PROCEEDINGS OF SCIENCE

Status of the LST project

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Thanks to their large reflectors and improved photon collection efficiency, the Large-Sized Telescopes (LSTs) of the Cherenkov Telescope Array (CTA) target the lowest gamma-ray energies observable from the ground, down to 20 GeV. A four LST sub-array is currently under construction at the CTAO-North site of La Palma (Spain). The first LST, LST1, in fact was already inaugurated in 2018. I report on the progress of the LST project in general and review the early science that LST1 is delivering during its commissioning phase.

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1. Introduction to the project

CTA[1, 2] will consist of two arrays of Imaging Atmospheric Cherenkov Telescopes (IACTs) in the northern and southern hemispheres. CTAO-North will be located at the Roque de los Muchachos observatory (La Palma, Spain) and CTAO-South at Cerro Paranal (Chile). The CTA IACTs will have mirrors of three different sizes optimised for overlapping energy ranges. The sub-arrays of Large-Sized Telescopes (LST) at CTAO-North and CTAO-South will be equipped with the largest mirrors and target the lowest energies down to an energy of ~20 GeV.

Major physics drivers in the LST energy range are transients (both galactic and extragalactic), pulsars and studies of the Extragalactic Background Light. One of the key goals of the project is the study of the short-lived prompt emission of Gamma Ray Bursts (GRBs). Consequently the telescope has a very low weight to allow repointing by 180° in azimuth and 90° in zenith in less than 20 seconds.

The CTA LST sub-consortium that is responsible for the design and deployment of the LSTs consists of 430 scientists and engineers from twelve countries: Brazil, Bulgaria, Croatia, Czech Republic, France, Germany, India, Italy, Japan, Poland, Spain and Switzerland[1].

LST is an alt-azimuth telescope with a mirror diameter of 23 m. The LST team completed the design of the telescope in 2015. The parabolic reflective surface is supported by a space frame 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 facets, which can be aligned using an Active Mirror Control (AMC) system: each facet is equipped with two actuators to compensate for small dish deformations when the telescope changes zenith angle. The optical dish collects and focuses the Cherenkov photons onto a camera focal plane, where a camera of 1855 photomultipliers convert the light into 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 and a photo-sensor. A 7-pixel module incorporates the readout electronics, which are based on the DRS4 chip[2], and trigger electronics, which are based on the shower topology and the temporal evolution of the Cherenkov signal produced in the pixels. In addition, the LST cameras in each array will have a hardware trigger connection in order to form an on-line coincidence trigger among the telescopes. More details of the LST technical design can be found elsewhere[3, 4].

2. Status of LST1 and first scientific results

The first LST (LST1) is also a prototype. However, this prototype is fully equipped and is meant to become a a final element of the CTAO-North array once it is validated. The next LSTs will follow the design of LST1 with any required modifications.

The LST1 foundation was built between July 2016 and January 2017. The full telescope, including mechanical structure, mirrors and camera, was put in place in only 15 months, ending with the official inauguration of the telescope on October 10, 2018. Figure 1 shows a picture of the telescope.

[1]see a full institution list at *http://www.lst1.iac.es/collaboration.html*
[2]https://www.psi.ch/en/drs

Figure 1: A picture of LST1 during its inauguration event in 2018.

LST1 is still under commissioning. This phase has been delayed due to the Covid-19 pandemic and the 3-month long volcano eruption at La Palma in 2021. The data-taking duty cycle still remains around 80%, mainly because the operation relies on non-professional operators, because the hardware is still going through minor upgrades and because the control software is not fully debugged. However, the telescope has already taken hundreds of hours of technical tests and ~800 hours of scientific data.

2.1 LST1: performance

The performance of the telescope will be the subject of an article that is about to be submitted for publication[5]. Let us review some of the key parameters that have been evaluated.

The analysis of IACT images to reconstruct the properties of the shower primary (particle nature, energy and direction) relies on detailed Monte Carlo (MC) simulations both of the shower development and of the telescope. Simulated events allow us to train the event reconstruction algorithms to be used on the real data. The same algorithms are also applied to an independent MC sample ("test" sample), from which the instrument response functions (IRFs) can be derived.

The optical efficiency in the MC is tuned to the real optical efficiency of the telescope obtained through the analysis of muon rings. The light collection efficiency of the telescope from November 2020 to March 2022 is shown in Fig. 2. As one can see, it has remained stable at the ~5% level. This parameter takes into account the transmission in all optical elements of the telescope and the mirror focusing. The observed variations can be attributed to measurement uncertainty and episodes of dust deposition (dust on our mirrors can only be cleaned by rain). As one can see in the same plot, there has been no long-term effect of volcanic ash deposition.

