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The Barcelona Raman LIDAR project and its prospects for the CTAO-North

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Abstract. The Cherenkov Telescope Array Observatory (CTAO) is a next-generation facility comprised of ground-based Imaging Atmospheric Cherenkov Telescopes (IACTs). The observatory, currently under construction, will include more than 70 telescopes at two locations: in the northern hemisphere, CTAO-North at the Observatorio del Roque de Los Muchachos (ORM), La Palma, Canary Islands, Spain, and in the southern hemisphere, CTAO-South at a site belonging to the European Southern Observatory (ESO), Cerro Paranal, Chile. IACTs indirectly detect high-energy cosmic photons in an energy range from tens of GeV to several hundreds of TeV by measuring Cherenkov light emitted by atmospheric showers of secondary particles, produced through interactions between incident photons and nuclei of atmospheric gasses in the upper layers. The size of the CTAO will improve the detection sensitivity in the designed energy range by about an order of magnitude with respect to present experiments and aim at improved energy and angular resolution, as well as greatly reduced systematic uncertainties. The key to achieving improvements in accuracy on the absolute energy and flux scales is the precise monitoring of the atmospheric properties for the Cherenkov light, which can be obtained with a specifically designed LIDAR. The Barcelona Raman LIDAR (BRL) prototype is the official CTAO-North Pathfinder and was deployed at ORM for extensive tests between February 2021 and May 2022. We report the BRL's prospects for the CTAO-North, emphasizing the technical implementation and the preliminary data taken during its deployment period.

1 Introduction

The Cherenkov Telescope Array Observatory (CTAO) is the next-generation observatory for the detection of high-energy photons from space. Currently under construction, the observatory will consist of ground-based Imaging Atmospheric Cherenkov Telescopes (IACTs) [1] and will be able to observe the entire visible sky. It will be built in two locations: in the northern hemisphere, CTAO-North at the Observatorio del Roque de Los Muchachos (ORM), La Palma, Canary Islands, Spain, at 2200 m a.s.l., and in the southern hemisphere, CTAO-South at a site belonging to the European Southern Observatory (ESO), Cerro Paranal, Chile, at 2100 m a.s.l. The final configuration of CTAO will consist of more telescopes than any other existing IACT array, with CTAO-North having 13 telescopes spread over 0.6 km^2 and CTAO-South having 58 telescopes covering an area of approximately 4 km^2.

IACTs detect individual cosmic photons indirectly in the Very High Energy (VHE) regime, ranging from tens of GeV to several hundreds of TeV. At these energies, photons interact with the nuclei of atmospheric constituents, generating extended atmospheric showers (EAS) of secondary charged particles. These are ultra-relativistic during most of the shower development and therefore emit Cherenkov radiation [2] which is observed on the ground as a few nanoseconds long burst of UV light with peak intensity at 350 nm. Most of the observed light originates from altitudes of 5–17 km a.s.l. (for vertical incidence) and from 8–18 km a.s.l. (for high zenith angles (Zd $\lesssim 75\,^\circ$) of observation) [2, 3], hence the illuminated area on the ground is of the order of $10^5 - 10^6$ m^2. The use of a number of telescopes located in this area, as will be the case at CTAO, will make it possible to achieve unprecedented sensitivities for cosmic VHE photon detection, larger by a factor of $5 - 10$ with respect to present experiments.

The use of the atmosphere as a calorimeter imposes a series of limitations on the accuracy of the shower energy reconstruction and the calibration of instrument exposure. The development of an EAS depends on the refractive index of air [4, 5], whereas the propagation of Cherenkov light to the ground is strongly influenced by atmospheric extinction. This is due to molecular and aerosol scattering of light in troposphere and lower stratosphere [3, 6, 7]. A large part of the systematic uncertainty in the reconstruction of the energy and flux of IACTs results from an inaccurate determination of the atmospheric transmittance of Cherenkov light [8, 9]. To correctly calibrate IACT measurements, constant monitoring of aerosol extinction in the observing direction is required. The best suited tool for this aim is a LIDAR operating in the same wavelength range as the IACTs. In contrast to using an elastic scattering LIDAR, which, due to various assumptions, retrieves an optical depth with an accuracy of about 20 % ($\leq$ 5 % for a carefully absolutely calibrated LIDAR [7]) we employed a Raman LIDAR. This system allows simultaneous and independent measurements of the extinction and backscattering coefficient profiles, reducing the uncertainty to well below 5 % [10].

