The Raman LIDAR for the pre-production phase of CTA.

Marco Iarlori – marco.iarlori@aquila.infn.it
CETEMPS/DSFC University of L’Aquila – Italy
with
Ermanno Pietropaolo, Vincenzo Rizi, Valerio Silvestri, Alberto Cirella, Carla Aramo, Laura Valore, Marco Marengo and Giovanni Dughera for CTA Collaboration.
How could a Raman lidar be useful for CTA?

- aerosol optical depth -> light transmission
- aerosol backscatter -> light scattering
- water vapour -> air refractive index
The Raman lidar (ARCADE) has undergone several performance tests (hardware/software quality insurance) in the laboratory of the CETEMPS/DSFC/UNIVAQ and INFN at L’Aquila.
The Transmitter section

Beam cleaning optics...

Beam exp x10 + extra cleaning

AtmoHEAD 2018 – Capri (Italy), 24-26 September 2018
LASER BENCH LAYOUT

ZEMAX© simulation
LASER beam footprint

Overall laser beam half angle divergence:
~ 0.32±0.05 mrad

• The Transmitter section

Centurion Laser @355 nm
100Hz repetition rate

AtmoHEAD 2018 – Capri (Italy), 24-26 September 2018
New DBS:
- Beam purity better than 99.9%
- LASER energy per pulse $5.8 \pm 0.2 \text{ mJ at } 354.7 \text{ nm}$

New BEx10:
- Better optical quality
• The Receiver section

ZEMAX© simulation
### The Receiver section

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
<th>Wavelength Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>IFN2</td>
<td>interference filter N2</td>
<td>386.7/0.5 nm</td>
</tr>
<tr>
<td>IFH2O</td>
<td>interference filter H2O</td>
<td>407.6/1.0 nm</td>
</tr>
<tr>
<td>IFAIR</td>
<td>interference filter air</td>
<td>354.7/0.5 nm</td>
</tr>
<tr>
<td>DBS1</td>
<td>dichroic beam splitter R</td>
<td>354.7 nm T 380-420 nm</td>
</tr>
<tr>
<td>DBS2</td>
<td>dichroic beam splitter R</td>
<td>386.7 nm T 400-420 nm</td>
</tr>
<tr>
<td>M</td>
<td>Elliptical Mirror 26.97mm Minor Axis</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>LA1805-A lens, f = 30 mm</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>Marcon Telescope, 25cm f/3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aluminum-Magnesium Fluoride Coating Al + MgF2</td>
<td></td>
</tr>
</tbody>
</table>
• The Receiver section
• The Receiver section

Verticality better than 0.3 mrad
• The Receiver section

steering mirrors
diaphragm
field lens
AtmoHEAD 2018 – Capri (Italy), 24-26 September 2018

- The Receiver section

steering mirrors
diaphragm
field lens
• The Receiver section
The Receiver section

Telescope infinity focus position

- Telescope
- Receiver

Mirror (M)

- to telescope
- to receiver

Distance:
- 280 mm
- 197.1 mm
- 32.9 mm
- 50.0 mm

Raw indetermination ± 0.2 mm
ZEMAX© simulation

• The Receiver section

full overlap at 500 m range
Receiver spectral efficiencies measurements

• The Receiver section
• The Receiver section
Both the DBS transmits almost all the H2O Raman signal.

The AIR and the N2 signal are efficiently removed by the DBS and after the IF407 no significant residual unwanted light are present.
IFAIR interference filter air 354.7/0.5 nm specifications

- The Receiver section

Transmission

Optical depth
Spectra efficiencies simulation of receiver

• The Receiver section
Total T(%) in the RM@355 channel = 9.135%

- The Receiver section

AtmoHEAD 2018 – Capri (Italy), 24-26 September 2018
Total T(%) in the RM@355 channel = 9.135%

• The Receiver section
Lidar Signal simulator

The Receiver section

AtmoHEAD 2018 – Capri (Italy), 24-26 September 2018
Signal Count Rate $<100$ MHz @ range>500m (i.e. when the estimated overlap efficiency reaches its max value) to avoid photon counting pile-up effect.

- The Receiver section

AtmoHEAD 2018 – Capri (Italy), 24-26 September 2018
Neutral density filters

- The Receiver section
ND attenuation:
AIR: $1.2 \times 10^{-4}$
N2: $1.4 \times 10^{-1}$

The Receiver section
photomultipliers  N2/386.7 nm

51 mm (2") photomultiplier
ET 9829QB -> QE% optimized for the UV

POSSIBLE SETUP OF PMTs’HV and threshold signal level

- air PMTs 1550 V
- N2 PMTs 1550 V
- H2O PMTs 1500 V

common threshold level -10 mV
TIMING MEASUREMENTS for «zero-bin» estimation.

