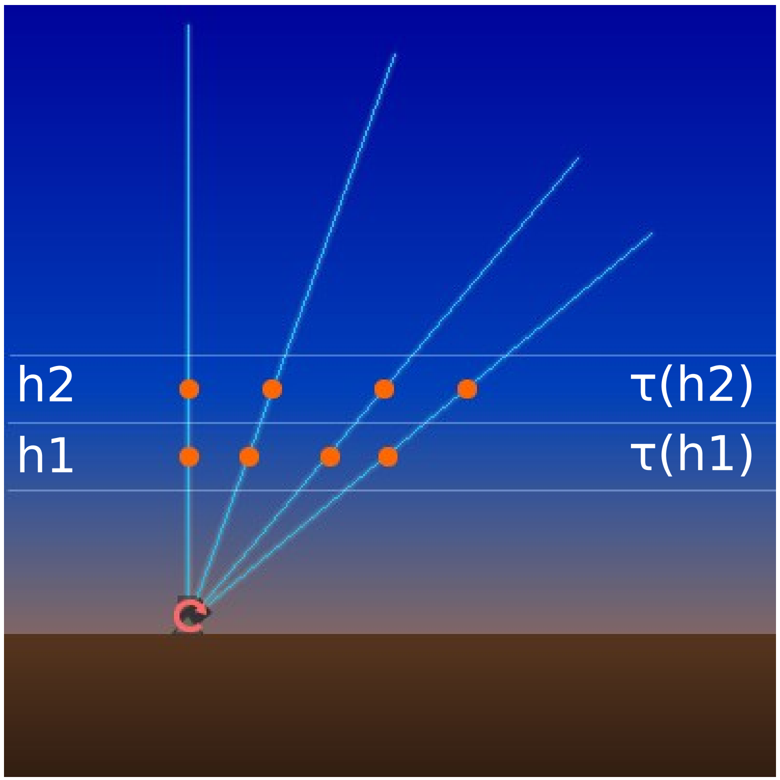


Lidar system



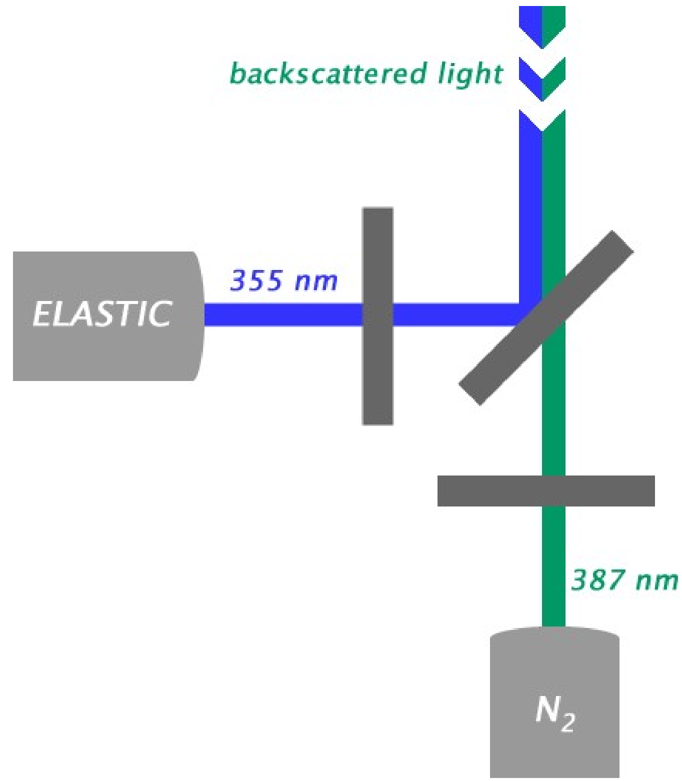
Analyses techniques applicable with the "old" ARCADE configuration

