The IFAE/UAB Raman LIDAR for the CTA-North

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Abstract. The IFAE/UAB Raman LIDAR project aims to develop a Raman LIDAR suitable for the online atmospheric calibration of the CTA. Requirements for such a solution include the ability to characterize aerosol extinction to distances of more than 20 km with an accuracy better than 5%, within time scales of less than one minute. The Raman LIDAR consists therefore of a large 1.8 m mirror and a powerful pulsed Nd-YAG laser. A liquid light-guide collects the light at the focal plane and transports it to the readout system. An in-house built polychromator has been characterized thoroughly with respect to its capability to separate efficiently the different wavelengths (355 nm, 387 nm, 532 nm and 607 nm). It was found to operate according to specifications, particularly that light leakage from the elastic channels (532 nm and 355 nm) into the much dimmer Raman channels (387 nm and 607 nm) could be excluded to less than 2×10^{-7}. We present here the status of the integration and commissioning of this solution and plans for the near future. After a one-year test period at the Observatorio del Roque de los Muchachos, an in-depth evaluation of this and the solutions adopted by a similar project developed by the LUPM, Montpellier, will lead to a final Raman LIDAR proposed to be built for both CTA sites.

1 Introduction

The Cherenkov Telescope Array (CTA) [1] will observe cosmic γ-rays from few tens of GeV to several hundreds of TeV with greatly improved sensitivity, angular and energy resolution over current experiments [2]. Such improvements must come along with a significant reduction of systematic uncertainties in energy and flux reconstruction [3], dominated by atmospheric effects [4]. The local troposphere and lower stratosphere must hence be monitored, such that telescope data can be corrected offline before dissemination. The CTA has opted for a combination of two complementary instruments to achieve this goal: A wide-field telescope optimized for stellar photometry [5, 6] across a field-of-view as large as that of CTA and a powerful Raman LIDAR [7] capable of characterizing aerosol extinction from ground to about 20 km a.s.l. during the short time scales on which the CTA telescopes either change observation target or Wobble position [8].

The Institut de Física d'Altes Energies (IFAE) and the Universitat Autònoma de Barcelona (UAB) joined in the *IFAE/UAB Raman LIDAR project* and designed such LIDARs [9], as well as another group at LUPM, France, tailored to the requirements of CTA: precise characterization of the aerosol extinction over a large dynamic range

on short time scales using two wavelengths characteristic for the measured Cherenkov light, and their corresponding Stokes lines due to Raman scattering on atmospheric nitrogen. Detailed link-budget simulations [10] have predicted the basic functioning of the chosen solution, but construction of a working prototype has met several difficulties so far, related to the large optics required and the corresponding dimensions of the polychromator [11]. We present here the first commissioning results of the working prototype, demonstrating its basic performance.

2 The IFAE/UAB Raman LIDAR

The LIDAR consists of a Q-switched Nd:YAG laser, frequency doubled and tripled to 532 nm and 355 nm, respectively, and a 1.8 m diameter parabolic receiving mirror, adopted from the discontinued CLUE experiment [12]. At the telescope focus, an 8 mm wide liquid light guide (LLG) of type Lumatec Series 300[1] transports the light to a polychromator unit, mounted on the back part of the LIDAR telescope structure. The polychromator separates the four wavelengths and detects the light with four Hamamatsu R11920 photomultiplier tube (PMT) units, identical to the ones used in the CTA Large Size Telescopes (LSTs) cameras [13]. The PMT signals are registered by a com-

