PROCEEDINGS OF SCIENCE

First IACT Waveform Analysis Based on Deep Convolutional Neural Networks Using CTLearn

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Imaging atmospheric Cherenkov telescopes (IACTs) detect extended air showers (EASs) generated when very-high-energy (VHE) gamma rays or cosmic rays interact with the Earth's atmosphere. Cherenkov photons produced during an EAS are captured by fast-imaging cameras, which record both the spatial and temporal development of the shower, along with calorimetric data. By analyzing these recordings, the properties of the original VHE particle—such as its type, energy, and direction of arrival—can be reconstructed through machine learning techniques. This contribution focuses on the Large-Sized Telescopes (LSTs) of the Cherenkov Telescope Array Observatory, a next-generation ground-based gamma-ray observatory. LSTs are responsible for reconstructing lower-energy gamma rays in the tens of GeV range. We explore a novel event reconstruction technique based on deep convolutional neural networks (CNNs) applied on calibrated and cleaned waveforms of the IACT camera pixels using CTLearn. Our approach explicitly incorporates the time development of the shower, enabling a more accurate reconstruction of the event. This method eliminates the need for charge integration or handcrafted feature extraction, allowing the model to directly learn from waveform data.

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1. Introduction

Very-high-energy (VHE; approximately above 20 GeV) gamma-ray astronomy enables the study of some of the most extreme and energetic phenomena in the universe, such as pulsars, active galactic nuclei, and gamma-ray bursts. Ground-based detection of these gamma rays is made possible by Imaging Atmospheric Cherenkov Telescopes (IACTs), which observe the Cherenkov radiation emitted by extensive air showers (EASs) initiated when VHE particles interact with the Earth's atmosphere. The Cherenkov photons, typically in the near-ultraviolet to visible range, are collected by segmented mirrors and imaged onto fast cameras capable of capturing both the spatial distribution and temporal evolution of the shower.

The reconstruction of the primary particle's properties, such as its type, energy, and arrival direction, from these recordings is a central challenge in IACT data analysis. Traditional approaches rely on charge integration over the waveform, followed by handcrafted feature extraction, such as Hillas parameters [1], and classification or regression models built on these features [2]. While effective, these methods can be limited by their reliance on prior assumptions and may discard potentially informative temporal data embedded in the calibrated waveforms.

The Cherenkov Telescope Array Observatory (CTAO) [3], currently under construction, represents the next-generation ground-based observatory for very-high-energy (VHE) gamma rays. With sites in both the northern and southern hemispheres, CTAO will provide full-sky coverage and improved operational duty cycle. It will employ a hybrid array of telescopes of different sizes to maximize sensitivity across the VHE gamma-ray spectrum. The Large-Sized Telescopes (LSTs), with their large mirror area and fast electronics, are optimized for detecting low-energy gamma rays in the tens of GeV range, where precise waveform processing is especially critical for accurate event reconstruction.

Advances in machine learning (ML) over the last decades, particularly deep learning (DL) with convolutional neural networks (CNNs), offer an opportunity to revisit the reconstruction problem by allowing models to learn directly from minimally processed data. In this work, we present a novel event reconstruction approach for the LSTs using CTLearn[1] [4, 5], a DL framework developed for IACT data analysis. Our method applies CNNs to calibrated and cleaned waveforms from the IACT camera pixels, preserving the full temporal structure of the recorded signals. By avoiding intermediate charge integration and feature engineering steps, the model learns to extract discriminative features directly from the waveform data, enabling improved reconstruction of particle energy and direction.

2. Data analysis pipeline

The analysis is carried out using a simulated, mono-telescope dataset specifically tailored to the LST-1 prototype and its observational configuration. This dataset was generated with `CORSIKA` [6] and `sim_telarray` [7], following the standard CTAO simulation procedures. The raw simulation data were processed into calibrated waveforms and cleaned images using `ctapipe` [8], the prototype low-level data processing pipeline for CTAO. The resulting dataset conforms to the `ctapipe`

[1] https://github.com/ctlearn-project/ctlearn

reference implementation of the CTAO data format and includes calibrated waveforms for each event. This specific simulated dataset was also employed in the LST-1 performance study [9].

To make the training of the DL models feasible, we restricted the dataset to a narrow range of observation altitudes. Specifically, we used for the training of the models only two adjacent pointing nodes, following the strategy of [10]. For the gamma-diffuse simulations, these correspond to zenith angles of 9.579° and 16.087°, and azimuth angles of 126.888° and 108.090°, respectively. Due to the limited number of proton events available in each pointing node, we also included the two immediate neighboring pointing nodes, as well as four pointing nodes with the same zenith angles but opposite azimuth directions. This allowed us to construct a more balanced training set between gamma-ray and proton samples. A generic model trained on a wide range of pointing nodes, as done in [10] using integrated and cleaned images, is not yet feasible with waveform data due to current limitations in hardware capabilities and data throughput.