ELASTIC LIDAR
Multi-angle analysis



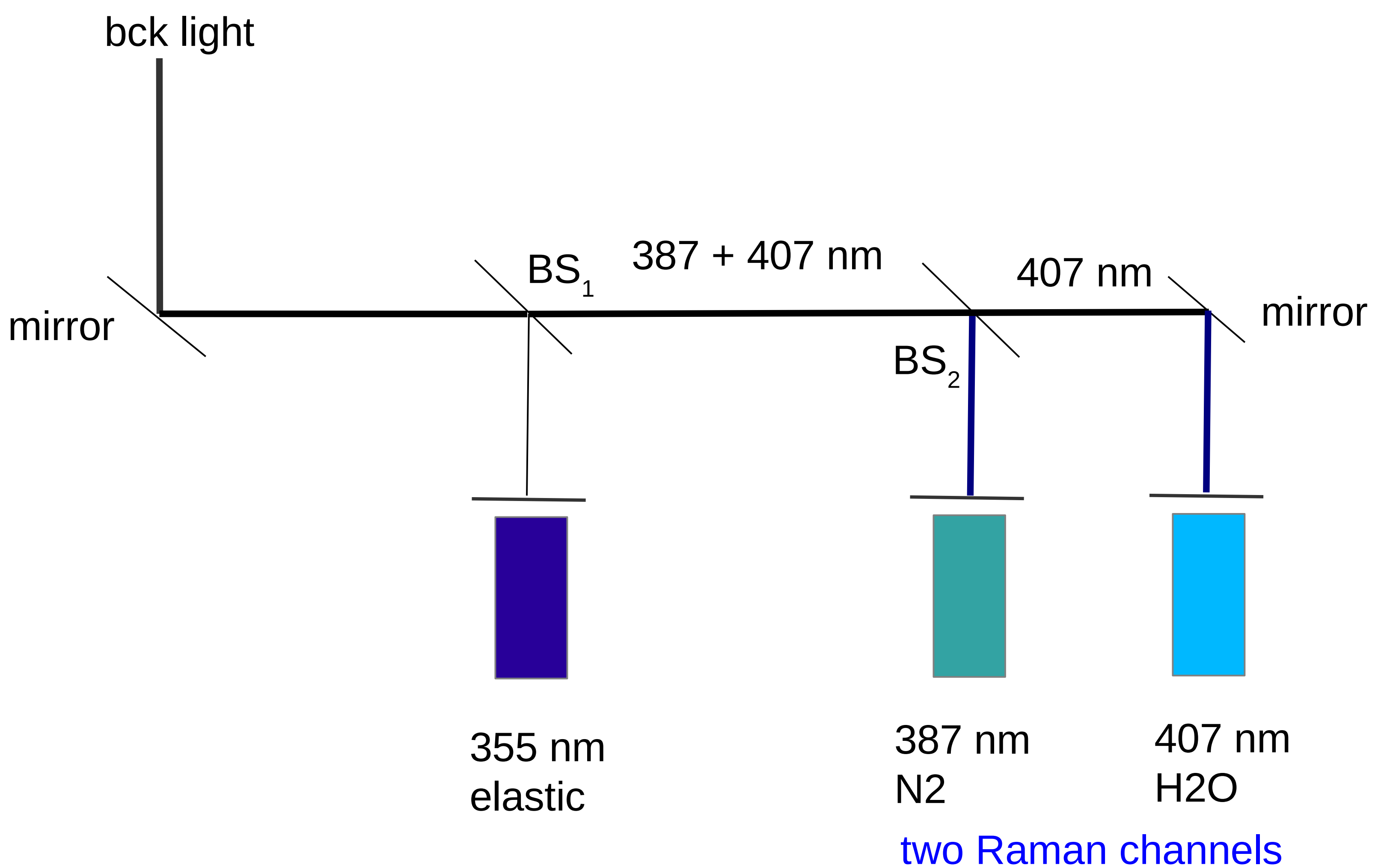
Hp: horizontally homogeneous atmosphere

RAMAN LIDAR
Vertical and inclined shots