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mercial data acquisition system from LICEL[2]. The laser of type Brilliant from Quantel[3] is mounted on an *XY*-table with stepping motors at the side of the telescope structure (see Fig. 1). The beam exits along the optical axis of the main mirror in a coaxial configuration thanks to two 5″ dichroic guiding mirrors (tailored to our needs and produced by Optoprim Italia), which act also as absorbers of the spurious 1064 nm wavelength, which itself could not be blocked at the laser. Table 1 lists further specifications of the system.
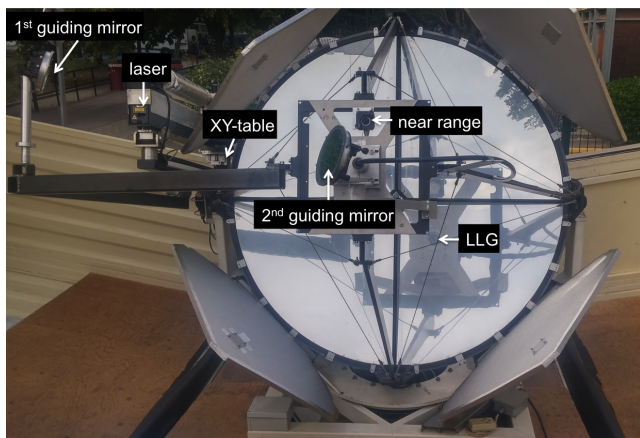

Figure 1. Photo of the IFAE/UAB Raman LIDAR with the laser, the XY-table and the two guiding mirrors. In the reflection of the primary mirror, the focal plane is visible with the liquid light guide (LLG) in its center. Slightly above the second guiding mirror, the near-range receiver is already installed.

Laser wavelengths	355 nm, 532 nm
Raman wavelengths	387 nm, 607 nm
Energy per pulse	100 mJ , 200 mJ
Pulse duration	4 ns
Beam divergence	$\approx$1 mrad
Mirror area	2.5 m^2
Focal length	1.8 m
Point spread diameter[†]	3.3 mrad (6 mm)
Receiver Field of view	4.4 mrad (8 mm)
Full overlap at	<150 m[*]
Number channels	4[*]
Filters width FWHM	10 nm
Sampling speed	20 MS/s
Spatial resolution	7.5 m

Table 1. IFAE/UAB Raman LIDAR specifications.
[†] 80% encircled energy
[*] does not yet include a dedicated near-range optics and readout.
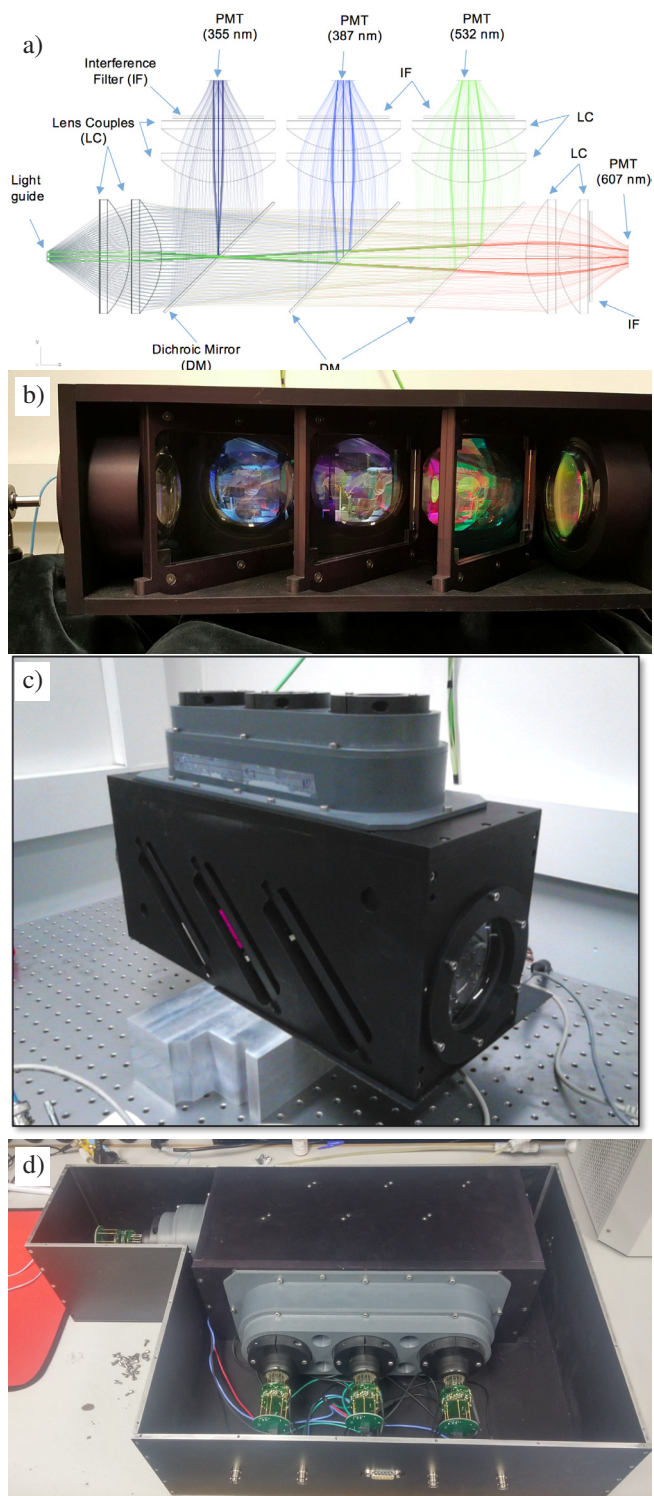