CTAO requirements for the LIDAR are adapted to the needs of the observatory: the atmosphere above the CTAO must be characterized in the entire observing volume (vertical range of 20 km and 30 km range at 65° zenith angle [11]) with range resolution of at least 150 m for the retrieved transmission profile. Since IACTs detect Cherenkov photons within an energy (wavelength) range between 300 nm and 700 nm, the atmosphere should be characterized at at least two wavelengths in this range. Cherenkov light transmission due to the presence of aerosols should be measured with an absolute accuracy of 0.03. Aerosol/cloud transmission profiles with signal-to-noise ratio (SNR) of 10 need be measured in less than a minute. The LIDAR will need to characterize the atmosphere only under good or moderately good conditions (when integral aerosol/cloud transmission is greater than 0.5). In poorer conditions, CTAO will not be operational because sensitivity losses will become unacceptable.

2 CTAO-North Raman LIDAR Pathfinder

The Barcelona Raman LIDAR (BRL) [12, 13] was designed, maintained and operated in collaboration between Institut de Física d'Altes Energies (IFAE) and Universitat Autonòma de Barcelona (UAB), Spain, University of Nova Gorica (UNG), Slovenia, Università degli Studi di Padova (UniPd), Italy and CTAO gGmbH, Germany.

First tests of the system were performed in 2017 at UAB campus. In 2019 it was awarded the status of a CTAO Pathfinder, implying its potential for future permanent inclusion in the CTAO-North observatory. In 2020 BRL was deployed at the site of the first Large Sized Telescope (LST-1) at the ORM, where it underwent testing under the same operating conditions it will experience upon delivery to CTAO. In 2022 the BRL was returned to Barcelona where it is currently being upgraded into its final configuration. It is expected to be completed in 2025.

The BRL components are mounted on a steerable alt-azimuth mount. The transmitter is a 532 nm and 355 nm frequency-doubled and tripled Nd:YAG pulsed laser (Quantel Brilliant, green 160 mJ max, UV 70 mJ max, 10 Hz). The receiver is a 1.8 m parabolic mirror with $f/D = 1$, which was previously used in the CLUE experiment [14]. Re-aluminization of the mirror, which was protected by quartz coating was

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done in 2019 [11]. To avoid direct exposure to sunlight, four steerable petals were added to open and close the mirror. The backscattered light is fed into a liquid core light fibre mounted in the focal point of the mirror and led to the spectroscopic filter, which separates it into four operational channels: two elastic at 355 nm and 532 nm, and two Raman at 387 nm and 607 nm. Successively, the 607 nm channel was put on hold until the final configuration is completed. Light in all channels is converted to electric signals using photomultiplier tubes (PMT). These were amplified and digitized using Licel transient recorders. The LIDAR data were stored in Licel format for further processing. The entire LIDAR structure fits into a 20 ft standard Maritime container, which has been modified to open into two halves that lay flat on the ground, ensuring that they do not obstruct the field of view of the LIDAR within its steerable range (Figure 1).

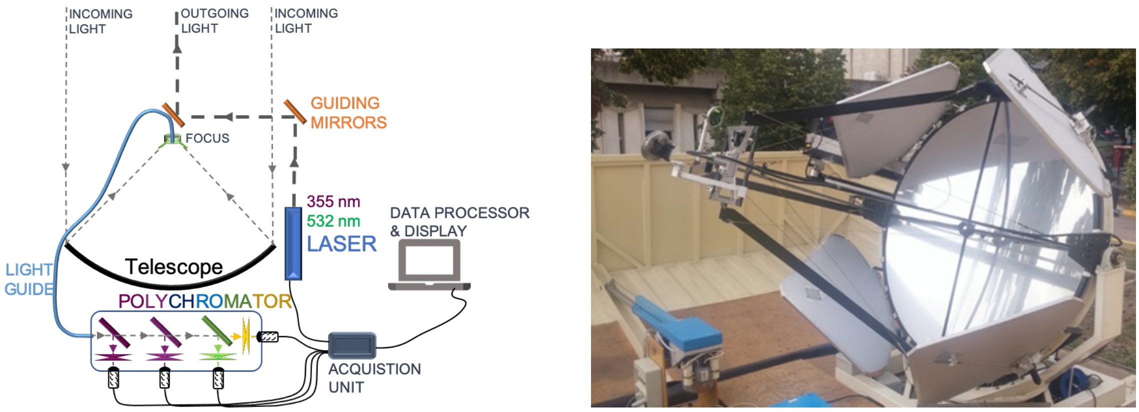

Figure 1: Left: Schematic drawing of the BRL with marked components. Right: BRL under construction at UAB, 2017.