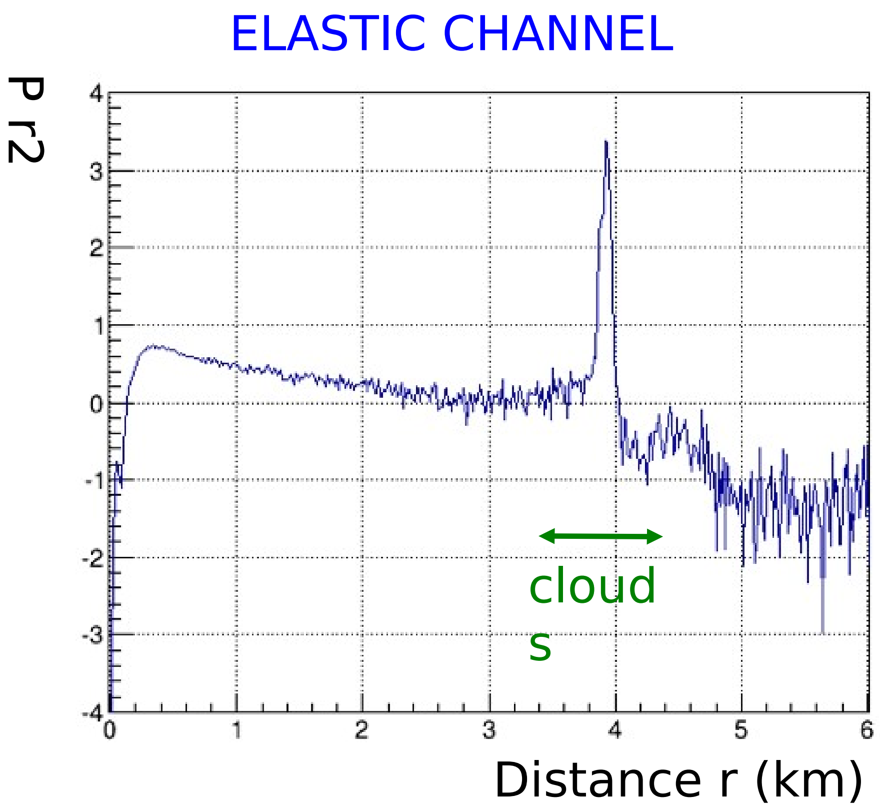


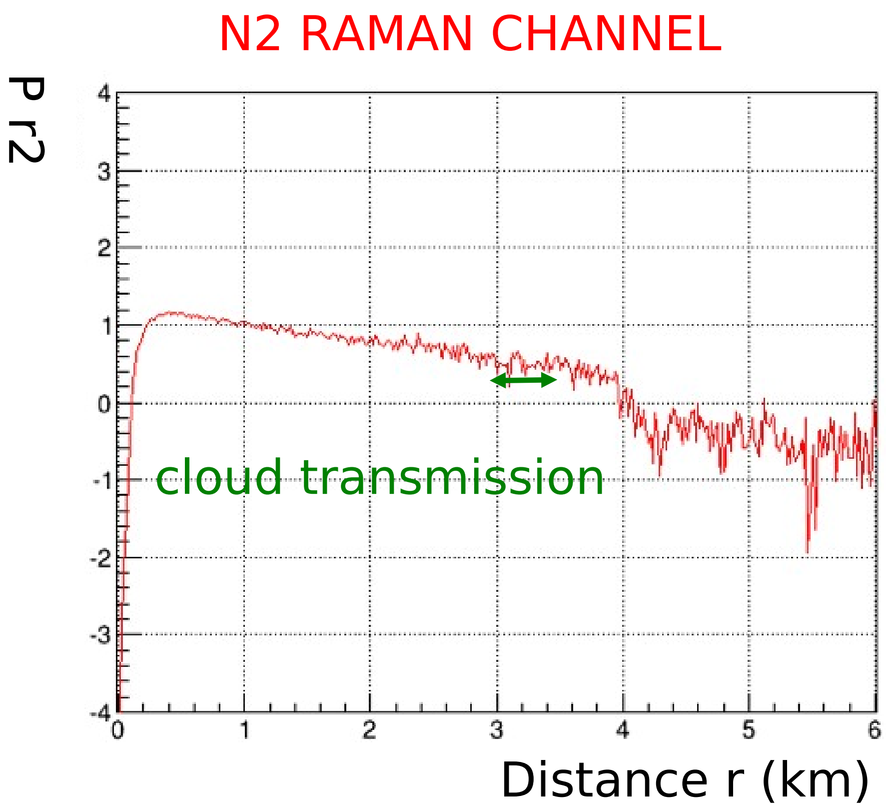
2 equations for two unknowns

The “new” ARCADE receiver, after the upgrade : adding the water vapour Raman channel

