（別紙様式２）

フォトンサイエンス国際卓越大学院プログラム（XPS）

光科学特別実習　報告書

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The Cherenkov Telescope Array (CTA) will be the next-generation atmospheric Cherenkov telescope array that will be observing very-high-energy gamma rays with unprecedented sensitivity. CTA is composed of three kinds of telescopes with different sizes. Among them, Large-Sized Telescopes (LSTs) play an essential role for achieving a low energy threshold. The first LST (LST-1) has been commissioned since its inauguration in 2018, and now it is moving towards scientific observations.

I have been working on calibration of the LST-1 camera since I joined the CTA collaboration. The LST-1 camera is composed of 1855 photomultiplier tubes (PMTs) with high quantum efficiency (QE). PMT signals are sampled at 1 GHz by Domino Ring Sampler version 4 (DRS4) chips and digitized by an analog-to-digital converter (ADC). The camera readout has two channels with different amplification, high gain (HG) and low gain (LG) channels, so that the wide dynamic range 1 photoelectron (p.e.) to 3,000 p.e. is covered. We have developed a camera calibration chain for LST-1 data analysis as part of the LST analysis pipeline. The calibration chain performs DRS4 pedestal corrections, absolute charge calibration by the so-called F-factor method and signal reconstruction.

This time I have attended the 37th International Cosmic Ray Conference (ICRC), which is one of the largest international conferences in the field of cosmic ray research, and presented our contribution “Camera Calibration of the CTA-LST prototype” on behalf of the LST-1 camera calibration team. The conference was held online, and I prepared materials such as proceedings, a poster and a recorded flash talk, cooperating with my colleagues. In the ICRC contribution, we have presented the status of the LST calibration chain and the performance obtained with it. The conference was meaningful, and I could interact with other researchers and exchange information. Fig. 1 is a snapshot of my flash talk where I was explaining our contribution. Below I would like to introduce briefly the contents of the contribution.

The first step of the camera calibration is the DRS4 pedestal corrections. DRS4 chips have intrinsic pedestal characteristics which should be corrected by analysis for minimizing pedestal noise in readout waveforms. The major characteristics to be corrected are offset of individual capacitors, dependence of offset on time since the last reading of the capacitor, and spikes which are jumps of offset values for particular capacitors under certain conditions. Our calibration chain deals with all of these systematic effects. We have checked pedestal distribution after each step of the corrections, and confirmed the corrections are working well. Average pedestal noise after all the corrections is 5.6 ADC count in HG channels and 3.4 ADC count in LG channels. This is compatible with 0.2 p.e. in HG and 3 p.e. in LG.

Absolute charge calibration, i.e., conversion of signal integrated charge in ADC counts to the number of p.e. produced by light pulses in each PMT, is obtained with the F-factor method. This is based on flat-field events achieved by the uniform illumination of the camera with the diffused light emitted by a laser placed in the center of the telescope mirror dish. The number of p.e. detected with each PMT is estimated by analyzing the first and the second order moments of the charge distribution in a high-intensity regime (80 p.e./pulse). We have applied the method to the LST-1 calibration data and confirmed both the HG and LG channels give equivalent results. We have also seen the higher number of p.e. for the inner part of the camera, which reflects the PMT sorting based on QE.

In order to examine performance of signal reconstruction by the calibration chain, charge and time resolution for the flat-field events have been evaluated. A set of flat-field runs with different light intensities is analyzed to obtain performance at each signal amplitude. Charge and time of signals are reconstructed by pulse integration with 8 ns time window around the pulse peak. Consistency with Monte Carlo (MC) simulation is also checked.

The charge resolution is evaluated as the relative root-mean-square error, which includes charge reconstruction bias. Fig. 2 shows the evaluated relative RMSE for both the data and MC simulation with comparison to the CTA requirements. We confirm the results meet the requirement at most of the intensities. The slight violation at the lowest intensity can be due to the bias by charge extraction with pulse peak search. Note that when reconstructing Cherenkov photons, the bias could be suppressed because the position of the pulse integration window can be determined based on overall time evolution of air showers. The data and MC simulation is basically consistent, and the worse resolution in the data above ~1,000 photons can be explained by systematic uncertainties which are specific to the data, such as uneven sampling interval of the DRS4 chips.

