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First Science Results from CTA LST-1 Telescope and status of LST-2-4

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The prototype Large-Sized Telescope (LST-1) of the Cherenkov Telescope Array (CTA) was inaugurated on La Palma, Canary Islands, in 2018. Since then, the telescope is in the commissioning phase and takes regular gamma-ray data on astrophysical sources while waiting for other CTA telescopes in La Palma to be constructed. Here we present the status of the commissioning, lessons learned, the telescope performance, and scientific highlights achieved in the last couple of years. The science results include the detection of active galactic nuclei flares, studies of pulsar wind nebulae and pulsars, the detection of a Nova, and searches for gamma-ray emission from gamma-ray bursts. We also present the status of the construction of the three further LST telescopes (LST-2-4) in La Palma and plans for their commissioning.

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[*] Speaker

Figure 1: Photograph of the LST1 telescope in La Palma during the inauguration in October 2018. Courtesy of Tomohiro Inada.

1. Introduction

Cherenkov Telescope Array (CTA) is the next generation worldwide observatory built on two sites: La Palma, Spain, in the northern hemisphere and Paranal, Chile, in the southern hemisphere. CTA will consist of arrays of Imaging Atmospheric Cherenkov Telescopes (IACTs) of different sizes, optimised for different energy ranges within the very-high-energy (VHE, $E > 20\,\mathrm{GeV}$) band. The largest IACTs of the array will be the Large-Sized Telescopes (LSTs), see Figure 1, with a focal length of 28 m and a parabolic mirror dish of 23 m diameter. LSTs target the lowest energies accessible to CTA, down to a threshold energy of $\simeq$20 GeV. For general CTA status and plans see [1].

LST-1, the first LST, is located in the CTA North site, at a height of 2200 m a.s.l. on the Roque de los Muchachos Observatory (ORM) on the Canary Island of La Palma, Spain (28°N, 18°W). The first LST-1 sky observations took place in December 2018, while regular LST-1 observations began in November 2019.

This paper is structured as follows. In Section 2 we describe the LST project. The performance of LST-1 as well as highlights of the early physics results are outlined in Section 3. The status of the LST-2, LST-3 and LST-4 construction is given in Section 4, while we conclude in Section 5. Details on the planning for LSTs for CTA South can be found in [2].

2. LST project

The LST project for CTA has been developed since 2006 under leadership of MPI for Physics in Munich, ICRR at the University of Tokyo, CIEMAT Madrid, IFAE Barcelona, INFN Pisa, INFN Padova, and LAPP in Annecy. Over the years the project grew and currently it consists of about 30 institutes from 11 countries: Brazil, Bulgaria, Czech Republic, Croatia, France, Germany, Italy, Japan, Poland, Spain, and Switzerland with more than 400 scientists and engineers involved. The telescope design is focused on two major aspects: (1) the fast repositioning of the telescope for reaction to transient phenomena, and (2) high sensitivity to gamma rays at lower edge of the VHE range. In fact, in the CTA design [1] LSTs cover the low energy end, dominating the CTA performance between 20 GeV and ~200 GeV, once the full CTA array is deployed. Without the full CTA array built the four LSTs will provide an excellent gamma-ray flux sensitivity up to energies of tens of TeV.

In order to achieve the desired performance, LST has a light-weight structure, parabolic dish, and a power system based on 2x300 kW VYCON FlyWheels to allow for the fast rotation to catch transient events like Gamma-Ray Bursts. LST is an alt-azimuth telescope, the parabolic reflective surface is supported by a tubular structure made of carbon fiber and steel tubes. The total moving weight of the telescope (excluding the rail) is around 100 tons. A reflective surface of ~400 m^2 is made of 198 mirror segments, which can be aligned independently using an Active Mirror Control (AMC) system, consisting of two actuators per mirror to compensate for small dish deformations at different zenith angles. The optical dish collects and focuses the Cherenkov photons into the camera, where 1855 photosensors convert the light in electrical signals that can be processed by dedicated electronics. The camera has a field of view of about 4.5° and has been designed for maximum compactness and lowest weight, cost and power consumption. Each pixel incorporates a light guide, a photo-sensor and the corresponding readout electronics. The electronics is based on the DRS (Domino Ring Sampler) chip [3]. The camera trigger strategy is based on the shower topology and the temporal evolution of the Cherenkov signal produced in the Camera. The analogue signals from the photosensors are conditioned and processed by dedicated algorithms that look for extremely short (few ns) light flashes. Furthermore, the LST Cameras have a hardware trigger connection in order to form an on-line coincidence trigger among the telescopes, which allows to suppress accidental triggers by up to a factor of $\approx$100.