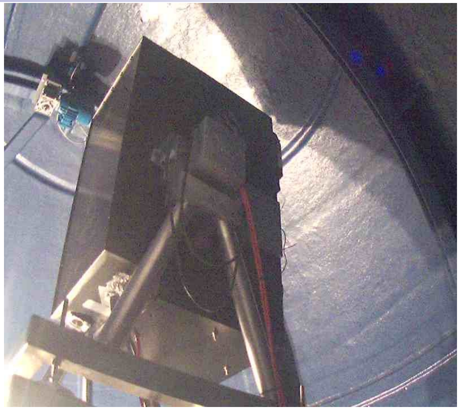


An example of the ARCADE lidar data





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

output are txt files not bigger than 500kB, stored inside the LidarPC

Data taking & problems

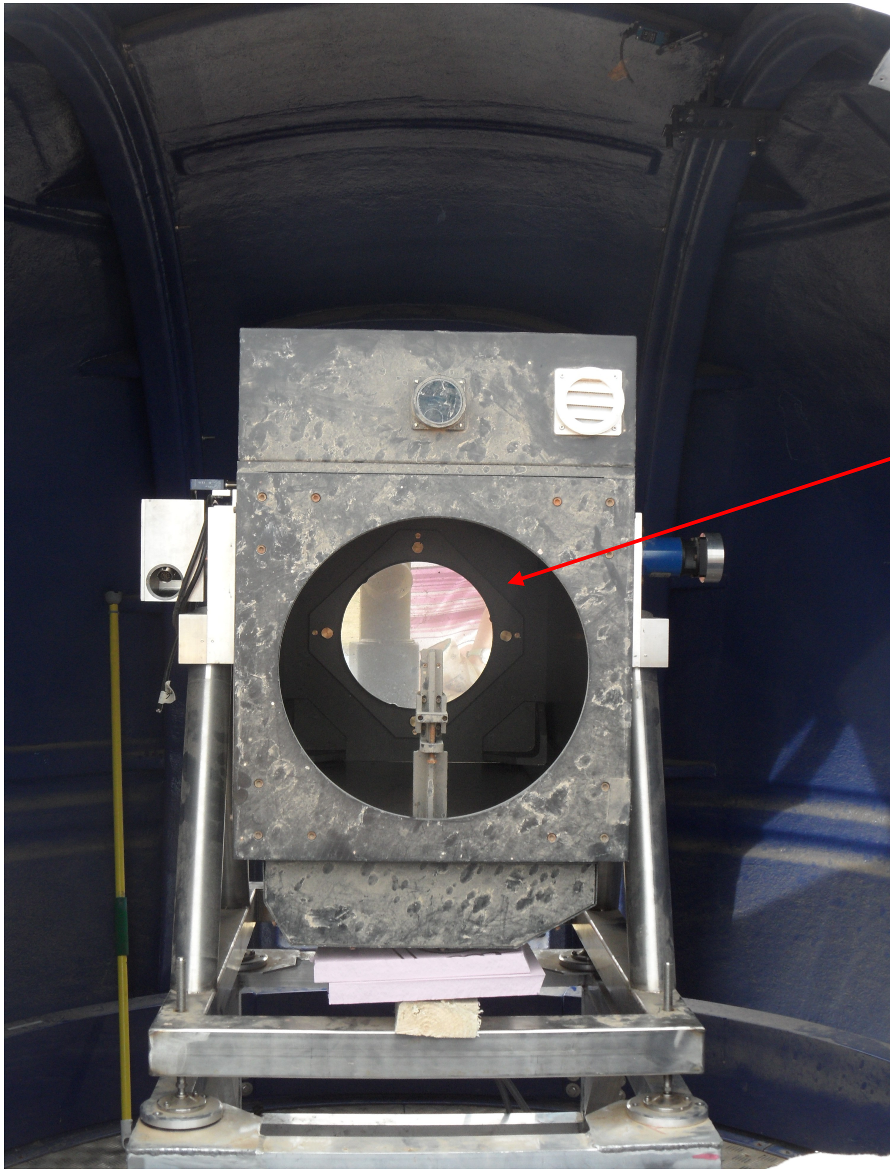
…. some interruption in the data taking period due to problems :

1. too low temperatures – laser heating failing when T < -5°C
2. GPSY on SBC failing, need to restart the system often (less problems if we plan to operate only vertically)
3. Zaber motorized mirror mount and Vaisala weather station sometimes disappearing – need to unplug and replug the cable
4. too low temperatures caused the UPS to fail and shutdown all the computers
5. network very unstable on site
6. weather rapidly changing and extremely dusty ...

Most of them can be solved easily if there is manpower on site! It is a custom made telescope : some item may show up and need manpower to solve it.

It is not recommendable to start the ARCADE site characterization directly in Armazones : we suggest to go first to La Palma for 1 year and then to Armazones.

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 ...

Some parts need to be replaced : quartz window, primary mirror

July 2015 – umounting the lidar in Colorado

needed to install the LIDAR at the CTA site :

