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Book of Abstracts

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DESIGN AND DEVELOPMENT OF A RAMAN LIDAR FOR THE CTA SOUTH SITE

Author: George Vasileiadis[1]

[1] *LUPM*

Corresponding Author: george.vasileiadis@lupm.in2p3.fr

The future Cherenkov Gamma Ray experiment CTA will reach a sensitivity and energy resolution never obtained until now by any other high energy gamma–ray experiment. Raman lidars can help reduce the systematic uncertainties of the molecular and aerosol components of the atmosphere so these performances can be reached. The motivation for Raman lidars and the design and development of the Montpellier Raman lidar system, to be installed at the CTA south site, is described. It provides both multiple elastic and Raman readout channels and custom-made optics design. Preliminary lidar tests and signals acquired at the OHP observatoiry confirms the actual performance of the lidar in consistency with the desired goals.

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A novel image correction method for cloud-affected observations with Imaging Atmospheric Cherenkov Telescopes

Author: Natalia Zywucka[1]

Co-authors: Dario Hrupec ; Dijana Dominis Prester [2]; Dorota Sobczynska [3]; Julian Sitarek [3]; Lovro Pavletić [4]; Mario Pecimotika [5]; Sasa Micanovic [6]

[1] *University of Lodz, Poland*

[2] *Department of Physics, University of Rijeka*

[3] *University of Lodz*

[4] *Faculty of Physics, University of Rijeka*

[5] *Ruđer Bošković Institute, Zagreb, Croatia*

[6] *University of Rijeka, Department of Physics, Croatia*

Corresponding Authors: dijana@phy.uniri.hr, n.zywucka@gmail.com, lpavleti@gmail.com, ds@kfd2.phys.uni.lodz.pl, mpecimotika@gmail.com, jsitarek@uni.lodz.pl, sasa.micanovic@phy.uniri.hr

The Imaging Atmospheric Cherenkov Telescopes observational technique employs the atmosphere as part of the detector, thus it is sensitive to all the changes taking place in it. Particularly, in the presence of clouds, the detector registers incomplete and degraded information caused by additional light absorption. Such observations are often rejected from further analysis process due to increased systematic errors. Therefore, we developed an innovative correction method on the image parameters based on a simple geometrical model which relates the pixel position on the camera to the expected height of the emitted Cherenkov light registered by that pixel.

We present the results of an investigation of a correction method applied to the Monte Carlo simulations, imitating the very-high-energy events affected by clouds registered by an array of four Large-Sized Telescopes, at the core of the future Cherenkov Telescope Array Observatory. We studied the one- and two-layer clouds located at different heights and assuming various transmission parameters. We show the effect of the correction method, which efficiently corrects the extinction of light in clouds and improves gamma-ray event reconstruction as well as overall system performance. The correction method eliminates a need for the additional time-consuming and computationally intensive Monte Carlo simulations.

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Estimation of the atmospheric transmission profile with the IACT background data

Author: Mario Pecimotika[1]

Co-authors: Abelardo Moralejo Olaizola [2]; Dario Hrupec ; Dorota Sobczynska [3]; Julian Sitarek [3]; Natalia Zywucka [4]

[1] *Ruđer Bošković Institute, Zagreb, Croatia*

[2] *IFAE Barcelona*

[3] *University of Lodz*

[4] *University of Lodz, Poland*

Corresponding Authors: moralejo@ifae.es, mpecimotika@gmail.com, dorota.sobczynska@uni.lodz.pl, n.zywucka@gmail.com, jsitarek@uni.lodz.pl

We present a novel method to determine the atmospheric transmission profile from the isotropic background events detected by the Imaging Atmospheric Cherenkov Telescopes. We construct a longitudinal distribution of the observed Cherenkov light by relating its emission height to a specific pixel in the camera. For this, we use a simple geometric model based on the parameters of the air shower. By comparing this distribution between cloudless and cloudy atmospheres, we are able to obtain the transmission profile during data acquisition.

Using Monte Carlo simulations of a subarray of four Large-Sized Telescopes of the upcoming Cherenkov Telescope Array Observatory, we have evaluated the performance of the proposed method and tested a number of possible systematic errors that could influence the method. The proposed method achieves typical systematic accuracy within a few per cent. The aggregated profiles of the observed Cherenkov light can be reconstructed with a statistical accuracy of $lesssim$ 5% with only a 5-minute exposure.