The time resolution is evaluated as the width of a gaussian fitted to the distribution of the reconstructed pulse time. The time resolution is obtained at each pulse amplitude bin, and dependence on the amplitude is fitted by a function allowing for Poissonian, linear and constant contributions. From the fit, we compute the time resolution for each pixel at 5 p.e. The differences from one pixel to another are not large, and a typical resolution is 0.95 ns. The LST-1 camera must fulfill a CTA requirement that the root mean square difference in the reconstructed signal arrival time for any two simultaneously illuminated pixels with amplitudes of 5 p.e. must not exceed 2 ns. This is roughly equivalent to the standard deviation of arrival times at each pixel to be below 1.3 ns. Thus, the requirement is fulfilled for all the pixels. Applying the same procedure at MC simulation we obtain a slightly higher value of 1.2 ns time resolution. The difference is much smaller than the size of the extraction window and typical time threshold for analysis of shower images, hence its effect on the final analysis is expected to be small.

In conclusion, we have developed the camera calibration chain for LST-1 data analysis and evaluated its performance. All the calibration steps are confirmed to be working fine. As for the signal reconstruction performance, we have evaluated both the charge and time resolutions based on flat-field events and confirmed that they basically meet the CTA requirements. We conclude that the calibration chain is ready for analysis of the LST-1 observational data.

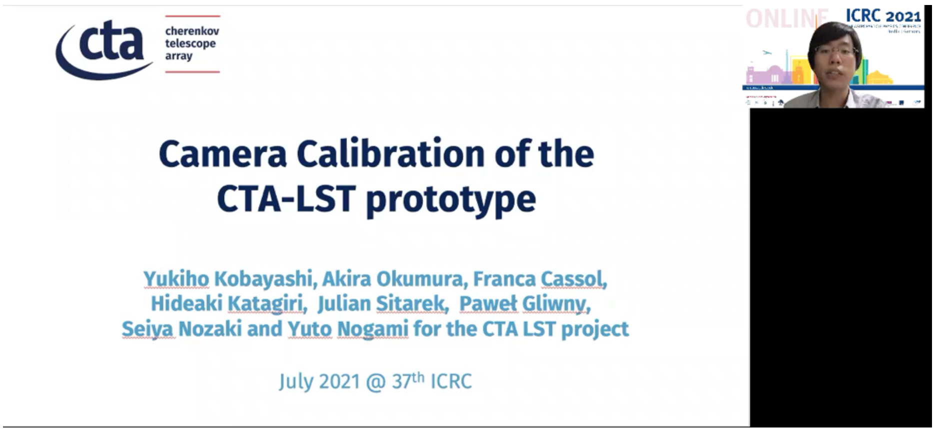

Figure 1: A snapshot of my flash talk submitted to the conference.

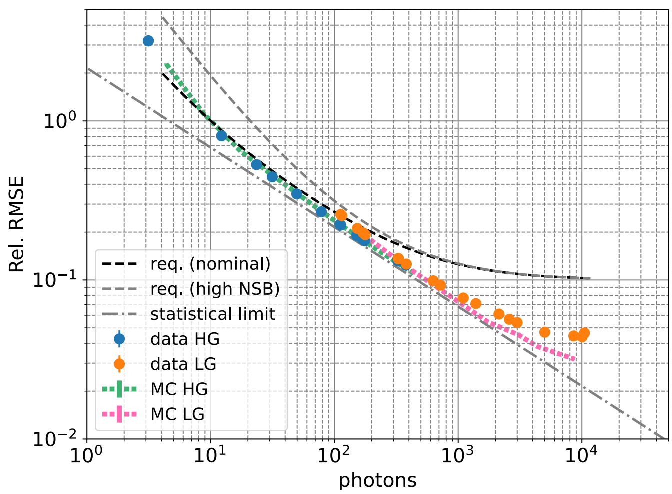

Figure 2: The charge resolution evaluated as relative root-mean-square error (RMSE).