Figure 2. a) Optical design (*Zemax*®) of the polychromator, b) view from below into the polychromator with the dichroic mirrors visible, c) image of the closed polychromator without housing and PMTs, d) image of the polychromator inside its housing and PMTs mounted.

3 The Polychromator

The polychromator consists of a series of lenses, dichroic mirrors and interference filters, used to separate efficiently the four wavelengths of interest and guide the light of each wavelength to its corresponding 1.5" PMT. The polychromator optics were designed in collaboration with the CNR Institute for Photonics and Nanotechnologies in Padova,

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[2]www.licel.com
[3]https://www.quantel-laser.com

Italy [11] and its mechanics was designed and built at IFAE.

The receiver telescope has a low f-number, i.e. 1.0, and a large point spread function, about 6 mm in diameter. Hence the dimension and the high divergence of the beam exiting the light guide (8 mm in size and 70° field-of-view) have been the main challenges for the polychromator optical design. The chosen optical solution adopts lenses having 100 mm of diameter hosted inside a box of 760×550×170 mm (see Fig. 2). The polychromator itself is housed in an anodized aluminum box. Its total mass is about 30 kg. At the beginning of the optical path, the light exiting the liquid light guide is collimated by a Lens Couple (LC), then it is separated in its different components by Dichroic Mirrors (DM), specifically designed for this purpose by Optics Balzers Jena GmbH. After this, in each channel, a second LC focalizes the beam onto the PMTs' photo-cathode. Before reaching the PMTs, the light passes through an interference filter with transmission centered at the desired wavelength and a FWHM of about 10 nm.

The Polychromator has been extensively tested (Figure 3) for correct functioning in the optics lab of IFAE [14]. Among others, possible light leakage has been measured and found to be less than 2×10^{-7} for all possible combinations of elastically back-scattered wavelengths leaking into a Raman channel readout of the polychromator.
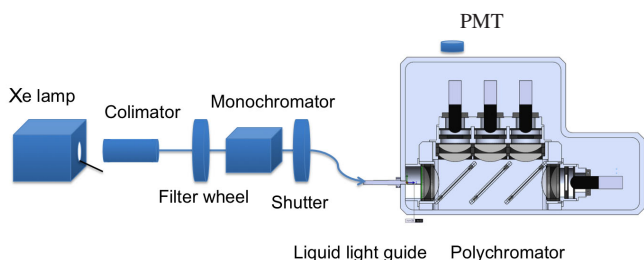

Figure 3. Sketch of the setup for polychromator tests: the collimated light of a stabilized Xe lamp passes first through a broad-band filter to discriminate unwanted harmonics of the grating monochromator. A shutter allows to remotely switch on and off the monochromatic light. Up to this stage, the setup is covered by a box (not shown here) to avoid light leakaging out of the system and entering the polychromator from outside. Finally, the light is fed into the very same liquid guide used for the LIDAR and coupled to the polychromator unit. Finally, the PMT current is analyzed by a picoampere-meter. Fast series of measurements with open shutter have been taken, immediately followed by background estimates using the closed shutter, until sufficient statistics have been accumulated.