The DL models were trained using diffuse gamma-ray and proton events, generated within cones of 2.5° and 8° radius, respectively. Regression models for energy and arrival direction reconstruction were trained only on the diffuse gamma-ray training set. Performance evaluation was carried out using independent samples of simulated protons ($\sim 10^7$ events; zenith 10.0°; azimuth 102.199°; energy range 10 GeV – 103.9 TeV) and pointlike gamma rays ($\sim 10^7$ events; zenith 10.0°; azimuth 102.199°; energy range 5 GeV – 54.5 TeV), assuming a gamma-ray point source uniformly from a 0.4° offset of the telescope pointing (ringwobble). Due to the lack of testing protons data, we can only evaluate the classifier model with the signal distribution.

`CTLearn` was employed for DL-based particle classification and event reconstruction, such as the regression for the energy and the arrival direction, using calibrated waveforms as input. The predictions of `CTLearn` are stored in `ctapipe`-compatible format, aligned with the CTAO reference data structure to ensure consistency and interoperability within the Data Processing and Preservation System (DPPS) of CTAO. To ensure reproducibility with minimal manual intervention, we utilized the `CTLearn-Manager` package, which provides an automated and configurable interface for streamlining DL training, evaluation, and data handling workflows.

3. Methodology

We adopt a similar methodological framework as presented in [10], with adaptations for the use of calibrated waveforms. Instead of integrated charge and peak arrival time images, we input the calibrated waveforms, cropped for 20 samples of 1 nanosecond per pixel, into the CNN. Although waveform data is used, we still apply the standard image cleaning mask from conventional IACT analyses to remove background-dominated pixels and retain those containing significant Cherenkov signal. This cleaning step improves robustness and maintains applicability to real observational data. In future work, this cleaning step is planned to be replaced by a DBSCAN-based algorithm applied directly to the waveform data (see section 5).

For this study, we employed the Thin-ResNet (TRN) architecture [11], a shallow residual neural network (ResNet) [12] with 33 layers. To accommodate the specific image input shape of the LST, the initial layer of the original TRN design was omitted. The model uses residual connections adding the input to the output at each stage, which enables deeper architectures by mitigating vanishing gradient issues. Each residual block incorporates a dual squeeze-and-excitation attention mechanism [13], allowing the network to emphasize the most informative features. Input images were pre-processed onto a Cartesian grid using bilinear interpolation from the `ImageMapper` module of the `DL1-Data-Handler`[2] [14], a package tailored for managing IACT data in DL workflows, enabling the use of standard convolutional layers [15].

4. Results

This section presents the performance evaluation of the CNN-based analysis using the TRN, applied to simulated waveform data from the LST-1 prototype. The goal is to assess the capability of the DL model to reconstruct and classify events using calibrated waveforms. We restrict the analysis to events in which the image contains more than 50 photoelectrons (PE) after the cleaning procedure, ensuring sufficient signal quality for accurate reconstruction.