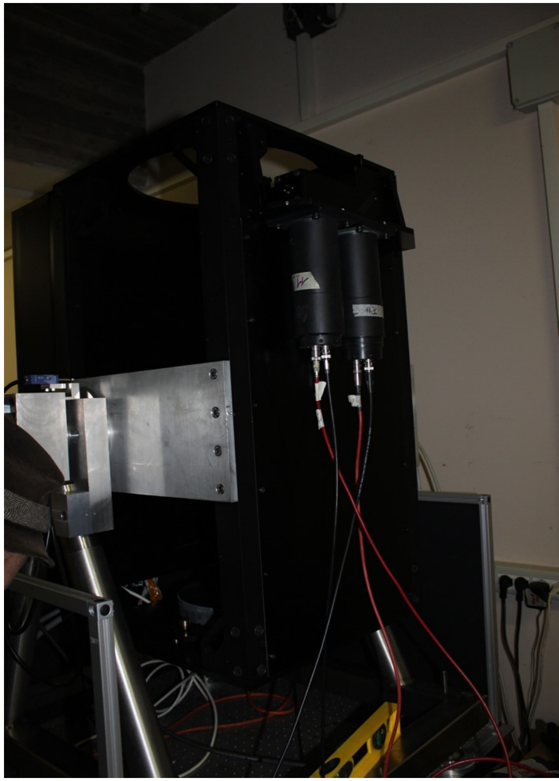
- a truck to bring the 20ft container to the site
- a crane to unload the container and to load the dome on top of the container

a roadto the site accessible for a truck and a crane is mandatory for this!

Lidar upgrade

Upgrade includes :
- new HV control
- new PMTs
- new easier DAQ modules
- additional H2O Raman channel
- replace damaged optics

- All the materials for the upgrade ordered and arriving (optics, electronics, ...)
- Design of the upgraded receiver under study *(Torino INFN technicians M. Marengo / G. Dughera)*



The ARCADE lidar is back in Torino since mid september

PLAN :
- end 2015 – early 2016 : upgrade in Torino
- mid 2016 : tests of the upgraded Lidar at CETEMPS /Department of Physics in L'Aquila : *simultaneous acquisition in parallel to the Lidar of the EARLINET network (V. Rizi – M. Iarlori)*
- end 2016 / beginning of 2017 : shipment to the first selected site for the installation. La Palma strongly preferred to Armazones

Conclusions

The target of ARCADE in CTA is to characterize the seasonal and climatological aerosol content on site.

It will measure the aerosol extinction $\alpha(h)$ and backscattering coefficient $\beta(h)$ profiles as well as the water vapour mixing ratio : all information will help to characterize the optical properties of aerosols on site.

PROPOSED PLAN :

go first to La Palma at the end of 2016 – beginning of 2017 → take data for 1 year (all 2017 and part of 2018). Then plan to unmount and move the ARCADE Lidar to Chile.

Thanks for your attention!

BACKUP

An example of the ARCADE lidar data

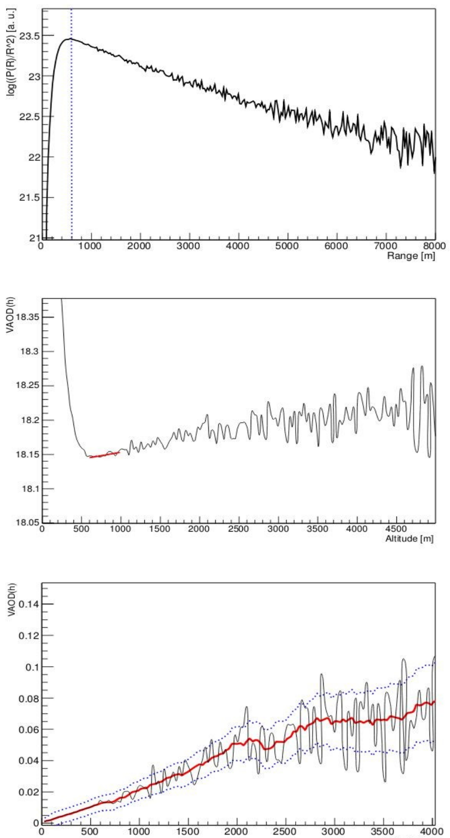


Fig. 5.7: Top: an example of a Raman signal resulting from the sum of 30000 laser shots. The dashed blue line indicate the altitude from where the analysis is performed. Middle: VAOD profile resulting from the analysis of the Raman signal before the evaluation of the integration constant. Bottom: corrected 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.

