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lstchain: An Analysis Pipeline for LST-1, the First Prototype Large-Sized Telescope of CTA

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Abstract. The future Cherenkov Telescope Array (CTA) will have telescopes of different sizes, the Large-Sized Telescopes (LSTs) being the largest ones. Located on the island of La Palma, the LST-1, the prototype of the first LST, started taking astronomical data in November 2019, detecting the first gamma-ray sources right afterwards. The analysis pipeline, that processes data from raw inputs until high level products is called `lstchain` and is heavily based in the CTA prototype pipeline framework `ctapipe`. In this presentation I'll show the pipeline that performs signal integration, image cleaning, image parameter calculation, and machine learning methods for true parameter reconstruction.

1. The Cherenkov Telescope Array

The Cherenkov Telescope Array (CTA) is the next generation ground-based observatory for gamma-ray astronomy at Very-High Energies (VHE, E $\geq$50 GeV). With more than 100 telescopes located in the Northern and Southern hemispheres, CTA will be the world's largest and most sensitive VHE gamma-ray observatory. The CTA telescopes obtain images of particle showers initiated in the atmosphere by VHE photons by detecting the Cherenkov light emitted by these particles when moving faster than the speed of light in the air.

1.1. The Large-Sized Telescopes of CTA

LSTs are the largest telescopes of the array, with a focal length of 28 m and a parabolic mirror of 23 m diameter and 400 m^2 area of each telescope. The telescopes operate in the energy range above 20 GeV and have a light carbon-fiber structure for fast repositioning to catch transient events (Cortina 2019). The camera is made of Photomultiplier tubes that transform photons into electrical signals recorded by a fast readout system digitalizing at 1 Gsample/s. `cta-lstchain` deals with data after they are written to disk by the Data AcQuisition (DAQ). The prototype of the first LST, called LST-1, is taking commissioning sky data since November 2019. LST-1 is the first prototype of a CTA telescope that is located in one of the final CTA sites.

2. cta-lstchain

`cta-lstchain` is the pipeline software that reconstructs the data from the LSTs. It is heavily based on `ctapipe` (Kosack & Peresano 2020), the framework for prototyping the low-level data processing algorithms for the Cherenkov Telescope Array. The pipeline workflow of cta-lstchain is shown in Fig. 1. It processes data from raw inputs (R0) and integrates pulses (low level calibration), calibrates the pulses into a number of observed photoelectrons (high level calibration), performs an image cleaning that selects pixels with signals dominated by the shower, rather than light of the night sky, and calculates image parameters, amongst them, the moments up to 3rd order of the light distribution of the images, producing the Data Level 1 (DL1). Random Forest models are trained on MonteCarlo simulations and applied to estimate the primary energy, arrival direction and to perform a separation between gamma-ray candidates and images produced by hadrons. These models are applied to the data and the output of this stage are the image parameters together with the reconstructed energy, direction and *gammaness*, producing the Data Level 2 (DL2). Finally, event selection is applied to select gamma-ray candidates producing the Data Level 3 (DL3) in which we search for significant signals using high level analysis tools such as `ctools` (Knödlseder et al. 2016) or `gammapy` (Deil et al. 2017), that are common to other CTA telescope types.

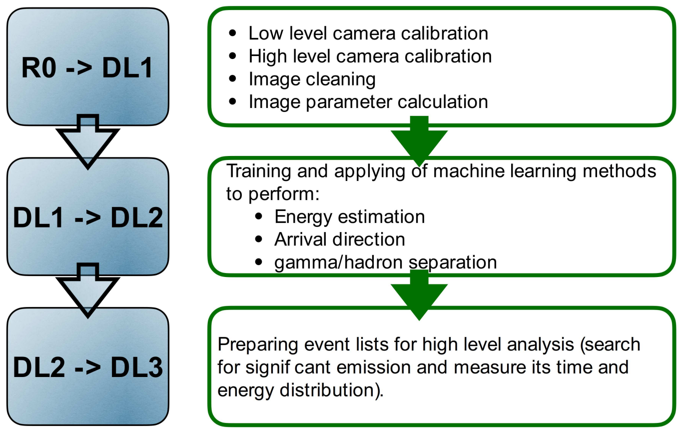

Figure 1. Workflow of the analysis of LST-1 data produced by *lstchain*. The raw inputs are processed until reaching the gamma-ray candidate list. Further data processing can be performed with the currently existing high-level gamma-ray analysis tools.