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Raman Lidar observations of the vertical profiles of aerosol optical properties and water vapour at the Pierre Auger Observatory

Author: Emanuele Avocone[1]

Co-author: Marco Iarlori [1]

[1] *Istituto Nazionale di Fisica Nucleare*

Corresponding Authors: marco.iarlori@aquila.infn.it, emanueleavocone@gmail.com

The observations of a Raman Lidar at the Pierre Auger Observatory in the Argentinian Pampa are reported. The Raman Lidar is utilized for real-time atmospheric monitoring along the detection of cosmic-ray air showers. The vertical profiles of the water vapor mixing ratio, aerosol optical depth, and the aerosol backscatter are presented and discussed, for an observation time of 7 years (2016-2022). The results could give insights into regional climate dynamics over the Argentinian Pampa.

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The Barcelona Raman LIDAR project and its prospects for the Cherenkov Telescope Array Observatory-North

Authors: Darko Kolar[1]; Otger Ballester[2]; Oscar Blanch Bigas[2]; Juan Boix[2]; Paolo G. Calisse[3]; Anna Campoy-Ordaz[4]; Michele Doro[5]; Lluis Font Guiteras[4]; Rafael Garcia[2]; Markus Gaug[4]; Roger Grau[2]; Manel Martinez[2]; Oscar Martinez[2]; David Roman[2]; Samo Stanič[1]; Santiago Ubach Ramirez[4]; Marko Zavrtanik[6]; Miha Živec[1]

[1] *University of Nova Gorica, Vipavska 13, 5000 Nova Gorica, Slovenia*

[2] *Institut de Fisica d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, 08193 Bellaterra (Barcelona), Spain*

[3] *Cherenkov Telescope Array Observatory gGmbH (CTAO gGmbH), Saupfercheckweg 1, 69117 Heidelberg, Germany*

[4] *Departament de Física, Universitat Autònoma de Barcelona and CERES-IEEC, 08193 Bellaterra (Barcelona), Spain*

[5] *Università degli Studi di Padova and INFN Sezione di Padova, Via Marzolo 8, 35131 Padova, Italy*

[6] *University of Nova Gorica, Vipavska 13, 5000 Nova Gorica, Slovenia; Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia*

Corresponding Authors: markus.gaug@uab.cat, samo.stanic@ung.si, marko.zavrtanik@ijs.si, miha.zivec@ung.si, darko.kolar@ung.si, blanch@ifae.es, michele.doro@unipd.it, martinez@ifae.es

The Cherenkov Telescope Array (CTA) is the next generation observatory of ground-based Imaging Atmospheric Cherenkov Telescopes (IACTs). The observatory, currently under construction, will be composed of more than 70 telescopes at two locations: in the northern hemisphere, CTAO-N at the Observatorio del Roque de Los Muchachos (ORM, La Palma, Canary Islands, Spain), and in the southern hemisphere, CTAO-S at a site belonging to the European Southern Observatory (ESO, Cerro Paranal, Chile). IACTs indirectly detect cosmic gamma rays 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 gamma rays and particles in upper layers of the atmosphere. CTAO's size will increase detection sensitivity in this energy range by a factor of 5 - 10 with respect to present experiments and aim for improved energy and angular resolution as well as greatly reduced systematic uncertainties. The key to reaching the 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) is the official CTA-N Pathfinder prototype and was deployed at ORM for extensive tests between February 2021 and May 2022. We report the BRL project's prospects for the CTAO-N, emphasizing the technical implementation and the preliminary data taken during its deployment period.

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Addressing the molecular atmosphere at the CTAO sites

Author: Georgios Voutsinas[1]

[1] *University of Geneva*

Corresponding Author: georgios.voutsinas@unige.ch

The Cherenkov Telescope Array Observatory (CTAO) has set ambitious goals in terms of energy and angular resolution. Achieving these goals requires a detailed understanding of the atmosphere over the CTAO sites and the development of atmospheric calibration methods. In this contribution, we focus on the molecular atmosphere. We discuss ongoing efforts to estimate systematic uncertainties in CTAO science performance introduced through atmospheric monitoring methods and variations in atmospheric conditions over different timescales. Subjects addressed include the validation of data assimilation system datasets over CTAO sites compared to weather station measurements, the effects of ozone variations (seasonal or stratosphere to troposphere transport events) on measured Cherenkov light density on the ground, and ongoing efforts to assess uncertainties introduced by the use of seasonal or tailored nightly molecular profiles. Finally, we discuss the molecular atmosphere

calibration suite implemented in the calibration pipeline of the Data Processing and Preservation System (DPPS) of CTAO.

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Optical Emissions Associated with Terrestrial Gamma-ray and Lightning Flashes at the Telescope Array Detector.

