Preliminary optical design of a polychromator for a Raman LIDAR for atmospheric calibration of the Cherenkov Telescope Array

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ABSTRACT

The preliminary design of a polychromator for a Raman LIDAR (Light Detection and Ranging) for atmospheric calibration in the framework of the Cherenkov Telescope Array (CTA) project is presented.

For obtaining high quality data from CTA, a precise monitoring of the atmosphere is needed. Remote-sensing instruments, like elastic/Raman LIDARs, have already been proven as a powerful tool in environmental studies, and a LIDAR installed and operated at the CTA site can be used for correcting systematic biases on the energy and flux scales through the determination of the atmospheric transmission. This LIDAR consists of a powerful laser that emits light pulses into the atmosphere, a mirror of 1.8 m diameter which collects the backscattered light and a polychromator unit where the collected light is analyzed. The laser is a pulsed Nd:YAG with the first two harmonics available at 355 and 532 nm and the polychromator has 4 read-out channels: two to analyze the elastic backscatter at 355 and 532 nm and two for the Raman back-scattered light on Nitrogen, at 387 and 607 nm, respectively.

The polychromator module has to be able to collect the majority of the light coming from the telescope, separate the different wavelengths and focus the beam onto photomultiplier detectors. The collection and focalization of the light are done by means of simple lens-couples and the separation with custom dichroic mirrors and narrow-band filters. The performance of the conceived optical design, the adopted design choice for the glass, surface figure and size of the lenses, and the expected throughput for the different channels will be described in detail.

Keywords: optical design, LIDAR, simulation, modelling, atmospheric correction

1. INTRODUCTION

CTA will be an advanced facility for ground-based gamma-ray astronomy in the GeV-TeV regime. The project is presently in the Preparatory Phase and foresees an array of next-generation Cherenkov telescopes [1][2]. Gamma-rays provide a powerful insight into the non-thermal universe and perhaps a unique probe for new physics beyond the standard model. Current experiments are already giving results in the physics of acceleration of cosmic rays in supernova remnants, pulsar and active galactic nuclei with a hundred sources detected at very-high-energies so far. The CTA project is being designed both to provide an expansion of the energy range down to a few tens of GeV and up to about 100 TeV and with at least 10 times improvement in sensitivity compared to current installations. This goal will be achieved using several tens of telescopes of 2· 3 different sizes distributed over a large area (several square km) and having a Field Of View (FOV) of up to 10 deg (see Figure 1).

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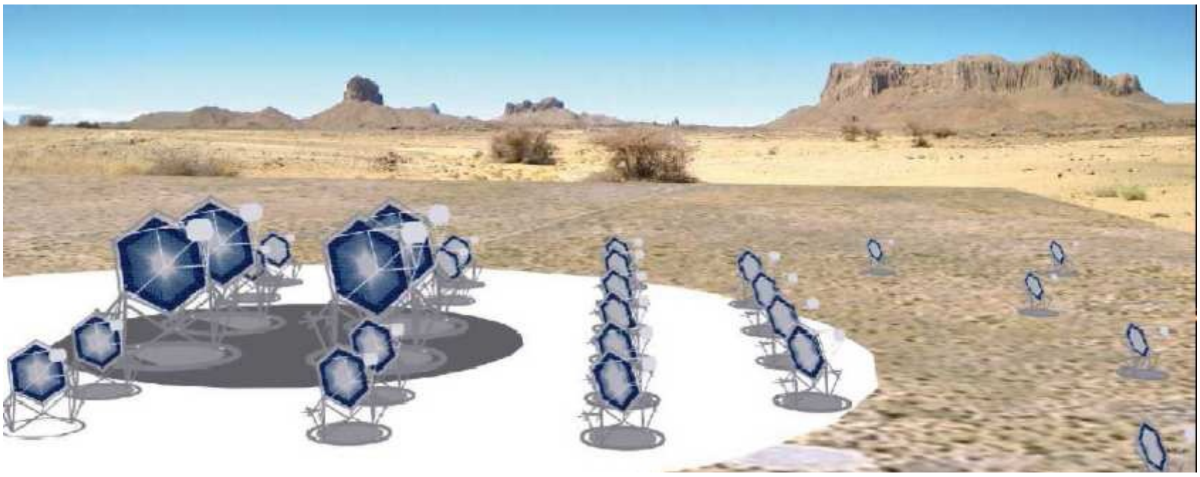


Figure 1. Artistic view of the compound different size telescope CTA system.