4 First commissioning data

Commissioning data of the integrated system was obtained over several nights, first with greatly reduced laser power for the alignment of the laser beam with the optical axis of the primary mirror. In a later step, data were taken with full laser power after 2 a.m., when the close-by airports of Barcelona and Sabadell close. The LIDAR was aligned first by eye, using the possibility to move the two dichroic guiding mirrors by hand. In a second step, the stepping motors of the laser mount are used, together with one of the two elastic lines connected to an oscilloscope, in order to fine-tune the alignment. Normally, both steps need to be iterated at least once, because the beam may easily move out of the second guiding mirror during fine-tuning. We needed to learn how to align efficiently the LIDAR during several nights, but are now able to align the system in less than one hour, even after starting from a completely misaligned state.

During one night with a sky uniformly covered by layer of high clouds, we tested that the system could correctly image the cloud after moving to different positions, reaching almost horizontal pointing. The alignment remains hence stable under movements of the bulky mirror.
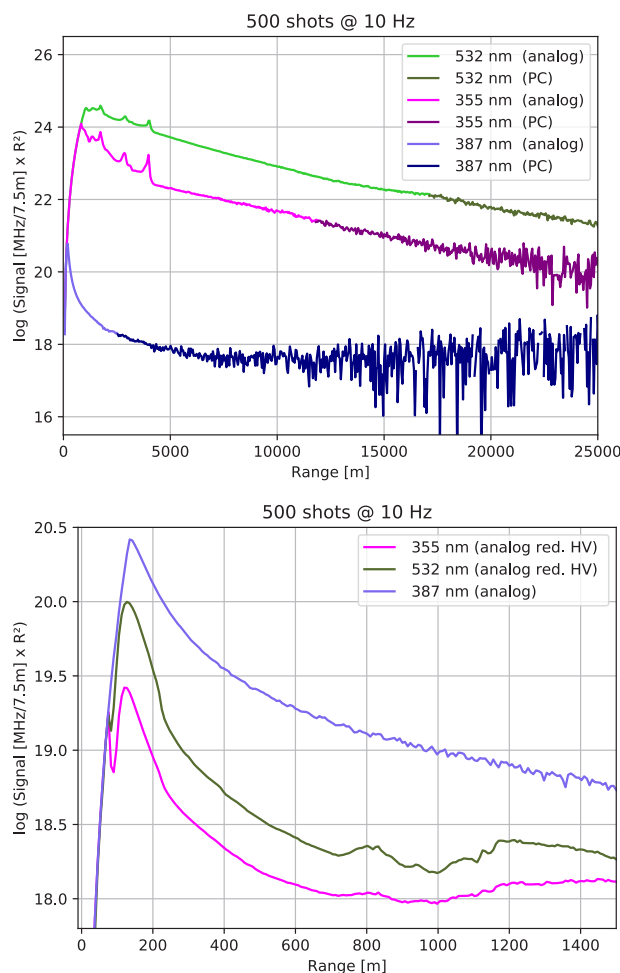

Figure 4. First commissioning signals of the Raman LIDAR at the UAB university campus. Top: The LIDAR has been operated with maximum PMT gain and laser power to demonstrate its long-range behaviour. A 45 m bin width is used here. Bottom: The LIDAR has been operated with reduced PMT gain for the two elastic lines to demonstrate its short-range behaviour. A 7.5 m bin width is shown here. The analog part of the signal was "glued" to the photon-counting (PC) part following the prescriptions of [15, 16].

Finally, Figure 4 shows the logarithm of the range-corrected signals for two configurations of the Raman LIDAR: in the upper part, the full power of the system was tested and the signals are shown up to 25 km distance, whereas the lower part shows a near-range configuration with the PMT gains of the two elastic lines reduced by a factor of several hundreds to avoid saturation. One can see that the system is easily capable of sensing the atmosphere to further than 25 km distance within less than a minute. On the near-range side, full overlap is already reached at 125 m, consistent with the theoretical expectation [17, 18]. Note also the Raman line of 387 nm saturates the readout below about 150 m distance.