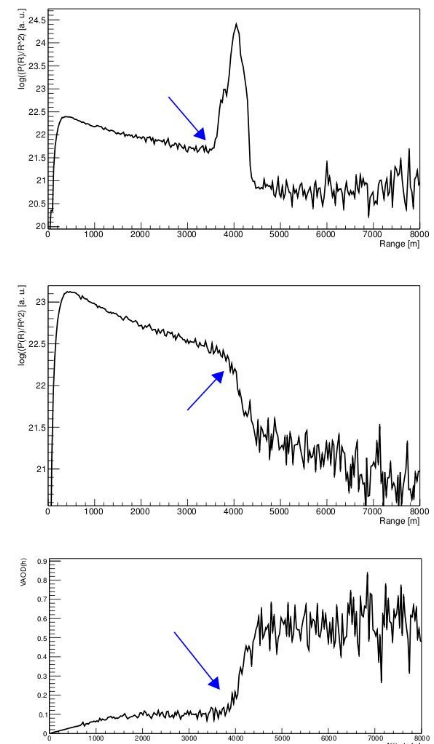
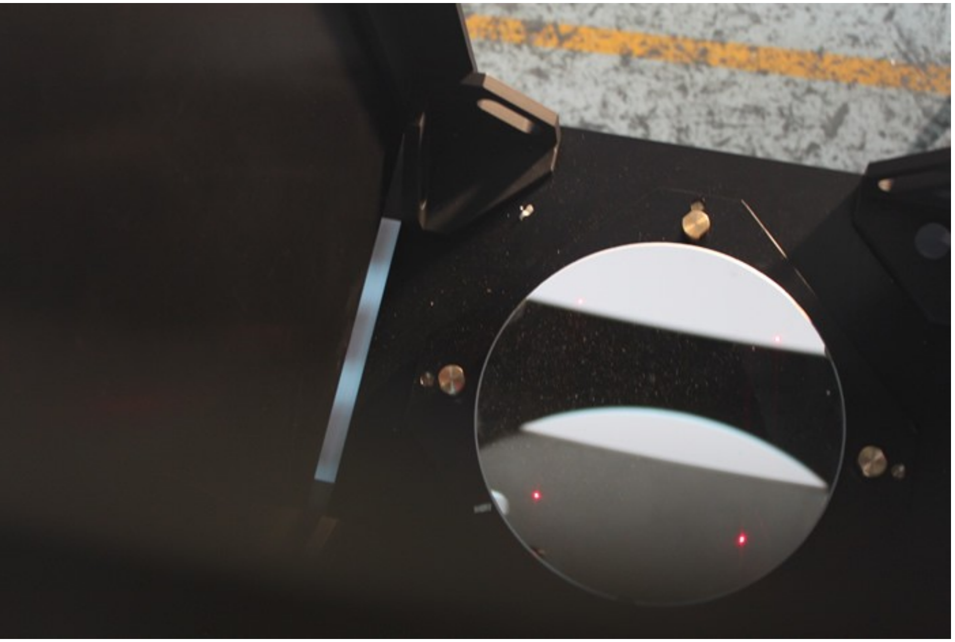
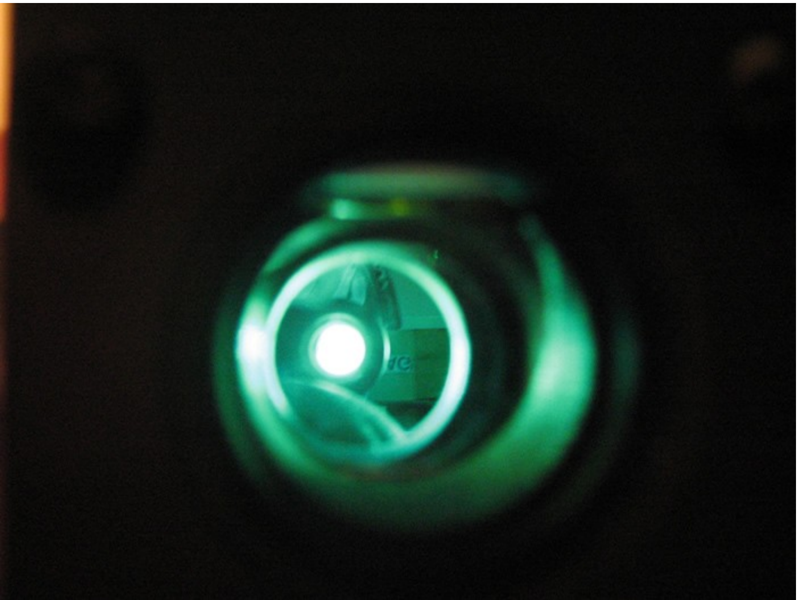
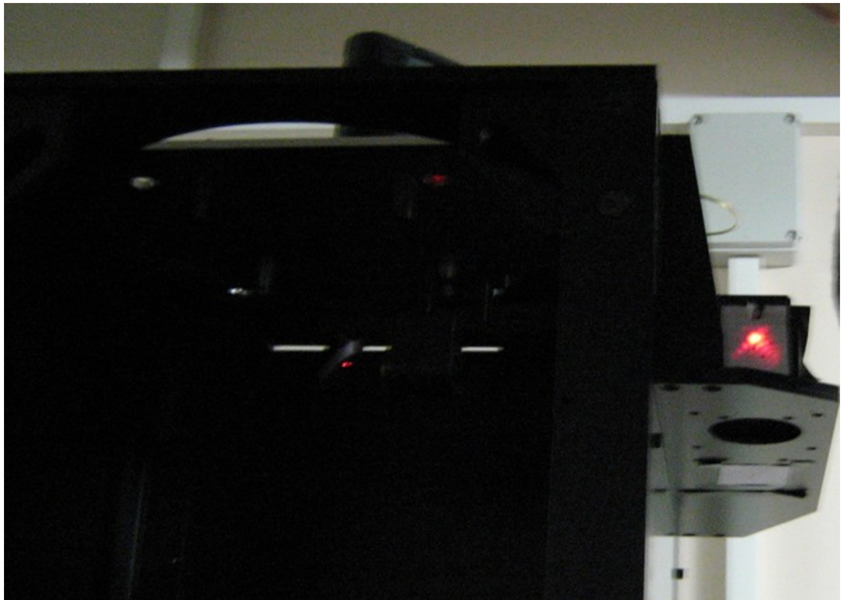