Author: Rasha Abbasi[1]

[1] *Loyola University Chicago*

Corresponding Author: rabbasi@luc.edu

Optical emissions linked to Terrestrial Gamma-ray Flashes (TGFs) have recently gained significance in both space-based and ground-based observations. These emissions are crucial in comprehending how TGFs are generated during thunderstorms. In this presentation, I will present the first time-resolved leader spectra of the optical component associated with downward TGFs, using a spectroscopic system. Additionally, I will showcase preliminary results of lightning flashes as observed by a photometer array installed at the Telescope Array site. This array shares the same field of view as the high-speed video camera and provides higher timing resolution, reporting on the atmospheric electrical discharge in the UV (associated with the streamer development) and infrared (associated with the stable leader propagation). These findings could illuminate the complex processes underlying the initiation and propagation of Terrestrial Gamma-ray Flashes and lightning flashes during thunderstorms, advancing our understanding of these phenomena.

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Investigating the effect of aerosol variations in high-level analyses of Cherenkov telescope data

Author: Tim Lukas Holch[1]

[1] *Deutsches Elektronen-Synchrotron DESY*

Corresponding Author: tim.lukas.holch@desy.de

As aerosols influence the optical transmission properties of the atmosphere, variations in atmospheric aerosols yield variations in the signals from extensive air-showers (EAS) measured with imaging atmospheric Cherenkov telescopes (IACTs).
With the optical transmission of the atmosphere affecting the amount of Cherenkov light reaching IACTs, wrongly accounted aerosol levels yield a misinterpretation of the brightness of the detected signals. And as the number of Cherenkov photons produced in an EAS is related to its primary particle's energy, such unaccounted aerosol variations cause errors in the reconstructed particle energies. As this reconstructed energy is commonly used to bin the data for further spectral, morphological or temporal modelling of the data, any error on the reconstructed air-shower energy propagates to all higher levels of an analysis. In this contribution, the effect of unaccounted aerosol variations on high-level physics results from IACT data is investigated by simulating observations with the CTAO in gammapy and adapting the reconstructed EAS energies as expected for variations in atmospheric aerosol content observed at the southern CTAO site. This data is then used to reconstruct the properties of the simulated gamma-ray sources and the results are compared to results obtained from simulated observations which are not affected by changing aerosol levels.

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Updates of the atmospheric monitoring at the Pierre Auger Observatory

Author: Bianca Keilhauer[1]

[1] *Karlsruhe Institute of Technology KIT*

Corresponding Author: bianca.keilhauer@kit.edu

Recent developments for the atmospheric monitoring at the Pierre Auger Observatory will be presented. These developments include new methods for cloud identification, and a status of our suit of instruments for atmospheric monitoring and the application of these data to air shower physics.

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Adding interferometric lightning detection to the Pierre Auger Observatory

Authors: Melanie Joan Weitz[None]; Pierre Auger Collaboration[None]

Corresponding Author: weitz@uni-wuppertal.de

The Pierre Auger Observatory has detected downward terrestrial gamma-ray flashes (TGFs) with its Surface Detector. A key to understanding this high-energy radiation in thunderstorms is to combine such measurements with measurements of lightning processes in their earliest stages. With eleven modified Auger Engineering Radio Array (AERA) stations we can build an interferometric lightning detection array working in the bandwidth between 30 −80 MHz inside the Surface Detector array to precisely measure lightning stepped leaders in 3D. These measurements allow us to decipher the cause of TGFs and clarify the reason for the observed high-energy particles in thunderstorms.

We will present the current status of the detection plans including the configuration of the interferometric lightning detection array and the steps to take as well as the reconstruction characteristics obtained with AERA.

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Instrumentation for mobile measurement in thunderstorms

Author: Martin Kákona[None]

Co-authors: Jakub Kákona [1]; Roman Dvořák [1]; Iva Ambrožová [1]; Olena Velichko [1]; Ondřej Ploc [1]; Jakub Šlegl [1]; Marek Sommer [1]; Vít Hanousek [2]

[1] *Nuclear Physics Institute of the Czech Academy of Sciences*

[2] *Institute of Information Theory and Automation of the Czech Academy of Sciences*

Corresponding Author: martin.kakona@gmail.com

In this speech, we will demonstrate the instrumentation used for measuring phenomena related to thunderstorms and discuss some important results from our measurements. Over the years dedicated to thunderstorm measurement, we have had to repeatedly revise our instrumentation as the characteristics of lightning proved significantly different from our initial assumptions. If logistics allow, I plan to transport the measuring vehicle by ferry to the conference venue, providing an opportunity to showcase the instruments firsthand. Regardless, I will present how lightning truly appears and how its representation varies across different devices.

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The INFN Raman LIDAR aerosol measurements at CTA North and its future deployment at CTA South.