The LST-1 was built on La Palma between 2016 and 2018 as a CTA prototype telescope and it was inaugurated in October 2018. Since then, LST-1 is in commissioning phase performed by the LST project members, and regular data taking is being performed starting from November 2019.

3. LST-1 performance and early physics results

The performance of LST-1 was studied extensively over several years by following the specially prepared commissioning procedure and by taking data on known gamma-ray emitters. Also, thanks to the presence of the two MAGIC telescopes next to LST-1, a cross-calibration between the instruments is possible, as well as joint data taking campaigns. To evaluate the achieved physics performance, a data set comprising of 48.0 hours of Crab Nebula data taken in dark conditions between November 2020 and March 2022 has been used and is reported in [4, 5]. An

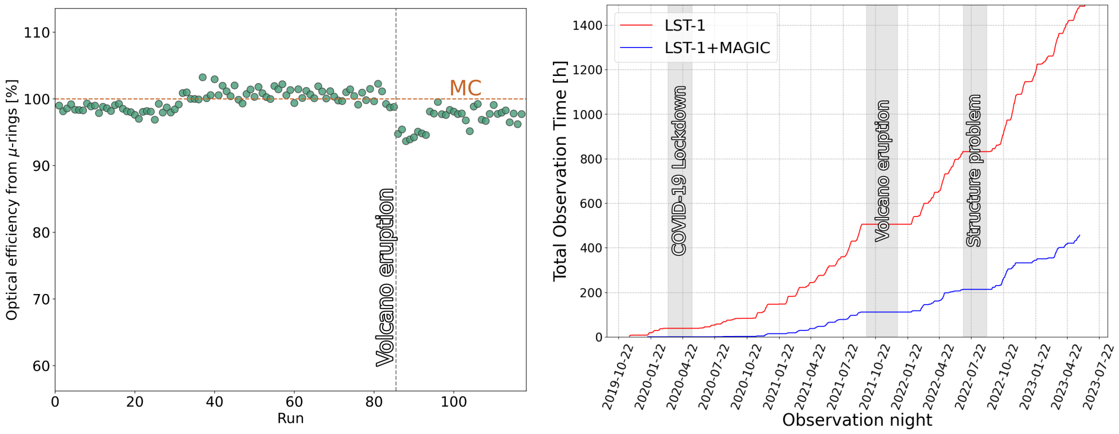

Figure 2: Left: run-wise LST-1 optical efficiency derived using muon ring intensity, for the sample of good-quality Crab Nebula observations. Right: data taken with LST-1 since Januray 2020 altogether (red) and those jointly with MAGIC (blue).

excellent agreement between the data and Monte Carlo (MC) simulations was found. The telescope performance in terms of the optical throughput, energy threshold and flux sensitivity was also found to be stable over time. The optical throughput obtained using an analysis of muon ring images recorded by LST-1 is shown in Fig. 2, left plot. One can see that the optical throughput is stable on a level of a few percent, with the exception of the time after the volcano eruption in La Palma. The Cumbre Vieja volcano (which was later called Tajogaite) erupted on September 19, 2021 and was active until December 13, 2021. It was the longest eruption of a volcano in La Palma in the recorded history of the last 500 years. The eruption caused a large damage on the island with almost 10% of the island infrastructure destroyed, leaving thousands of people without their homes. The ORM observatory, located around 15 km from the volcano, was largely on hold for the time of the eruption. During that time, we protected many sensitive parts of the LST-1 telescope by covering them, while the mirrors, due to their very large area, remained uncovered. Several occasions of volcano ash deposits on the mirrors took place. The mirror performance degraded after the restart of telescope operation in February 2022 but the mirrors recovered their reflectivity after a period of rain, which washed the volcanic ash from the mirrors.