CTA is will operate with a Southern and a Northern hemisphere site. This fact together with the large FOV of the telescopes in both installations will likely allow CTA to provide the first extended gamma-ray maps of the sky in the TeV region. The improved energy and angular resolution will enable more precise spectral and morphological observation. Ground-based Imaging Atmospheric Cherenkov Telescopes (IACT) are able to observe cosmic gamma-rays in the GeV-TeV regime by collecting the Cherenkov light produced by electrons and positrons when interacting in the top Earth atmosphere.

When a primary gamma-ray reaches the atmosphere an electron-positron pair is produced. The charged particles re-emit secondary gamma-rays via Bremmstrahlung. The secondary gamma-rays produce electron-positron pairs, and so on. Therefore, a shower of hundreds of particles is developed along several tens or hundreds of meters. The energy of the electrons in each step of the shower is roughly half of that of the previous step until it reaches the ionization yield and the shower dies [2]. In the first stages of the showers, the electrons travel at a speed greater than the speed of light in the atmosphere and, therefore, produce Cherenkov light. This light is a ultraviolet (UV)-optical flash lasting few nanoseconds and itÊs in the shape of a cone aligned with the primary gamma-ray direction. After having crossed the atmosphere, the Cerenkov light illuminates the ground in a circle of roughly more than 100 m radius. Whenever an IACT is placed inside the Cherenkov light pool and given that enough Cherenkov photons hit the mirror, the shower is recorded and through an image reconstruction, the energy, direction, and arrival time of the primary gamma-ray are obtained [5].

The current generation of IACTs, and specially HESS, MAGIC and VERITAS [4], has most of the systematic errors in the energy reconstruction and absolute scale of the gamma-ray measured fluxes due to systematic errors in the determination of atmospheric parameters. Of particular concern is the poorly known total extinction that Cherenkov photons undergo in their travel from the emission region, typically located between 20 and 10 km a.s.l., to the ground. For obtaining high quality data from CTA, the atmosphere should be monitored continuously and precisely. A remote-sensing instrument, such as a LIDAR, installed and operated at the CTA site can be used for correction of the systematic biases in reconstructed energy and flux.

2. ATMOSPHERIC LIDAR FOR CTA

LIDAR (Light Detection And Ranging) is an optical remote sensing technique analogous to the RADAR principle. Mainly, it is based on a laser which emits light pulses to the atmosphere, a telescope which collect the backscattered light, a polychromator unit where the light is distributed to the sensors and a recorder unit. Since light travels at a known speed, the atmosphere can be characterized from the time delay of the received back-scattered light pulses. When the laser beam interacts with the atmospheric components, the light is scattered basically in all directions and a small part can be collected by the LIDAR telescope on-ground.

The interaction of the laser with the atmospheric components can be elastic or inelastic. For the elastic scattering, such as the Mie scattering for the aerosol or the Reyleigh scattering for the molecules, the scattered light has the same frequency (wavelength) of the incident radiation. For the inelastic scattering, e. g. the Raman scattering, the frequency of the scattered radiation is different from the incident one because molecular roto-vibrational energy levels are excited. The emitted light frequency depends on the chemical composition, i.e. each type of molecule has its own wavelength shift. Elastic scattering produces most of the back-scattered radiation. While the molecular component of the atmosphere is quite stable with time and varies slowly from adjacent places, the aerosol can have important variation in a time-scale of hours.

Lidars are often called following the back scattered radiation they are able to measure, the elastic LIDAR is the simplest technique and provides information about the atmosphere constituents, aerosols, and clouds; the inelastic Raman LIDAR, usually employed together with an elastic LIDAR, is able to determine that molecular concentration in function of the altitude. LIDARs have already been proved as powerful tools in environmental studies and the characterization of atmosphere can be successfully done at night using an elastic/Raman lidar system [6][7][8]; thus this technique is viable for the needs of CTA. With this aim, several institutes members of CTA, in the context of the Atmospheric Calibration (ATAC) working group of CTA, are currently designing a non-scanning pulsed elastic/Raman lidar system to be used for systematic data error correction due to poorly known molecular and particle extinction coefficients. The lidar(s) should be installed and operated at the CTA site, currently under definition, with the goal of reducing the systematic uncertainties of the imaging atmospheric Cherenkov technique of the telescope and increasing the duty cycle thanks to a better knowledge of the atmosphere. Three groups working independently and in collaboration are formed: in Barcelona, the Institut de Fisica dÊAltes Energies (IFAE) and the Universitat Autonoma de Barcelona (UAB) are collaborating for a design of a lidar. Two other groups are also developing Raman lidars for CTA: the LUPM (Laboratoire Univers et Particules de Montpellier) in Montpellier (France) and the CEILAP (Centro de Investigaciones Lser y sus Aplicaciones) group in Villa Martelli (Argentina).