Fig. 5.8: A cloud is present above the lidar: it appears as a bump in the elastic signal (top) and as a depression in the Raman one (middle). The value of the VAOD increases at the altitude correspondig to the cloud base (bottom)

Receiver alignment



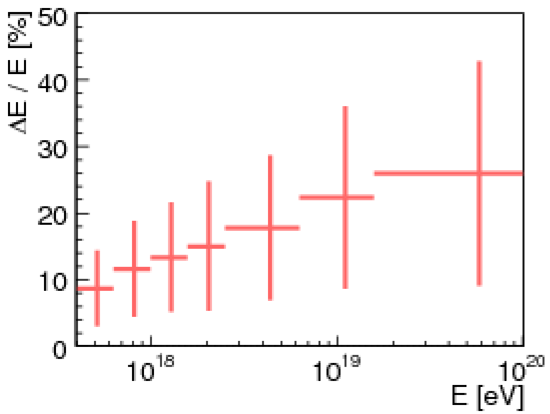


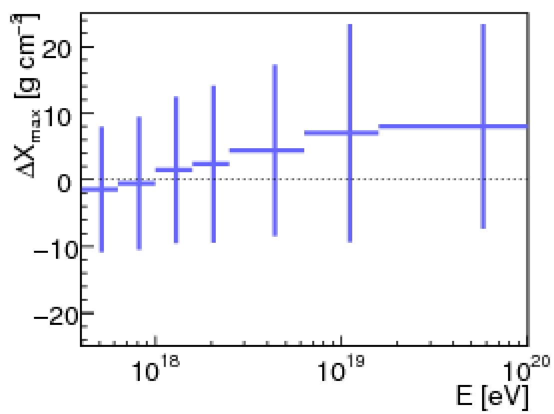


The effect of aerosol conditions on air fluorescence measurements

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

The LIDAR signal

LIDAR Signal

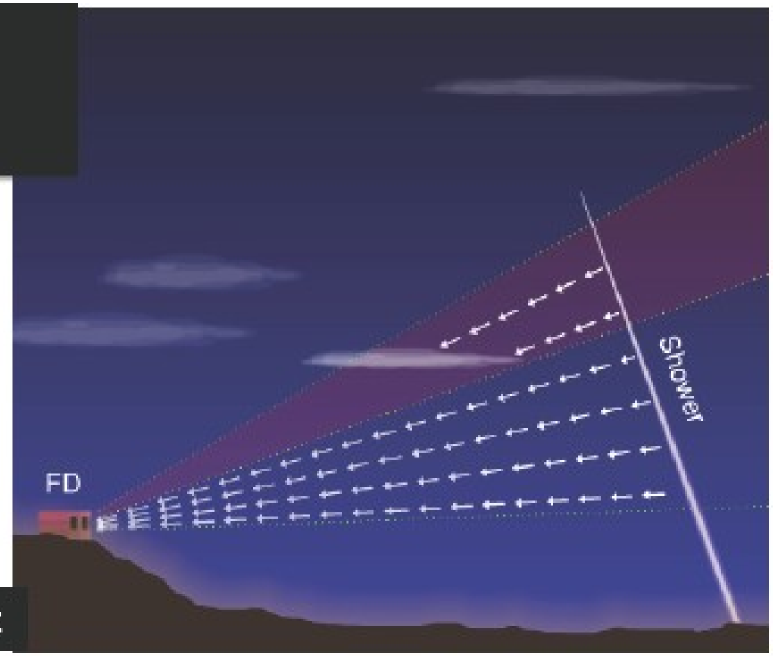
$$N_{em}(x) \propto \frac{N_{ph}^{FD}(x)}{T(x)}$$