Fig. 3, left plot shows the comparison in distribution of the parameter *Width* between data taken from the Crab Nebula and MC simulations. The distribution of gamma-like excess events from the Crab Nebula (marked as Data access) is compared with the one from MC gamma rays (marked as gamma MC). The good agreement is evident. For comparison, hadron-like events (marked Data Off) are also shown. The flux sensitivity obtained from the Crab Nebula data set is shown in Fig. 3, right plot. The sensitivity is shown for two different analysis chains: one with an assumption of the source position (so-called source dependent analysis) and the other one without this assumption (so-called source independent analysis). The sensitivity is computed for both analysis chains for two different assumptions: one requiring a minimum gamma-like excess of at least 5% of the remaining background and the other one without this requirement (labeled "without 5% background"), i.e.

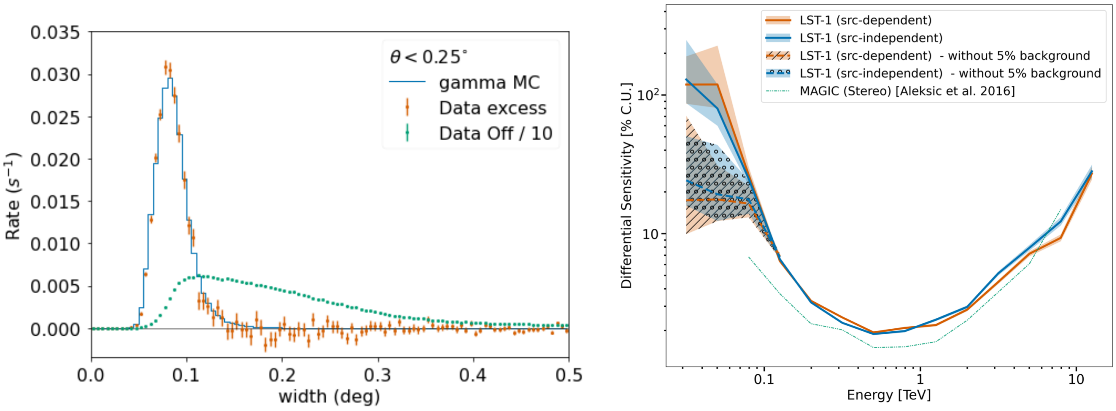

Figure 3: Left: Comparison between gamma-ray excess data and MC simulation for the Width parameter. Right: Differential sensitivity of LST-1 telescope.

the sensitivity is calculated using a 5-σ excess criterion only. It can be clearly seen that at lowest energies the 5% background criterion is the limiting factor in the telescope performance. At the lowest gamma-ray energies the suppression of the background is thus the main focus of the analysis, which is expected to be drastically improved with the construction of more telescopes. More details on the LST-1 telescope physics performance can be found in [4].

Several other astrophysical sources have been observed with the LST-1 telescope. The targets are either known gamma-ray emitters or those where one expects to find a gamma-ray signal. The accumulated hours of data taken, at any sky position since January 2020, is shown in Fig. 2, right plot by a red line. Overall, more than 1500 hours of data has been accumulated between January 2020 and June 2023. The blue line shows the number of accumulated hours of joint data with the MAGIC telescopes. The combination of LST-1 data and data obtained with the MAGIC telescopes on same targets simultaneously offers a better flux sensitivity and an improved performance due to the stereoscopic shower reconstruction. Details on the combined performance achieved can be found in [6]. Using the LST-1 data analysis chain (see [4] for details and in this conference [5]) a significant signal was detected from several known gamma-ray sources (AGNs, PWNs, the Galactic Center, pulsars) as well as from Nova RS Ophiuchi. Results of observations from the gamma-ray source LHAASO J2108+5157 can be found in [7]. Several other publications in refereed journals are being prepared and we expect to submit them in the next several months. Some of the results are presented in this conference: BL Lac flare [8], AGN observations [9], observations of RS Ophiuchi [10], the Galactic Center [11, 12], and pulsars [13]. Performanace of the real time analysis of the LST-1 data is shown at this conference in [14]. Details on the implementation of the hardware stereo strigger betweeen MAGIC and LST can be found in [15], and optimization of the trigger strategy on the IceCube alerts in [16]. Progress towards LST cameras based on Silicon photomultipliers are discussed in [17, 18].