MEASUREMENTS WITH FAST PHOTODIODE of the laser emission at laser exit

MEASUREMENTS WITH OSCILLOSCOPE of the local reflection/echoes

MEASUREMENTS WITH APC26-DAQs of the local reflection/echoes


To reduce the «zero bin» indetermination even the smallest sources of delays must be taken into account.
\[
\frac{d}{dr_d} \alpha_p (r, r_d) \approx -\frac{2}{1 + f_p} \frac{1}{(r - r_d)^2}
\]
SUMMARY PhC
Q switch sync out and laser pulse emission at DAQ

MEASUREMENTS WITH FAST PHOTODIODE
of laser emission

MEASUREMENTS WITH OSCILLOSCOPE
of local reflections/echoes

MEASUREMENTS WITH APC26-DAQs
of local reflections/echoes

110 ns 115 ns 120 ns 125 ns 130 ns 135 ns 140 ns

110-120 ns

115 ns ± 5 ns 120 ns ± 20 ns
The DAQ control (command-line version) enables to:
• open/close the dome;
• control the altazimuth movements;
• read the weather station data;
• power up/starts all the lidar hardware;
• start/stop the acquisition accordingly to the ORM policy;
• shutdown the system in emergency situation;
• process the data analysis.
\[ P_{\lambda_0}(z) = K_{\lambda_0} \frac{O(z)}{z^2} \left[ \beta_{\lambda_0}^{\text{aer}}(z) + \beta_{\lambda_0}^{\text{mol}}(z) \right] \]
\[ \times \exp \left\{ -2 \int_0^z \left[ \alpha_{\lambda_0}^{\text{aer}}(\zeta) + \alpha_{\lambda_0}^{\text{mol}}(\zeta) \right] d\zeta \right\} \]

**Elastic lidar EQ**

\[ P_{\lambda_R}(z) = K_{\lambda_R} \frac{O(z)}{z^2} N_R(z) \frac{d\sigma_{\lambda_R}(\pi)}{d\Omega} \]
\[ \times \exp \left\{ - \int_0^z \left[ \alpha_{\lambda_0}^{\text{mol}}(\zeta) + \alpha_{\lambda_0}^{\text{aer}}(\zeta) \\
+ \alpha_{\lambda_R}^{\text{mol}}(\zeta) + \alpha_{\lambda_R}^{\text{aer}}(\zeta) \right] d\zeta \right\} . \]

**Raman lidar EQ**
\[ \alpha_{\lambda_0}^{\text{aer}}(z) = \frac{d}{dz} \left[ \ln \frac{N_R(z)}{P_\lambda(z)z^2} \right] - \alpha_{\lambda_0}^{\text{mol}}(z) - \alpha_{\lambda_R}^{\text{mol}}(z) \]

Aerosol extinction
(from N\textsubscript{2} signal)

\[ \beta_{\lambda_0}^{\text{aer}}(z) = -\beta_{\lambda_0}^{\text{mol}}(z) + \left[ \beta_{\lambda_0}^{\text{aer}}(z_0) + \beta_{\lambda_0}^{\text{mol}}(z_0) \right] \]

\[ \times \frac{P_{\lambda_R}(z_0)P_{\lambda_0}(z)N_R(z)}{P_{\lambda_0}(z_0)P_{\lambda_R}(z)N_R(z_0)} \]

\[ \exp \left\{ - \int_{z_0}^{z} \left[ \alpha_{\lambda_R}^{\text{aer}}(\zeta) + \alpha_{\lambda_R}^{\text{mol}}(\zeta) \right] d\zeta \right\} \]

\[ \times \exp \left\{ - \int_{z_0}^{z} \left[ \alpha_{\lambda_0}^{\text{aer}}(\zeta) + \alpha_{\lambda_0}^{\text{mol}}(\zeta) \right] d\zeta \right\} \]

Aerosol backscatter
(from AIR & N\textsubscript{2} signal)
\[ \tau_{aer}(z) = - \log \left( \frac{K_{\lambda_{R}} z^2 P_{\lambda_{R}}(z)}{T_{mol,\lambda_{0}}(z) T_{mol,\lambda_{R}}(z) N_R(z)} \right) \]

\[ 1 + \left( \frac{\lambda_{o}}{\lambda_{R}} \right)^k \]

\[ T_{mol,\lambda}(z) = \exp \left( - \int_{z_0}^{z} \alpha_{mol,\lambda}(\zeta) \, d\zeta \right) \]

OR...