In the rest of this paper, we will discuss the design of the polychromator unit for the Barcelona Raman LIDAR.

3. POLYCHROMATOR OPTICAL DESIGN AND PERFORMANCE

3.1 The Barcelona Raman LIDAR

The Barcelona Raman LIDAR schematics is shown in Figure 2. The laser is a pulsed Nd:YAG with the first two harmonics available at 532 and 355 nm. The laser backscattered light from the atmosphere is collected by a parabolic mirror of 1.8 m diameter and then fed - through a liquid light-guide - to the polychromator module. The polychromator currently foresees 4 read-out channels: two to analyze the elastic-backscatter at 355 and 532 nm and two for the Raman back-scattered light of Nitrogen, at 387 and 607 nm, respectively. The characteristics of the LIDAR instrument are reported in Table 1.

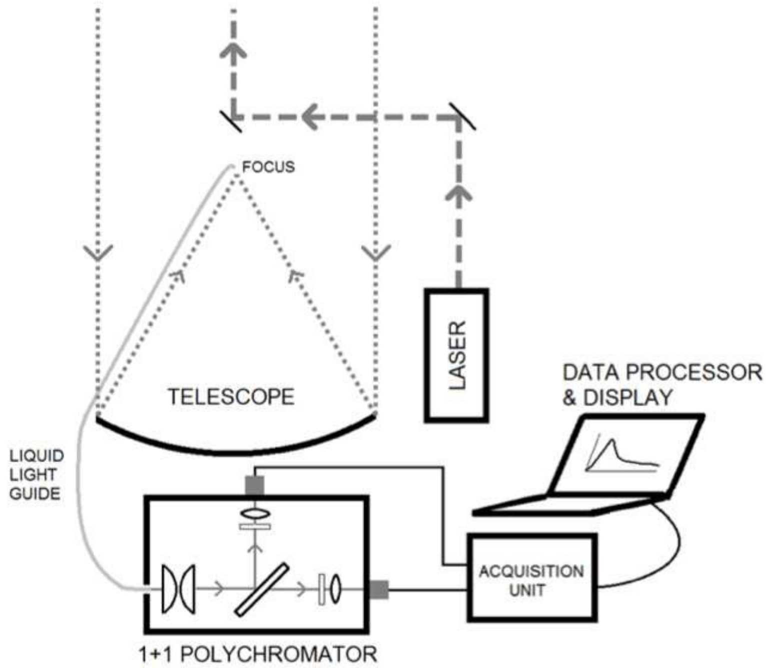


Figure 2. Schematics of the IFAE-UAB LIDAR system.

Table 1. Lidar characteristics.

EMITTER		
Laser	Type	Nd-YAG
	Emitted wavelength	355 nm(/532 nm)
	Pulse Energy/Repetion/Duration	60 mJ/n20 Hz /5 ns
	Beam waist (diameter)	6 mm
RECEIVER		
Telescope	Layout	1-mirror Parabolic
	Mirror diameter	1.8 m
	Focal length	1.8 m
	F number	1
	Shadow diameter	0.08 m
Liquid guide	Coupling efficiency to telescope	0.9
	Active area diameter	8 mm
	Numerical aperture	0.59 (34° half angle)
	Transmissivity	>0.7 (in the UV)
Photodetectors	Type/Active area diameter	PMT/22 mm

3.2 Optical requirements

The polychromator module has to guarantee that most of the light fed through the liquid guide is collected, separated in the different wavelengths and focalized onto photon detectors. The efficiency of the system has to be high enough to guarantee the correct detection of the signal coming from the different layers in the atmosphere.

The scientific and optical characteristics of the polychromator are summarized in Table 2.