3 Performance

BRL performance was assessed on datasets both from its initial tests at UAB in Barcelona and from ORM during the 2021-2022 commissioning campaign. Data from UAB focus on the determination of the maximum achievable range of the device while the ORM data demonstrate its performance under realistic conditions at the future CTAO site, such as clear sky conditions, presence of mineral dust from the Saharan desert (Calima), presence of clouds, and presence of volcanic ash (the Tajogaite eruption on La Palma in 2021).

3.1 UAB Data

In order to test whether the BRL design was able to meet the CTAO requirements, we performed a computational analysis to assess the sensitivity and performance capabilities of our system. We developed a `python` code to calculate the expected return power and signal-to-noise ratio (SNR) for single shots at various altitudes, considering different weather conditions and laser wavelengths. The code computes the time required for the BRL to achieve an SNR of 10 under various atmospheric scenarios for the different laser wavelengths. The results indicate that even under the most challenging weather conditions (Saharan dust intrusions – Worst Case Calima), the time required to attain an SNR of 10 for the 387 nm line was sufficient to meet the CTAO requirements, see Figure 2.

The test data on the UAB campus were taken during night time from 2017 to 2019. Figure 3 shows the logarithm of range-corrected signals in the two elastic channels and one Raman channel, using the fully-powered laser. The analog and photon counting signals have been connected using an adapted method of [15]. The data were summed over 500 shots, taken at 10 Hz, which is less than a minute of data taking.

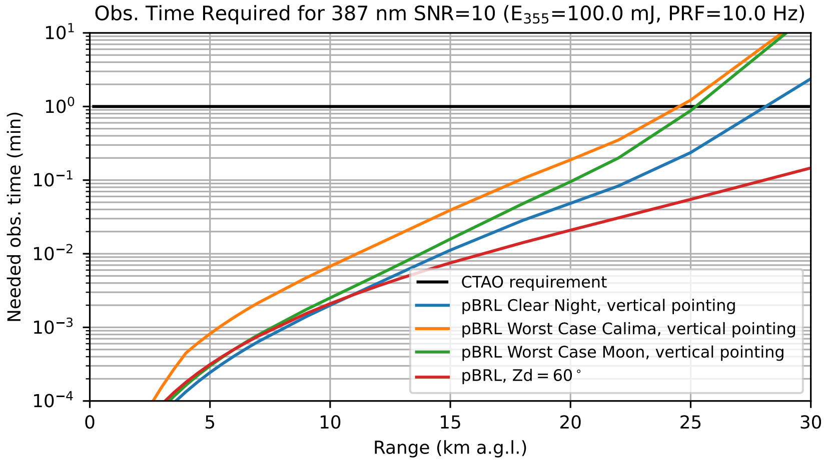

Figure 2: Time, required to reach an SNR of 10 within the 387 nm line with different conditions.

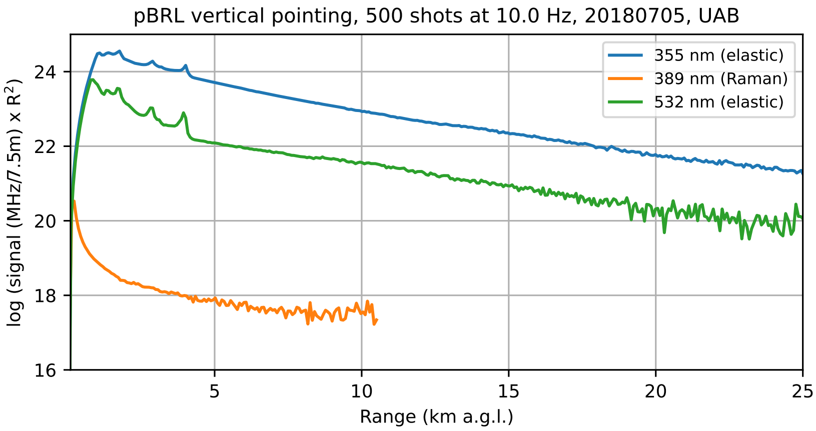

Figure 3: Backscattering signals in the two elastic channels at 355 nm (blue) and 532 nm (green) and one Raman channel at 532 nm (orange).

The detectable range (signal-to-noise ratio greater than 1) in the elastic channels was 25 km, while the detectable range for the Raman signal at 387 nm reached approximately 10 km. This range will be improved further, when the upgraded laser (Litron, 50 mJ, 200 Hz) will be operative and full voltage applied to new gated PMTs, with the re-aluminized main mirror.