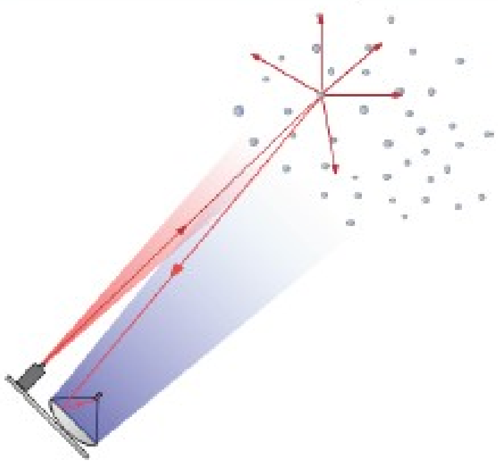
Transmission

$$T(x) = e^{-\tau(x)} = e^{-\int_0^x \alpha(x')dx'}$$

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

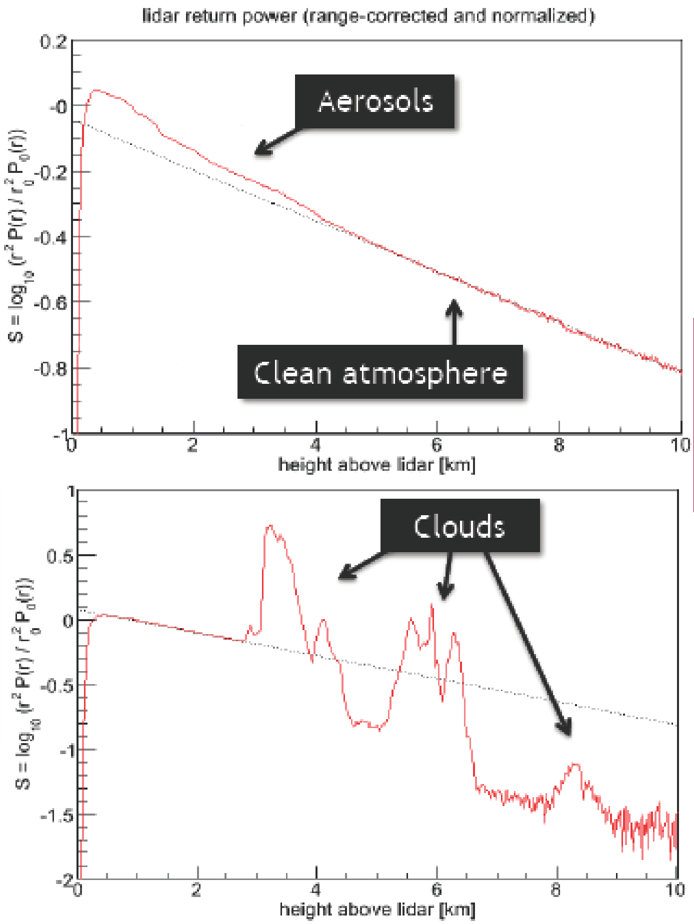
LIDAR data analysis: VAOD(h)

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)

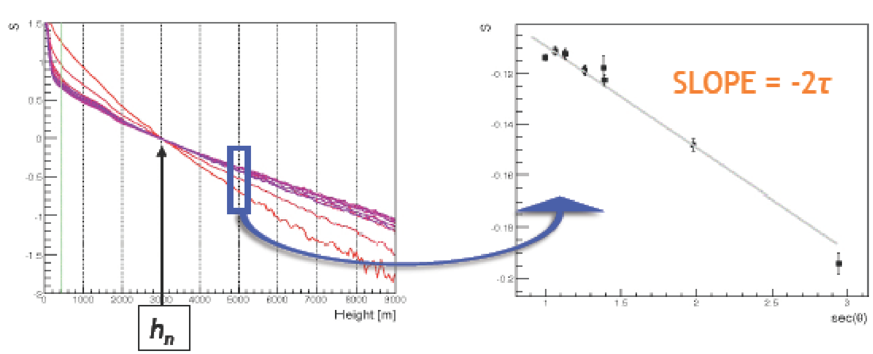
based on the assumption of a horizontally uniform atmosphere : **r = h/cosθ**

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

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



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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 = $\alpha^{\lambda 0}_{aer} / \beta^{\lambda 0}_{aer}$

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

The Raman Lidar

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

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

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 !