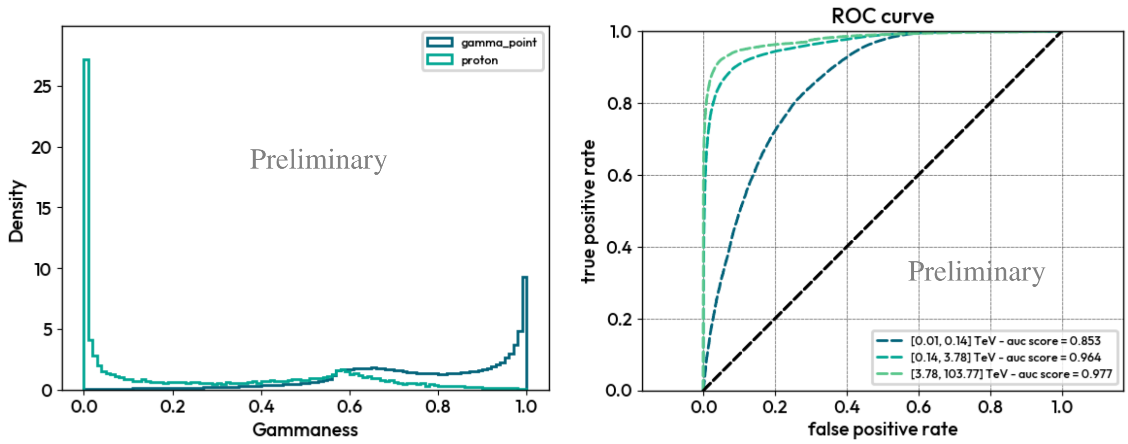

Figure 1: (**Left**): Gammaness distribution for the testing pointlike gamma sample. Only events with more than 50 PE are considered. The bump located at around 0.6 gammaness value is caused by faint events, which can be removed by increasing the threshold of PE (see also [10]). (**Right**): ROC curves for three different energy bins, illustrating the classifier performance across energies. The AUC score for each bin is shown in the legend, demonstrating improved separation power at higher energies.

The classification model can be tested using the gammaness distribution for the different particle types (see left panel of Fig. 1) and the Receiver Operating Characteristic (ROC) curves together with its Area Under the Curve (AUC) score for different energy bins (see right panel of Fig. 1). The separation between gamma-ray and hadronic events is functioning as intended. Direction reconstruction accuracy is evaluated by comparing predicted arrival directions to the true ringwobble source position, which is set to an uniformly offset of the telescope pointing of 0.4° (see left and middle panels of Fig. 3). Energy reconstruction is assessed through energy migration matrices, showing good agreement between true and reconstructed energies for pointlike gamma rays (see left and middle panels of Fig. 2). We then evaluate the angular and energy resolution as a function of the true energy using a global gammaness cut of 0.9 (see right panels of Fig. 2 & 3).

The angular resolution is defined as the angular distance within which 68% of the reconstructed gamma-ray events fall, relative to the direction of the simulated point source of gamma rays. It is

[2] https://github.com/cta-observatory/dl1-data-handler

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computed in logarithmic true energy bins. Similarly, the energy resolution in each true energy bin is defined as the 68% containment of the distribution of $(E_{\rm reco} - E_{\rm true})/E_{\rm true}$. These results serve as a first step toward validating the applicability of CNN-based models for LST observations using waveform data as input.

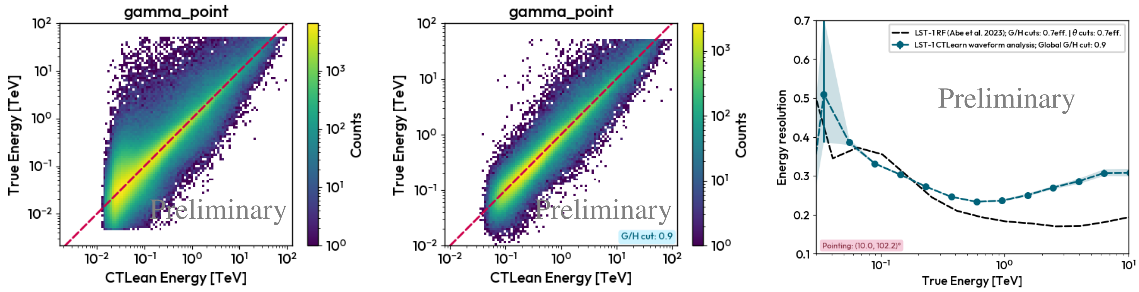

Figure 2: (**Left**): Energy migration matrix for pointlike gamma rays including all events with more than 50 PE. (**Middle**): Energy migration matrix for events passing an additional global gamma/hadron separation cut of 0.9. (**Right**): Energy resolution as a function of true energy for events passing an additional global gamma/hadron separation cut of 0.9. As a reference, the LST-1 performance [9] obtained with the Random Forest method is indicated as the dashed black line. The reference curve is shown only for illustrative purposes and should not be directly compared to our results, as the optimization of the analysis cuts differs between methods.