3.2 ORM Data

The BRL was deployed at ORM from February 2021 to May 2022. During this period, the BRL operated for a total of 33 nights and accumulated approximately 20 hours of data. The BRL was installed next to the LST-1 telescope, near its intended final location at CTAO-North. It recorded first light on March 25, 2021. Because its operation was not included in ORM's Laser Traffic Coordinates System (LTCS) [16, 17], it was limited to periods of astronomical twilight during full moon nights, when the rest of the observatory was not operational. This constraint, along with the need to reduce high-voltages of the PMTs of the elastic channels after the primary mirror had been re-coated and PMT gating was not yet available, resulted in reduced LIDAR performance as the system was designed to operate during dark nights. In addition, the BRL faced various technical challenges that impaired its operation, including problems with the LST-1 site safety interlocks, laser heating problems due to low environmental temperatures falling even below 0 °C, and minor issues with the data acquisition software (DAQ). Additionally, adverse weather conditions such as rain, fog, and sleet often prevented the BRL from operating. The eruption of the Cumbre Vieja volcano, now known as Tajogaite, in September 2021 and subsequent deposition of volcanic ash led to the suspension of observatory activities, including the BRL testing. Operation resumed only in January and lasted until May 2022, before the BRL was finally brought back to Barcelona. Despite these limitations and challenges, the BRL provided valuable measurements during interesting atmospheric phenomena [10], such as Calima, which occurred in the fourth and fifth week of August 2021.

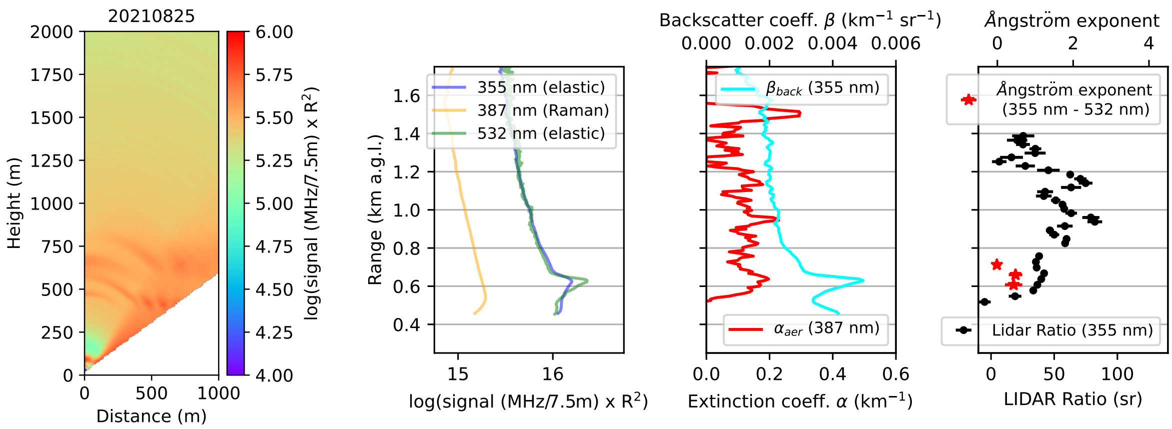

Figure 4: Left: Spatial distribution of clouds and aerosol loading above the ORM on 25 August 2021. Right: Atmospheric properties on 25 August 2021 (vertical pointing) - range square corrected lidar returns (corrected for signal decrease in distance) in the three channels, backscattering coefficient retrieved from 355 nm channel and extinction coefficient of aerosols retrieved from Raman 389 nm channel and Ångström exponent profile (355 nm - 532 nm).

BRL data allowed us to explore atmospheric properties and characterize aerosol types present above the observatory. A more detailed analysis was performed on the data collected in the evenings of 25 and 26 August 2021. On both days, the average lidar ratios were found to be around 40-50 sr and Ångström exponent was below 1.5, which implies scattering on large, irregularly shaped particles, such as mineral dust. A drop in the extinction coefficient at about 1.5 km, which occurred on both days, is probably associated with the top of the dust layer. Especially interesting is the case on 25 August 2021, where a scan revealed dust that was not uniformly distributed throughout the lower troposphere (see irregular density profile patterns in Figure 4, left). Instead, there are visible elevated layers of scatterers about 400 m and 700 m above the ground (Figure 4, left).

4 Conclusion

The measurements performed at UAB and ORM taught us how to make the BRL meet the strict CTAO requirements for atmospheric characterization. Currently, strong signal saturation impedes us to fulfil the range resolution requirement of 150 m at near ranges. For this reason, ongoing upgrades of the laser and PMTs will facilitate permanent inclusion of the BRL into the CTAO-North observatory.

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