3. First results

The pipeline has been essential to deal with commissioning data, monitor, spot and solve problems with the Data Acquisition, Optics and Drive system of the telescope, and to monitor the optical efficiency of the system. It has also been used to monitor the improvement of the performance of the telescope since the beginning of the commissioning period. Apart from technical observations, the LST-1 is regularly observing the Crab Nebula, the calibrator in VHE gamma-ray astronomy, that was detected the first night the telescope took sky data. A sky map of the region is shown in the left panel of Fig. 2. To detect VHE gamma-ray emission from the Crab pulsar during the commissioning phase was more challenging, but the signal was significantly detected in 11 hours of exposure, as it is shown on the right panel of Fig. 2. Other known VHE gamma-ray sources have also been detected by the telescope during this phase thanks to the pipeline analysis presented in this poster and the quick data processing from LSTOSA (Ruiz, J.E. et al. 2021).

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References

Cortina, J. 2019, PoS, ICRC2019, 653

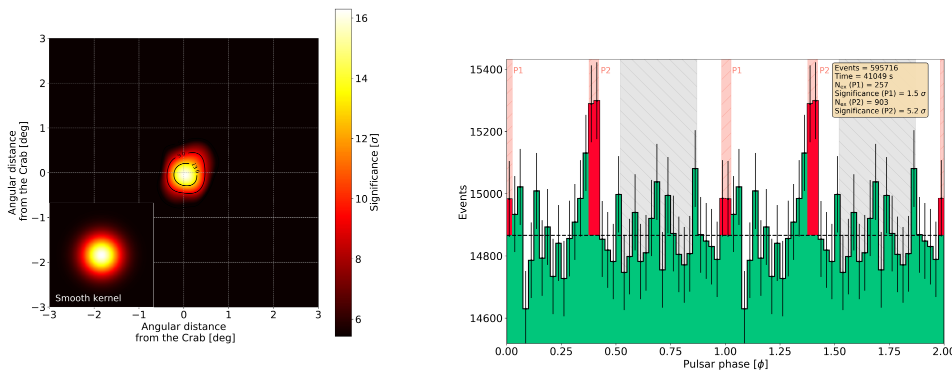

Figure 2. Left panel: Two-dimensional smoothed excess map of the gamma-ray signal from the direction of the Crab Nebula for an exposure of 269 minutes. Right panel: Phaseogram of the Crab Pulsar for an exposure of 11.4 hours.

Deil, C., Zanin, R., Lefaucheur, J., Boisson, C., Khelifi, B., Terrier, R., Wood, M., Mohrmann, L., Chakraborty, N., Watson, J., Lopez-Coto, R., Klepser, S., Cerruti, M., Lenain, J. P., Acero, F., Djannati-Ataï, A., Pita, S., Bosnjak, Z., Trichard, C., Vuillaume, T., Donath, A., Consortium, C., King, J., Jouvin, L., Owen, E., Sipocz, B., Lennarz, D., Voruganti, A., Spir-Jacob, M., Ruiz, J. E., & Arribas, M. P. 2017, in 35th International Cosmic Ray Conference (ICRC2017), vol. 301 of International Cosmic Ray Conference, 766. 1709.01751

Knödlseder, J., et al. 2016, Astron. Astrophys., 593, A1. 1606.00393

Kosack, K., & Peresano, o. b. o. t. C. C., Michele 2020, PoS, ICRC2019, 717

Ruiz, J.E., Morcuende, D., Saha, L., Baquero, A., Contreras, J.L., & Aguado, I. 2021, in ADASS XXX, edited by J. E. Ruiz, F. Pierfederici, & P. Teuben (San Francisco: ASP), ASP Conferences Series