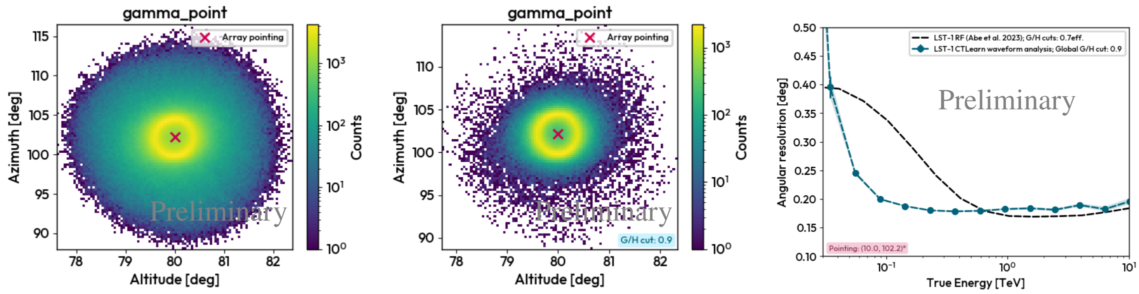

Figure 3: (**Left**): Sky map of reconstructed positions for pointlike gamma rays including all events with more than 50 PE. (**Middle**): Sky map of reconstructed positions for events passing an additional global gamma/hadron separation cut of 0.9. (**Right**): Angular resolution as a function of true energy for events passing an additional global gamma/hadron separation cut of 0.9. As a reference, the LST-1 performance [9] obtained with the Random Forest method is indicated as the dashed black line. The reference curve is shown only for illustrative purposes and should not be directly compared to our results, as the optimization of the analysis cuts differs between methods.

5. Discussions and conclusions

This work presents a proof-of-concept demonstrating for the first time that full event reconstruction (particle classification, energy estimation, and directional regression) can be achieved using IACT waveform data as input to CNNs. By leveraging the temporal structure contained in calibrated waveforms, our approach bypasses the need for traditional image parameterization, marking a significant step forward in the application of DL to low-level data products in the analysis chain

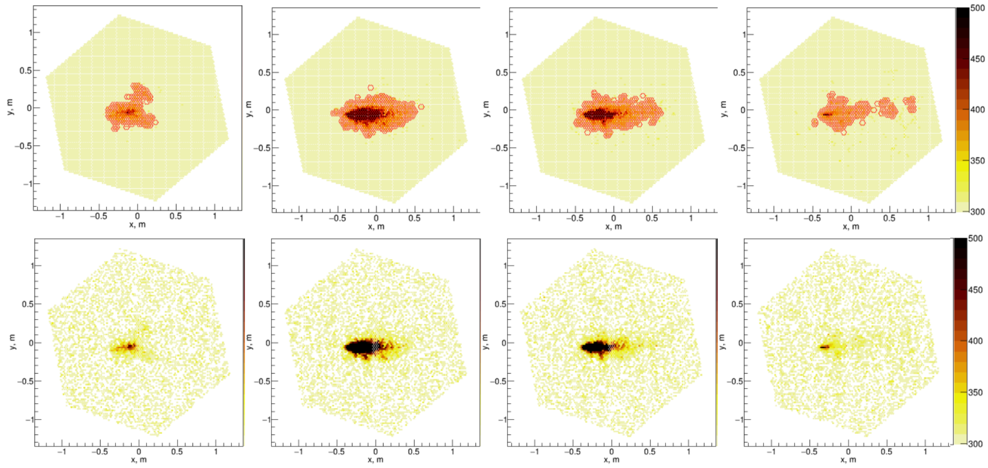

Figure 4: Four raw waveform samples with 3 nanosecond intervals for a bright 1.4 TeV gamma-ray event. The bottom panels show waveforms including night sky background noise, while the top panels display the pure Cherenkov signal. The red overlaid pixels indicate the mask detected by the DBSCAN-based cleaning algorithm at each waveform sample. The colorbar represents signal amplitude in ADC (Analog-to-Digital Converter) units.

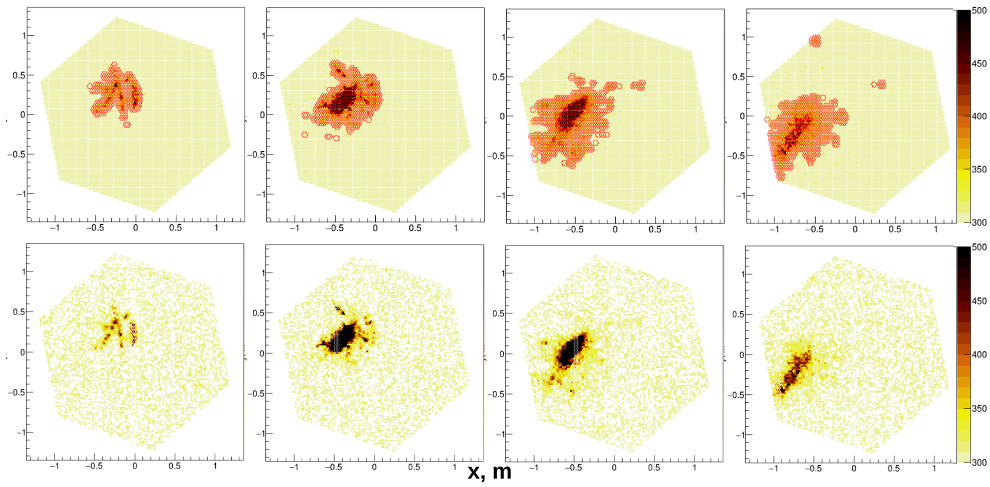

Figure 5: Same as Fig. 4, but for a bright 1.9 TeV proton event. Unlike the narrow, compact development of gamma-ray showers, the proton shower produces a much wider and more diffuse signal, reflecting the more complex hadronic interactions in the atmosphere.