Author: Marco Iarlori[1]

Co-authors: Africa Barreto [2]; Carla Aramo [1]; Emanuele Avocone [3]; Ermanno Pietropaolo [1]; Vincenzo Rizi [1]

[1] *Istituto Nazionale di Fisica Nucleare*

[2] *IARC/AEMET, Spain*

[3] *Università degli studi dell'Aquila & INFN/LNGS*

Corresponding Authors: ermanno.pietropaolo@aquila.infn.it, emanueleavocone@gmail.com, marco.iarlori@aquila.infn.it, carla.aramo@na.infn.it, vincenzo.rizi@aquila.infn.it

For the pre-production phase of Cherenkov Telescope Array (CTA), the INFN Raman Lidar (IRL) has collected vertical profiles of aerosol optical properties in the UV region at Roque de los Muchachos Observatory (ORM) up to December 2022, in automatic and unattended mode.
The data analysis has been tested and improved also by comparison with the measurements of the nearly located AERONET sunphotometer. A survey of the atmospheric aerosol climatology will be presented together with an overview of case studies.
The IRL is currently at our laboratory in L'Aquila (Italy) and an overview about the status of the upgrades (already implemented and on going) to improve its performances, before its deployment at the CTA South site, is also presented.

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FRAM Next Generation: cloud monitoring in the age of CMOS cameras

Author: Jan Ebr[1]

[1] *Institue of Physics, Prague*

Corresponding Author: janebr@email.cz

The visibility of stars is often used for cloud detection using all-sky cameras, which have however only a limited reach and resolution near the horizon due to the lack of detectable stars. At the Pierre Auger Observatory, it is also used by the current generation of FRAM robotic telescopes, but –due to their limited field of view –only for a small number of selected showers. Thanks to the recent development in astronomical CMOS cameras, we are able to propose a new type of device, specifically tailored to the field of view of the fluorescence detectors (FD) of the Pierre Auger Observatory. The sub-second readout times available with CMOS cameras allows the efficient use of short exposures, and so the field of view of one FD can be covered within half a minute with resolution and reach sufficient to detect small clouds with a setup that is significantly smaller, simpler and cheaper than the current FRAMs. The FRAM Next Generation (framNG) device will be able not only detect clouds, but also assess their optical thickness, provide information on aerosol extinction, sky brightness and possible even record atmospheric phenomena and astrophysical transients. The main challenge lies in the large data volume produced which necessitates reliable real-time data processing.

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Probing the context of TGF events at the Pierre Auger Observatory using VLF sensors

Author: James Sanchez[1]

Co-authors: Adonis Leal [2]; David Smith [1]; John Ortberg [1]; Roberta Colalillo [3]

[1] *University of California, Santa Cruz*

[2] *New Mexico Institute of Mining and Technology*

[3] *Istituto Nazionale di Fisica Nucleare*

Corresponding Authors: dsmith8@ucsc.edu, adonis.leal@nmt.edu, roberta.colalillo@na.infn.it, jortberg@ucsc.edu, jatsanch@ucsc.edu

Data from radio instruments are imperative to understanding the context of high-energy events in the atmosphere. Terrestrial gamma-ray flashes (TGFs) are extremely dynamic events that have several distinctive radio profiles in VLF including slow pulses (Pu et al. 2019) and energetic intracloud pulses (EIP; Lyu et al. 2021) in upward TGFs, both recently detected in association with downward TGFs as well (Chaffin et al. 2024). In addition, downward TGFs have been associated with powerful compact return strokes (CRS) in -CG lightning (Wu et al. 2021; Wada et al. 2022). The relationship between TGFs and their radio emissions can be very complicated, as indicated by a multi-pulse TGF event coupled with VLF recordings observed by our group during a winter thunderstorm in Japan in 2015, which we will briefly present. VLF technology can be used to determine localization of TGF events as well as indicate the occurrence of specific lightning processes such as leader steps and subsequent return strokes. Employing a large enough dynamic range remains the primary challenge to VLF-LF instruments that aim to effectively characterize leader steps at the same time as the most powerful return strokes. The Pierre Auger Observatory provides a unique opportunity to perform simultaneous VLF-LF and gamma-ray measurements of TGF events in a format that allows for the optimal geometrical setup for VLF-LF sensors involving a separation distance which is outside the near radiation field but close enough to be sensitive to distinguish leader steps on weaker events.