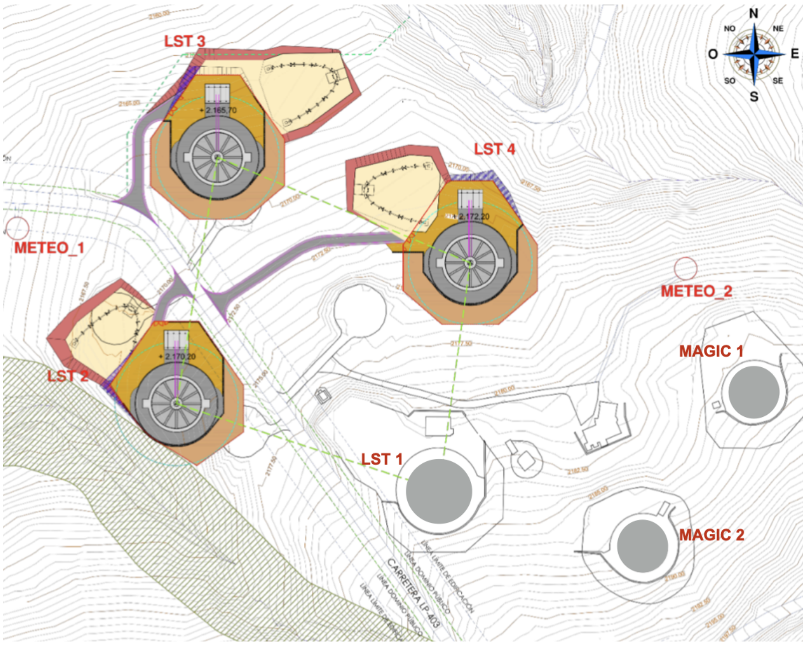

Figure 4: The LST-2-4 civil work construction plan. Credits: Instituto de Astrofísica de Canarias.

4. LST-2 – LST-4 status

The funding for the CTA LST-2, LST-3 and LST-4 has been secured in years 2017–2020. The lessons learned from the LST-1 construction have been retrofitted into the procurement and installation plan. In particular, wind shedding had to be improved on several long tubes of the telescope dish to avoid them from strong vibrations. Also, a high attention is given to the quality control during the civil works execution.

The three telescopes have been procured in years 2017–2023 by the members of the CTA-LST project. The area plan of the construction can be seen in Fig. 4. The telescopes are shown together with the corresponding assembly area for the camera access tower and the camera support structure. The assembly areas will be renaturalized after the telescope construction is finished. The schedule foresees the end of the civil works in Q3 2023 and the telescope erection in years 2024-2025, which will be performed almost in parallel. We expect to finalize the LST-2-4 assembly, integration and verification phase in 2025-2026 and deliver the telescopes to the CTA observatory soon after.

The civil works for the LST-2-4 telescopes, i.e. the construction of the telescope foundations and as well as the necessary power and data infrastructure, is led by the Instituto de Astrofisica de Canarias (IAC) and started in November 2022. As of June 2023 the progress of the civil works is quite advanced and the works are expected to finish in August 2023. In Fig. 5 one can see the status of the LST-4 foundation as of beginning of June 2023. The erection of the LST-2-4 telescopes is a common effort by the CTA-LST project members and the coordination of works is shared between IAC and the LST management. The commissioning phase of the telescopes will be coordinated by the LST management and we expect an integration of the LST telescopes into the CTA array in 2026.

Figure 5: Status of the civil works at the LST-4 site, as of June 2023. Courtesy by Javier Herrera (IAC).

5. Conclusion and Outlook

The prototype CTA LST-1 telescope began commissioned in La Palma starting at the end of 2019. The physics performance obtained with the telescope is shown to be very good. Last steps of the telescope verification are under way and are expected to be finalized by the end of 2023. At the same time, several early physics results are being achieved with this CTA prototype telescope. The construction of the other three LST telescopes in La Palma started in November 2022 with the start of the civil works and is expected to finish by the beginning of 2026. The construction is being executed without significant delays so far.

Acknowledgements

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