\[ \tau_{aer}(z) = \int_{z_0}^{z} \alpha_{aer,\lambda_{0}}(\zeta) \, d\zeta \]
Water Vapor mixing ratio (g/kg)
From H₂O & N₂ signal

\[ m_{H₂O} = \frac{\rho_{H₂O}(z)}{\rho_{air}(z)} \sim \frac{N_{H₂O}(z)}{N_{N₂}(z)} \]

\[ m_{H₂O} = C_{H₂O} \frac{P_{H₂O}(z)}{P_{N₂}(z)} \frac{\exp \left[ -\int_{0}^{z} \alpha_{\lambda N₂} (\xi) d(\xi) \right]}{\exp \left[ -\int_{0}^{z} \alpha_{\lambda H₂O} (\xi) d(\xi) \right]} \]
C_{H_2O} = 0.7808 \frac{M_H}{M_{\text{dryair}}} \frac{d\sigma_N(\pi)}{d\Omega} \frac{d\sigma_H(\pi)}{d\Omega} K_{N,H}

m_{H_2O} = m_{\text{RAOB}}^{\text{H}_2\text{O}} \quad \rightarrow \quad C_{H_2O} \quad \text{Can be determined with linear regression } Y = AX

RAwinsonde OBservation (RAOB)

Linear regression \( C_{H_2O} = 14\pm0.15 \)

Stability \( \pm0.3 \) (very first estimation)
Molecular density profile

Lat (+N/-S) 42.38
Lon (+E/-W) 13.31
station height (m) 656
range gate (m) 30

date chosen (click to change it)

GO!

GDAS DATA 1°x1° ➔ GDAS 0.5°x0.5°
NOW ➔ FUTURE (...or even 0.25°x0.25°)

AtmoHEAD 2018 – Capri (Italy), 24-26 September 2018
AIR SIGNAL 6-7 june 2018

• Aerosol & Water Vapor profiles

PhC (a.u.)
Rayleigh Fit

• Aerosol & Water Vapor profiles

![Graph of Rayleigh Fit showing aerosol and water vapor profiles with different signal strengths and ranges.](image)
AtmoHEAD 2018 – Capri (Italy), 24-26 September 2018

Aerosol & Water Vapor profiles

15 June 2018
Derivative algorithm has a low pass digital filter embedded: **vertical resolution reduction because the removal of high frequency (small detail -> higher resolution).**

Finite impulse response (FIR) filter have:

\[ y(n) = \sum_{k=-N}^{N} h(k)x(n-k) \]

The above Eq. is a representation of the *non-causal Linear Time Invariant (LTI) Finite Impulse Response (FIR) digital filter*, whose *frequency response* is:

\[ H(\omega) = \sum_{k=-N}^{N} h(k)e^{-j\omega k} \]

**NOISE REDUCTION RATIO:**

\[
\text{NRR} = \frac{\text{Var}_{\text{OUT}}}{\text{Var}_{\text{IN}}} = \sum_{k=-N}^{N} [h(k)]^2
\]

The ERes can be written by means of a general equation that depends only to the low-pass filter chosen:

\[
\Delta R_{\text{eff}}^{L(\hat{\rho})}\big|_{\text{NRR}} = \frac{\Delta R_{\text{raw}}}{\text{NRR}^{L(\hat{\rho})}}
\]
\[
NRR = \frac{\text{Var}_{\text{OUT}}}{\text{Var}_{\text{IN}}} = \sum_{k=-N}^{N} [h(k)]^2
\]

\[
NRR^{SG0(N)} = \sum_{k=-N}^{N} [h^{SG0(k)}]^2 = \frac{1}{2N+1};
\]

\[
\Delta R_{\text{eff}}^{SG0(N)}|_{\text{NRR}} = (2N + 1) \Delta R_{\text{raw}} = \frac{\Delta R_{\text{raw}}}{NRR^{SG0(N)}}.
\]

\[
\Delta R_{\text{eff}}^{L(\hat{p})}|_{\text{NRR}} = \frac{\Delta R_{\text{raw}}}{NRR^{L(\hat{p})}}.
\]
Smoothing Optimization

The smoothing of a signal could not always lead to significant improvement in the SNR (saturation effect when almost all the noise is removed). For this reason, in a smoothing operation it seems very relevant to find the limit over which the (undesirable) distortion of an underlying input signal could become more relevant than the concurrent (desirable) decrease of the noise level.
\[
\sigma_R^2 = \sum [Y - y]^2 = \sigma_d^2 + (\sigma_{IN}^2 - \sigma_{OUT}^2)
\]

\[
\frac{d^2 \sigma_R^2}{dL(\hat{p})^2} = 0
\]

More smoothing

Random Noise Removed

Signal Distortion

\( \sigma_{in}^2 - \sigma_{out}^2 \)

Y raw data

Y smoothed data

Y Random Noise Level
\[ H^{(1)}(\omega) = j\omega = \omega e^{j\pi/2}, \quad 0 \leq \omega \leq \pi; \]
\[ |H^{(1)}(\omega)| = \omega. \]