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Terrestrial gamma-ray flashes with ADELE, GODOT and THOR

Authors: David Smith[1]; John Ortberg[1]

Co-authors: Gregory Bowers [2]; Jeffrey Chaffin [3]

[1] *University of California, Santa Cruz*

[2] *Los Alamos National Laboratory*

[3] *U.S. Air Force Institute of Technology*

Corresponding Author: dsmith8@ucsc.edu

Over the past 15 years, the high-energy atmospheric physics group at the University of California, Santa Cruz, has developed and deployed instrumentation for the detection of TGFs on the ground and aboard aircraft. While the nature of this observing strategy is that far fewer events are observed than can be seen from spacecraft, with their very large (~600km radius) detection footprint, there are many discoveries that can only be made by observing up close, and our group and other groups internationally have had numerous successes. Using our three generations of detector arrays (ADELE, 2009-2015; GODOT, 2014-present; and THOR, 2021-present) we have observed:

- the downward reverse beam from an upward TGF (Bowers et al. 2018)
- neutrons produced as a byproduct of TGF gamma-rays and electrons (Bowers et al. 2017)
- the absence of TGFs from most lightning, with luminosity limits up to a factor of 10^7 lower than expected TGF luminosities (Smith et al. 2011, 2018)

- downward TGFs associated with unique classes of radio emission that had previously been connected with upward TGFs seen from space (slow pulses and energetic intracloud pulse (EIPs)); (Chaffin et al. 2024)
- downward TGFs detected from unexpectedly large distances, suggesting a much broader beam than has been inferred for upward TGFs (Ortberg et al. 2024)
- evidence for production of bursts of radiation all during downward leader propagation taking place at the top of the growing channel, transitioning gradually to a "full"TGF during the return stroke current (unpublished work).

There are six copies of THOR, our latest generation of detector, deployed worldwide to investigate TGF production in distinct environments: mountaintop and low-elevation, coastal and inland, tropical and temperate, and regions that primarily experience summer or winter lightning. The primary technical advances of THOR over the previous generations of instrument are 1) microsecond absolute timing using GPS, and 2) a dual data mode that returns both a list of individual photon events (time and energy tagged) with 100% coverage, and small bursts of data with the direct digitized output of the photomultiplier tubes at 12.5 nanosecond resolution when a bright event like a TGF occurs.

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Aerosol Measurement in B, V, and R Filters using Wide-field Photometry

Author: Shefali Negi[None]

Co-authors: Jan Ebr [1]; Jiri Eliasek [1]; sergey karpov [1]

[1] *Institute of Physics of the Czech Academy of Sciences*

Corresponding Authors: karpov@fzu.cz, ebr@fzu.cz, negi@fzu.cz, eliasek@fzu.cz

The new method for aerosol measurement using wide-field stellar photometry was originally developed for B-filter data. The dependence of VAOD (vertical aerosol optical depth) on wavelength can be used to understand the physical characteristics of aerosol. The method has been extended for V and R filters using the Gaia stellar photometric catalog as the reference. We calculated the coefficients of the equation describing molecular and aerosol extinction of the atmosphere. For data in a particular filter, they depend on the telescope's location. Light towards shorter wavelengths has higher extinction. The VAOD, calculated in B, V, and R filters does not show monotonous dependence on wavelength, and there is increased dependence on the photometric methods for V and R filters. We studied the possible reasons for this unexpected behavior.

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The Gamma-Flash Project: High-energy radiation and particles in thunderstorms, lightning, and terrestrial gamma-ray flashes

Authors: Alessandra Tiberia[1]; Alessandro Ursi[2]; Paolo Calabretto[3]

[1] *ASI*

[2] *ASI-INAF*

[3] *INAF-OAS Bologna*

Corresponding Authors: paolo.calabretto@inaf.it, alessandra.tiberia@asi.it, alessandro.ursi@asi.it

The Gamma-Flash program, funded by the Italian Space Agency (ASI) and led by the National Institute for Astrophysics (INAF), aims to study high-energy emissions related to thunderstorms, such as terrestrial gamma-ray flashes (TGFs) and gamma-ray glows. The program led to the development of two main detection systems: a ground-based system, installed at the "O. Vittori"Observatory on top of Mt. Cimone (Northern-Central Italy), and an airborne payload, installed on a Cessna CITATION Mustang aircraft, for in-flight campaigns.

The ground-based detection system consists of five γ-ray and three neutron detectors, and has been collecting data from Jul 2022 to Oct 2023, overall experiencing 95 days of thunderstorm activity (36% of the total). During this first observational survey, a gamma-ray glow of 1.5 min was revealed. The event light curve shows an abrupt interruption at the end, coinciding with the occurrence of a CG lightning discharge, that took place within 2 km from the detectors.

The avionic payload consists of 6 γ-ray and 2 neutron detectors. Up to now, only a first test flight with clear sky was performed, in December 2023. The purpose of this second payload is to collect additional data by flying nearby convective systems, in order to observe high-energy emissions directly from the sky. Further flights are planned to be conducted in June-September 2024.