Tests are still ongoing to understand the currently too-weak Raman line at 607 nm and to commission a dedicated near-range optics to further increase the dynamic range of the system and to access the altitude range from ground to about 200 m where most of the aerosols are normally expected [19]. That solution [14] combines a collimator of type RC12SMA-F01 from Thorlabs[4] with a standard 1.5 mm fibre[5]. For the moment, the near-range light will be registered by only one PMT, of the same type as those used for the polychromator, in a small "monochromator" box, with just one interference filter for the elastic 532 nm line.

5 Conclusions

The IFAE/UAB Raman LIDAR prototype is now almost complete and has shown to perform as expected for two elastic and one Raman line. Another Raman line at 607 nm is currently being commissioned as well as a small near-range solution. Further, easy-to-achieve improvements concern a general cleaning of the mirror, expected to significantly increase its reflectivity, and to increase the laser rate from currently 10 Hz to 20 Hz. Moreover, we concentrate on further robotization of the system and to achieve compliance with all safety and engineering requirements as well as the communication protocols used by the CTA. Once these steps are completed, the LIDAR will undergo a one-year test at the Observatorio del Roque de los Muchachos, participating in a cross-calibration campaign with an EARLINET-calibrated LIDAR for site characterization [20]. An in-depth evaluation of this and the solutions adopted by a similar project developed by the LUPM, Montpellier, will lead to a final Raman LIDAR proposed as in-kind contribution for the CTA at both sites.

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[4]www.thorlabs.com/thorproduct.cfm?partnumber=RC12SMA-F01
[5]www.thorlabs.com/thorproduct.cfm?partnumber=FT1500UMT

References

[1] B.S. Acharya et al., Astroparticle Physics **43**, 3 (2013)

[2] T. Hassan et al., Astroparticle Physics **93**, 76 (2017), `1705.01790`

[3] M. Gaug et al., in *Proc. SPIE Observatory Operations: Strategies, Processes, and Systems V* (2014), Vol. 9149, p. 914945

[4] M. Gaug, in *EPJ Web of Conferences* (2017), Vol. 144, p. 01003

[5] J. Ebr et al., *New developments in aerosol measurements using stellar photometry*, in *these proceedings* (2018)

[6] P. Janeček et al., *FRAM telescopes and their measurements of aerosol content at the Pierre Auger Observatory and at future sites of the Cherenkov Telescope Array*, in *these proceedings* (2018)

[7] U. Wandinger, in *Lidar Range-Resolved Optical Remote Sensing of the Atmosphere* (Springer, 2005), chap. 9, pp. 241–271

[8] M. Doro et al., in *Proc. First AtmoHEAD Conference, Saclay* (2014), arXiv:1402.0638

[9] A. López-Oramas et al., in *Proc. 33*[rd] *ICRC* (2013), p. 0210, arXiv:1307.5092

[10] M. Eizmendi, Master's thesis, Universitat Politécnica de Catalunya (UPC) & Universitat Autònoma de Barcelona (UAB) (2011)

[11] V. Da Deppo et al., in *Proc. SPIE Optical Systems Design* (2012), Vol. 8550, p. 85501V

[12] D. Alexandreas et al., NIM A **360**, 385 (1995)

[13] T. Toyama et al., NIM A **787**, 280 (2015)

[14] O. Calpe Blanch (2017), bachelor thesis, Universitat Autònoma de Barcelona

[15] R.K. Newsom et al., Appl. Opt. **48**, 3903 (2009)

[16] D. Lange et al., Revista Boliviana de Física **20**, 4 (2012)

[17] G. Biavati, G. Di Donfrancesco, F. Cairo, D.G. Feist, Applied Optics **50**, 5872 (2011)

[18] A. López-Oramas, Ph.D. thesis, Universitat Autònoma de Barcelona (2014)

[19] M. Gaug et al., in *EPJ Web of Conferences* (2017), Vol. 144, p. 01010

[20] M. Iarlori et al., *The Raman LIDAR for the pre-production phase of CTA*, in *these proceedings* (2018)