...the goal is to design a band-limited differentiator that, for frequencies higher than a certain cut-off value, will ideally remove the high-frequency component:

\[ H^{(1)L}(\omega) = H^{(1)}(\omega)H^L(\omega). \]

\[ H^{(1)L}(\omega) = -j \sum_{k=-N}^{N} h^{(1)L}(k) \sin(\omega k) \]

\[ H^L(\omega) = \frac{H^{(1)L}(\omega)}{j\omega} = \frac{-\sum_{k=-N}^{N} h^{(1)L}(k) \sin(\omega k)}{\omega} \]

• Aerosol & Water Vapor profiles
“Epic failures: 11 infamous software bugs” reports as the most likely reason of the Mariner 1 space mission failure was caused by a not smoothed time derivative of a radius:

“...Without the smoothing function, even minor variations of the speed would trigger the corrective boosters to kick in. The automobile driving equivalent would be to yank the steering wheel in the opposite direction of every obstacle in the driver's field of vision...”.

AtmoHEAD 2018 – Capri (Italy), 24-26 September 2018
15 June 2018

**Effective resolution from 300m to 1200m**

*AtmoHEAD 2018 – Capri (Italy), 24-26 September 2018*
AtmoHEAD 2018 – Capri (Italy), 24-26 September 2018

• Aerosol & Water Vapor profiles

15 June 2018

Same Effective resolution (750m)

-3dB level

Frequency response (H)

Similar behavior in pass-band

Gaussian filter has a better high frequency suppression
15 June 2018

- Aerosol & Water Vapor profiles

AtmoHEAD 2018 – Capri (Italy), 24-26 September 2018
AOD AERONET DATA

AtmoHEAD 2018 – Capri (Italy), 24-26 September 2018

15 June 2018

• Aerosol & Water Vapor profiles
AtmoHEAD 2018 – Capri (Italy), 24-26 September 2018

15 June 2018

- Aerosol & Water Vapor profiles

Statistical error

$<1.5 \times 10^{-5} \text{ m}^{-1}$

below 3km

range [m]

aerosol extinction [m$^{-1}$]
\[ \tau_{\text{aer}}(z) = -\log\left(\frac{K_{\lambda R}z^2P_{\lambda R}(z)}{T_{\text{mol,}\lambda_0}(z)T_{\text{mol,}\lambda R}(z)N_{R}(z)}\right) \]

\[ 1 + \left(\frac{\lambda_0}{\lambda_R}\right)^k \]

\text{Statistical error} < 0.015
\text{< 0.003 (smoothed) below 3km}

Smoothed profile: less random error
• Aerosol & Water Vapor profiles

RAOB WV profile, allows to estimate how down to ground the Raman Lidar AB and WV profiles can go. The AB profile, in red at raw resolution, in blue smoothed at the same AE resolution. The WV profile from the RLdata (red) compared with co-located RAOB (blue).
Aerosol & Water Vapor profiles

Statistical error

\(<1.5 \times 10^{-7} \text{ m}^{-1} \text{ sr}^{-1}\)

\(<0.5 \times 10^{-7} \text{ m}^{-1} \text{ sr}^{-1}\) (smoothed)

below 3km
• Aerosol & Water Vapor profiles

![Graphs showing aerosol backscatter, aerosol extinction, and lidar ratio profiles.](image)
• Aerosol & Water Vapor profiles

Statistical error < 0.4 g kg\(^{-1}\) below 3km
From L’Aquila…

To Turin…

… @ ORM
Conclusion

The ARCADE RL has been partially upgraded and extensively tested in L’Aquila:

- The overall optical performances have been significantly improved.
- A number of practical standard procedure have been developed to setup the system for automatic measurements once in ORM.
- An efficient DAQ control software and a certified lidar signals inversion code have been also developed in house.
- Further optimization of the system in both the hardware and software section are possible in order to reduce the uncertainties.
- We expect that the system will be operative from the second week of October 2018.
**EXPERIMENTAL SETUP**

trigger configuration of DAQs

- **Laser control unit**
  - Q-Sw sync. OUT
  - 1.5 m cable

- **fast photo-diode**
  - ~ 0.5 m distance

- **laser**

- **oscilloscope**

- **Signal IN**
  - 1.5 m cable

- **Trigger IN**

**MEASUREMENTS WITH FAST-PHOTODIODE**

- **linear regime**
  - $\Delta t = 120 \pm 2.5$ ns

The trigger-laser light out delay ($\Delta \tau_L$) is:

$$\Delta \tau_L = \Delta t [120.0 \pm 2.5 \text{ ns}] +$$

- [photodiode trans. time ([2-3 ns ± 2 ns] + [+ 1.5 m BNC (7.5 ± 1 ns) - 1.5 m BNC (7.5 ± 1 ns)]) - [laser path in air (2 ns)]] = 115 ns ± 5 ns
• Aerosol & Water Vapor profiles
Rayleigh Fit

• Aerosol & Water Vapor profiles