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An innovative compact lidar for atmospheric aerosol, water vapour and transmissivity measurements

Authors: Riccardo Damiano[1]; Matteo Manzo[1]; Zeeshan Ali[1]; Salvatore Amoruso[1]; Alessia Sannino[1]; Salvatore Spinosa[1]; Antonella Boselli[2]

[1] *Università Federico II di Napoli*

[2] *IMAA-CNR*

Corresponding Authors: antonella.boselli@cnr.it, zeeshan.ali@unina.it, riccardo.damiano@unina.it, matteo.manzo@unina.it, alessia.sannino@unina.it, salvatore.amoruso@unina.it, salvatore.spinosa@unina.it

The Naples observation station serves as a National Facility for the ACTRIS European network. In this frame, an innovative lidar system was recently made operational as part of the transportable atmospheric analysis equipment at the University of Naples "Federico II", located at CeSMA (Advanced Metrological and Technological Services Center).
The system is compact and transportable, using two wavelengths to retrieve both elastic and Raman backscattered light, and also providing depolarization analysis. Its emitter is a solid-state Nd:YAG laser source with a repetition-rate of 2 kHz, sending the second (532 nm) and third harmonic (355 nm) of the fundamental wavelength (1064 nm) into the atmosphere. The receiver operates in a monostatic configuration and employees a Ritchey-Chretien telescope with a 20 cm diameter and a 50 cm focal length. Moreover, the advanced scanning systems permits measurements at desired angle with respect to the zenith and azimuth angles.
The spectral selection box splits the light into the various wavelength and polarization components, and in particular into channels for the acquisition of backscattered light of the same wavelength sent in the atmosphere, analysing elastic scattering, and also channels for the acquisition of wavelengths from anelastic, or Raman, scattering. In particular, Raman echoes for the 355 nm initial wavelengths are acquired, 386 nm for N2 and 407 nm for H2O. This last channel is fundamental to obtain information on the water vapour presence in atmosphere, which is one of the most variable in concentration component.
This system allows to carry out measurements of atmospheric transmissivity in the UV region. A special interest for this spectral region comes also from the development of new methods to detect very high-energy cosmic rays through the UV Cherenkov light emitted by the electromagnetic showers generated in the atmosphere, few kilometres above surface level. The transmissivity depends on scattering and absorption processes at the various wavelengths from molecules and aerosol in atmosphere, with the latter term being the most difficult term to estimate. Measurements made by

this lidar will be reported, showing off how this instrument can conduct in-depth analysis of atmospheric particulate matter, obtaining optical properties of the particles and transmissivity of the atmosphere.

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Impact of Climate Change on the MAGIC and CTAO Sites

Authors: Markus Gaug[1]; Alessandro Longo[None]; Stefano Bianchi[2]; Lluís Font[1]; Hararld Kornmayer[3]; Michele Doro[4]; Alexander Hahn[5]; Oscar Blanch Bigas[6]; Wolfango Plastino[7]; Daniela Dorner[8]

[1] *Universitat Autònoma de Barcelona and CERES-IEEC*

[2] *Università degli Studi di Roma Tre*

[3] *Duale Hochschule Baden-Württemberg*

[4] *University of Padova*

[5] *Max Planck Institute for Physics*

[6] *IFAE*

[7] *ROMA3*

[8] *Universität Würzburg*

Corresponding Authors: bianchi@fis.uniroma3.it, ahahn@mpp.mpg.de, hkornmayer@dhbw-mannheim.de, michele.doro@unipd.it, wolfango.plastino@uniroma3.it, dorner@astro.uni-wuerzburg.de, alessandro.longo@uniroma3.it, markus.gaug@uab.cat, lluis.font@uab.cat, blanch@ifae.es

The Observatorio del Roque de los Muchachos (ORM) will host the northern site of the Cherenkov Telescope Array Observatory, in an area about 200~m below the mountain rim, where the optical telescopes are located. The area hosts the MAGIC Telescopes, which have gathered a unique series of 20 years of weather data.
We use advanced profile likelihood methods to determine seasonal cycles, the occurrence of weather extremes, weather downtime and long-term trends correctly taking into account the data gaps. We find significant differences with respect to the mountain rim in terms of the behaviour of wind and relative humidity. The impact of climate change is observed through an increase in temperature, the diurnal temperature range, and relative humidity, accompanied by a decrease in trade wind speeds. The occurrence of extreme weather, such as tropical storms and long rains seems to remain constant over time. We find a significant correlation of temperature with the North Atlantic Oscillation Index and multifractal behaviour of the data.
No hints are found of a degradation of weather downtime under the assumption of a linear evolution of environmental parameters with
time.