of IACTs. However, due to the computational complexity and the time-intensive training process, spanning several weeks on high-performance hardware, we do not propose this waveform-based method as a replacement for the standard data processing pipeline used in routine IACT observations. Instead, we see its value in targeted analyses of scientifically significant or rare astronomical events, where a potential performance gain can justify the higher computational cost.

Despite the absence of a fair, one-to-one comparison, primarily due to differing optimization procedures, our proof-of-concept demonstrates that the performance achieved lies within the same bulk region as the conventional Random Forest-based analysis [9]. This indicates that our method

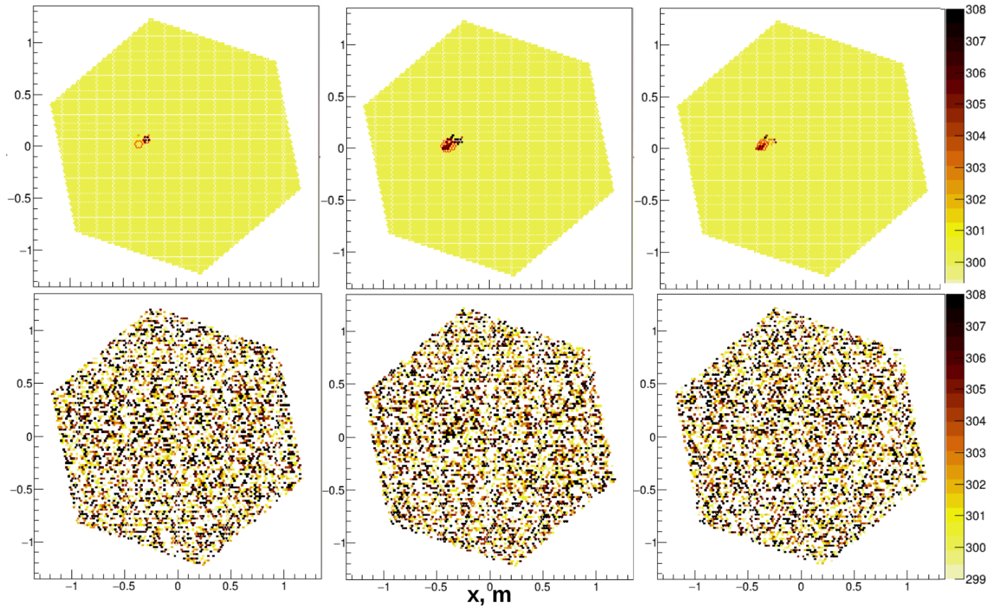

Figure 6: Three raw waveform samples with 2 nanosecond intervals for a faint 10 GeV gamma-ray event, where the signal is at the noise level but still captured thanks to the exploitation of temporal and spatial correlations.

holds strong potential and warrants further investigation, particularly with harmonized optimization strategies that would allow a more rigorous and direct comparison.

To further advance this framework, we are developing a waveform-based DBSCAN cleaning algorithm to replace the default cleaning stage of the standard IACT analysis. This unsupervised ML technique for waveform cleaning is being designed for the next-generation IACT cameras (AdvCam for LSTs [16] but is also applicable to current-generation IACT data. Figures 4 through 6 showcase preliminary results: Fig. 4 highlights a bright gamma-ray event, Fig. 5 a bright proton, and Fig. 6 a faint gamma-ray event of 10 GeV. These examples demonstrate the algorithm's ability to exploit temporal-spatial correlations in the waveform data, enabling the detection of faint events at noise levels that would likely be suppressed by conventional cleaning methods.

This waveform-based reconstruction method also opens the door for implementing advanced AI-driven trigger systems, as proposed to be integrated for the next-generation AdvCam cameras [17]. By directly analyzing the raw, time-resolved signals with DL models, it becomes feasible to identify and classify events in real time with high accuracy, potentially improving trigger efficiency and reducing background rates. Such AI-trigger systems could significantly enhance the sensitivity and responsiveness of future IACT arrays, making this approach a promising direction for the evolution of gamma-ray astronomy instrumentation.

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