Table 2. a) Polychromator requirements; b) polychromator optical characteristics.

a)

Input FoV	70°
Input source diameter	8 mm
Encircled Energy	> 80% inside the detector
Wavelength coverage	355/387/532/607 nm
Filters	4 filters: one per each sub-channel

b)

Optical concept	Simple identical plano-convex lens couples		
Lens Couple Focal length	60 mm		
Lens diameter	100 mm		
Lens Focal ratio	*F*/1.5		
Detector	PMT		
	QE	@355&387	15%
	QE	@532	10%
	QE	@607	5%
Dichroic mirror band pass	15 nm (TBC)		
Filter band pass	10 nm (TBC)		

Since the wavelength range is extended in the UV region, the glasses to be used for the design have to be transparent at that radiation. The fused silica glass, or the BK7, can be a good choice, while the flint glasses normally used for designing achromatic doublet cannot be adopted due to their poor transmission. The polychromator design is conceived so that the light emitted by the fiber is collected and collimated, then the different wavelengths are successively separated using dichroic mirrors and at the end the beam is focalized on the detector passing through a narrow band filter for the final wavelength selection. The present design foreseen 4 readout channels: two for the elastic backscattered at the 355 and 532 nm laser lines, and two Raman at the 387 and 607 Nitrogen lines.

3.3 Possible optical design

Different layouts have been taken into account. The drivers for the design have been to limit the number of optical elements, their dimensions, and figuring complexity, while maximizing the collective effectiveness and global efficiency. The design choice has also been determined by the need of hold down the system costs. The preliminary optical simulations have been done with Zemax ray-tracing code.

The layout selected for the optical design of the polychromator is depicted in Figure 3. The incoming light is at first collimated then after the wavelength selection it is focalized on the PMT detector. The light received by the telescope and re-emitted by the optical fiber with a 70° aperture angle is collected by a two identical lens couple (LC). To collimate such a diverging beam a two lens system in necessary to be able to control the aberrations, a three lens system can be designed but with a decreasing of the total efficiency of the whole system. For the sake of simplifying the procurement, all the lenses in the system are identical plano-convex lenses with a focal length of about 150 mm and 100 mm diameter. The lenses are in BK7 glass. They could be made in fused silica glass to have a higher total system transmission, but this latter glass is more expensive and thus it was discarded during the selection process. After the collimation, the light is separated in its different component lines via dichroic mirrors. Each of the dichroic mirror (DM) reflects one of the wavelength and transmits the others. With 3 DM, the 4 channel is completely separated. After the separation in wavelength, in each channel a LC, identical to the first LC, focalizes the beam towards the detector, the beam is passing through an interference filter (IF) for a further selection of the wavelength. Care has to be taken in the definition of the band for the DM and IF, since the light is impinging on them with angles as high as 30° and the transmission band is shifting with incident angle. The IF out of band transmission has to be defined in order to cut unwanted spurious light coming from reflection and diffusion inside the instrument, particularly taken into account that the Raman light is two to three order of magnitude less than the elastic lines.