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Multiple ELVES and more TLEs at the Pierre Auger Observatory

Author: Roberto Mussa[1]

[1] *Istituto Nazionale di Fisica Nucleare*

In the last ten years, the Pierre Auger Observatory has exploited a dedicated trigger and extended readout, and its very high time resolution, to record the world's largest sample of multiple ELVES. By comparing the time gaps between flashes with waveforms recorded by the antennas of the ENTLN network, we observe the correlation expected by models for what concerns double ELVES. On the

contrary, using a large sample of triple ELVES, from four different thunderstorms, we refute the ground reflection mechanism.
In the same data sample, we could observe another type of TLE, the halo, a few hundred microseconds after some ELVES. This has motivated the installation, in December 2023, of new cameras, to complement the observations done with our Fluorescence Detector. Preliminary results, including the first observation of SPRITES in Auger, will be shown.

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Characterisation of the Atmosphere in VHE gamma-astronomy with MAGIC elastic LIDAR and CTAO FRAM

Author: Dijana Dominis Prester[1]

Co-authors: Marta Kolarek [1]; Jan Ebr [2]; Markus Gaug [3]; Shefali Negi ; sergey karpov [4]; Petr Janecek [5]; Jiri Eliasek [4]; Marina Manganaro [1]; Alexander Hahn [6]; Felix Schmuckermeier [7]; Razmick Mirzoyan [8]

[1] *University of Rijeka, Faculty of Physics*

[2] *Institue of Physics, Prague*

[3] *Universitat Autònoma de Barcelona & IEEC-CERES*

[4] *Institute of Physics of the Czech Academy of Sciences*

[5] *Institute of Physics AS CR*

[6] *Max Planck Institute for Physics*

[7] *Max Planck Institut fuer Physik*

[8] *Max-Planck-Institute for Physics*

Corresponding Authors: dijana@uniri.hr, karpov@fzu.cz, eliasek@fzu.cz, ahahn@mpp.mpg.de, markus.gaug@uab.cat, janebr@email.cz, janecekp@fzu.cz, negi@fzu.cz, martakolarek@gmail.com, razmik@mppmu.mpg.de, manganaro.marina@gmail.com

Ground-based observations of Very-High-Energy (VHE) gamma rays from extreme astrophysical sources are significantly influenced by atmospheric conditions. This is due to the atmosphere being an integral part of the detector when observing with Imaging Air Cherenkov telescopes. Clouds and dust particles diminish atmospheric transmission, thereby impacting Cherenkov showers and the reconstructed spectra within the VHE gamma-ray range.
Precise measurements of atmospheric transmission above Cherenkov observatories play a pivotal role in the analysis of the observed data, the corrections of the reconstructed energies of incoming gamma rays, and in establishing observation strategies for various gamma-ray emitting sources. The Major Atmospheric Gamma Imaging Cherenkov telescopes (MAGIC) and the Cherenkov Telescope Array Observatory (CTAO), both located at La Palma, Canary Islands, use different sets of auxiliary instruments for real-time characterisation of the atmosphere.
The study involves the analysis of contemporaneous sets of data spanning from 2018 to 2020. These data have been obtained from the elastic Light Detection and Ranging (LIDAR) system used in MAGIC and the F/Photometric Robotic Atmospheric Monitor (FRAM) telescope used as part of the future atmospheric characterisation equipment of CTAO. Correlations between the Vertical Optical Aerosol Depth (VAOD) as measured by both instruments are calculated. The effects of various factors influencing their correlations are discussed and an observational strategy considering real-time VAOD measurements is proposed.

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Results from the ALOFT-2023 Mission: A Flight Campaign for TGF and Gamma-Ray Glow Observations Over Central America and the Caribbean in July 2023

Authors: A. Fuglestad[1]; A. Mezentsev[1]; A. Santos[2]; B. Hasan Qureshi[1]; B. Husa[1]; C. Schultz[3]; C. Velosa[2]; D. Shy[4]; D. Walker[5]; David Sarria[1]; G. Heymsfield[6]; H. Christian[5]; I. Adams[6]; I. Bjørg Engeland[1]; J. Montanya[7]; J. Søndergaard[1]; J.A. Lopez[7]; J.A. Roncancio[7]; J.E. Grove[4]; K. Ullaland[1]; M. Cohen[8]; M. Fullekrug[9]; M. Pazos[10]; M. Quick[3]; M. Stanley[11]; M. Urbani[7]; Martino Marisaldi[1]; N. Lehtinen[1]; Nikolai Østgaard[1]; O. van der Velde[7]; P. Bitzer[5]; P. Krehbiel[11]; R. Blakeslee[3]; R. Kroodsma[6]; S. Cummer[12]; S. Yang[1]; T. Lang[3]; Y. Pu[12]

[1] *Department of Physics and Technology, University of Bergen, Norway*

[2] *Universidad Nacional de Colombia, Columbia*

[3] *NASA Marshall Space Flight Center, Huntsville, USA*

[4] *U.S. Naval Research Laboratory, Washington DC, USA*

[5] *Department of Atmospheric Science, Earth System Science Center, University of Alabama in Huntsville, Huntsville, USA*

[6] *NASA Goddard Space Flight Center, Greenbelt, USA*

[7] *Polytechnic University of Catalonia, Spain*

[8] *Georgia Institute of Technology, USA*

[9] *University of Bath, UK*

[10] *Instituto de Ciencias de la Atmosfera y Cambio Climatico, UNAM, Mexico*

[11] *New Mexico Institute of Mining and Technology, USA*

[12] *Duke University, USA*

Corresponding Authors: nikolai.ostgaard@uib.no, martino.marisaldi@uib.no

The Airborne Lightning Observatory for FEGS and TGFs (ALOFT) campaign, conducted during the summer of 2023 on-board a NASA ER-2 research aircraft, investigated Terrestrial Gamma-ray Flashes (TGFs) and gamma-ray glows from thunderclouds over Central America, the Gulf of Mexico, and the Caribbean. Flying at an altitude of 20 km, the NASA ER-2 was equipped with an advanced scientific payload: a suite of gamma-ray detectors with a dynamic range covering several orders of magnitude in flux and the full energy spectrum necessary for detecting TGFs and gamma-ray glows; the Fly's Eye GLM Simulator (FEGS), sensitive to various wavelengths; electric field change meters (EFCM); the Lightning Instrument Package (LIP) for three-component electric field measurements; an array of microwave radiometers and radars for cloud characterization, including the Advanced Microwave Precipitation Radiometer (AMPR), Configurable Scanning Submillimeter-wave Instrument/Radiometer (CoSSIR), Cloud Radar System (CRS), and X-band Radar (EXRAD). The suite was complemented by extensive ground-based radio observations.
Over the course of 10 flights totaling 60 hours (about 30 above thunderstorms), the campaign resulted in the detection of 130 transient gamma-ray events and hundreds of gamma-ray glows, revealing that thunderclouds can glow for hours and span several thousands of square kilometers—far exceeding previous estimations of duration and area. In this presentation, we will provide an overview of ALOFT's key findings related to Terrestrial Gamma-ray Flashes (TGFs), Flickering Gamma-ray Flashes (FGFs), and observations of Gamma-ray Glows and Glow Bursts.

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The Raman LIDAR technique

Author: Marco Iarlori[1]

[1] *Istituto Nazionale di Fisica Nucleare*

Corresponding Author: marco.iarlori@aquila.infn.it

The measurements of the vertical profiles of the atmospheric aerosol optical properties (i.e., the extinction and the backscatter coefficients) and water vapour mixing ratio, are based on the well-known single scattering lidar equation. The Raman scattering is an inelastic pure molecular scattering that has been successfully used in lidar remote-sensing techniques since the late 1960s. Focused on single wavelength raman lidar systems, an overview of the data retrieval techniques will be presented along with a coincise error analysis of the studied quantities. A brief overview of the preliminary hardware/software tests necessary to assure the quality of the data is also outlined.

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A TGF with Azimuthal Substructure at the Pierre Auger Observatory

Authors: John Ortberg[1]; Pierre Auger Collaboration[None]; Roberta Colalillo[2]

Co-authors: David Smith [1]; Joseph Dwyer [3]

[1] *University of California, Santa Cruz*

[2] *Istituto Nazionale di Fisica Nucleare*

[3] *University of New Hampshire*

Corresponding Authors: roberta.colalillo@na.infn.it, joseph.dwyer@unh.edu, dsmith8@ucsc.edu, jortberg@ucsc.edu

The Pierre Auger Observatory, designed to study ultra-high-energy cosmic rays, turned out to be a tremendous instrument for detecting and characterizing Terrestrial Gamma-ray Flashes (TGFs). In contrast to most TGF detections, which are almost exclusively from single locations, the vast array at the Auger Observatory yields upwards of 40 well spaced samples of the entire TGF footprint. As a consequence, we can show for the first time a TGF that is clearly asymmetric with regard to the vertical axis. Additionally, we can now show that the event had an azimuthal substructure with a primary and second peak in fluence in the SE and SW regions, respectively. While tilted TGFs have been predicted in the literature, azimuthal substructure has not. We examine some possible implications for spatial structure at the TGF source, and whether or not other events at the Auger Observatory show evidence of this similar substructure.