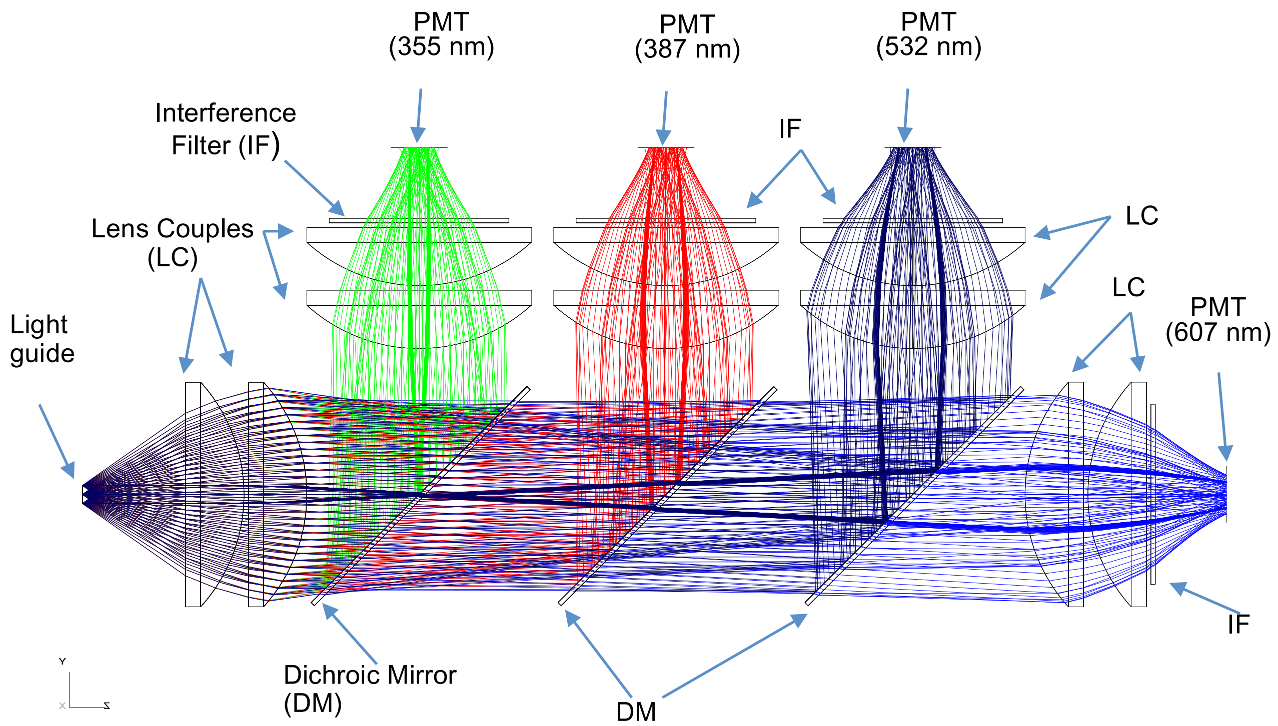
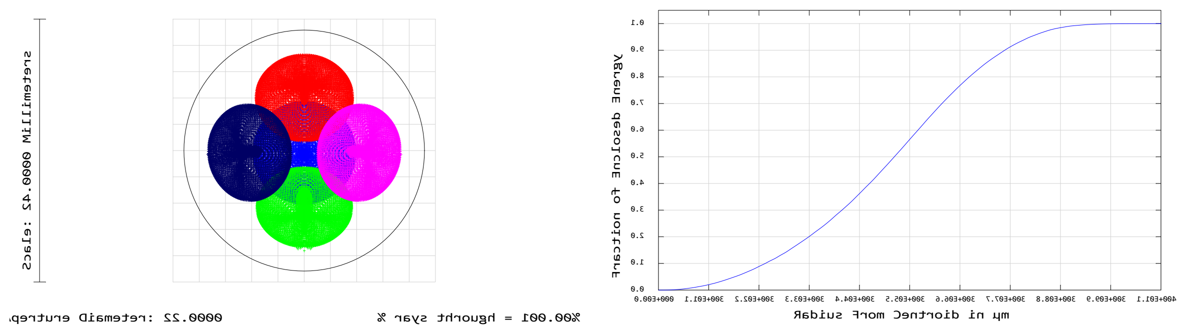


Figure 3. Polychromator layout. The raytracing of the four channels with lens couples (LC), dichroic mirrors (DM), interference filters (IF) and photomultipliers (PMT) detector are clearly visible.



a) b)

Figure 4. In a) footprint diagram and in b) encircled energy diagram on the PMT active area.

The performance of the four channel of the selected design have been analyzed, their performances are satisfying the requirements, for all the channels the footprint of the image is completely included inside the active area of the detector. In Figure 4 a) the footprint of 5 sample points, one the center and four at the edges of the input fiber area, are depicted wrt the 22 mm active area of the PMT detector. In Figure 4 b) the fraction of the image enclosed energy calculated for a uniform circular object of 8 mm in diameter, such as the input fiber, is shown. The total energy emitted by the fiber is collected and focalized on the PMT area.

4. CONCLUSIONS

The optical design solution for a polychromator for the Barcelona Raman LIDAR, to be used to characterize the atmosphere in the framework of the CTA telescope array for gamma-ray detection, has been described. A LIDAR system installed in the same site of the telescope array will be able to highly improve the data quality.

To cope with the scientific requirements, the preliminary polychromator optical design foreseen four channel for observing both the elastic atmospheric backscattered lines and some of the inelastic Nitrogen Raman ones. Each channel has one couple of identical lenses that is used to collect and collimate the light received by the telescope and which is transmitted to the polychromator via a liquid fiber. Dichroic mirrors, placed in the quasi collimated beam, are used to select the different lines, the final wavelength selection is done by interference filters, which are mounted near the detector to prevent unwanted light coming from the reflected or diffused light from the other channels to reach the detector. An identical lens couple is then used to focus the light on the photomultiplier detector.

The performance of each channel is satisfying the requirement of 80% of the image energy to be enclosed on the detector useful area. The image footprint is always completely enclosed inside the foreseen detector active area. The two-lens design is a trade-off between the need to collect as much light as possible, maintaining the system as compact as possible and having a relative high throughput to observe all the lines.

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