Fig. 3 shows the most relevant IRFs of LST1, namely the angular and spectral resolution along with the effective collection area. LST1 is a single telescope so one cannot expect to reach a

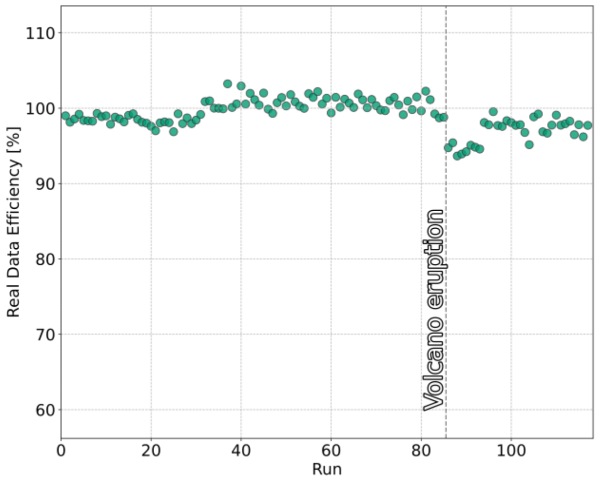

Figure 2: Optical efficiency of LST1 from November 2020 to March 2022 (preliminary). The uncertainty in the values is around 2% and can bring the efficiencies above 100%

performance comparable to a stereo array in terms of spectral or angular resolution. However these two parameters are already competitive to current IACT arrays below 100 GeV. It is also worth mentioning that the effective area is >1000 m^2 down to 20 GeV.

A total of 57.2 hours of Crab Nebula data with <35° zenith angle were collected between November 2020 and March 2022. Data were taken in so-called "wobble mode".

During this period, the telescope was in its commissioning phase, and different trigger settings were tested. In consequence the trigger threshold of the telescope was not stable. The trigger threshold in the MC simulations was set to the lowest value found in the data (20 GeV, which increases to ~30 GeV after analysis cuts).

We have used Crab Nebula observations to validate the MC simulation. We have compared the distributions of image parameters for the simulated γ-ray images and for the γ-ray excess recorded from the direction of the Crab Nebula.

In the distribution of the θ^2 parameter (squared angular distance between the reconstructed event directions and the direction of the source), one can see that the MC distributions are generally narrower than those of real data. The difference becomes more noticeable as the energy increases and angular resolution improves. It is consistent with a gaussian pointing uncertainty of σ=1.5 arcmin in each axis. This is much smaller than the angular resolution achieved even for the highest energy, so has no impact on the scientific results. We expect most of this discrepancy to disappear once we implement offline pointing corrections. The "gammaness" parameter, derived from a set of shower image parameters, is used to discriminate γ-rays from cosmic rays. A good agreement between Crab data and MC simulation is observed for gammaness and, as expected, from all individual shower image parameters.

The sensitivity of LST1 has been calculated and compared with the MAGIC two telescope array. As expected from a single telescope, above 100 GeV, MAGIC has a factor 1.5 better sensitivity

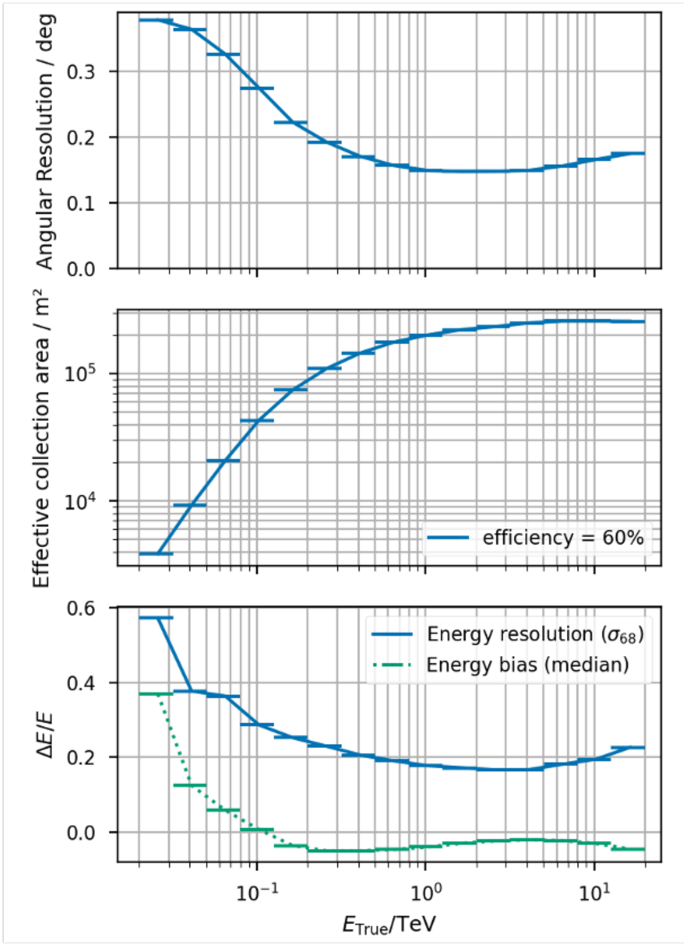

Figure 3: Angular resolution (upper panel), effective collection area (middle panel) and spectral resolution (lower panel) of LST1 as a function of energy (preliminary). The γ-ray incident angle is 10 deg and the detection efficiency is set to 60% via selection on how gamma-like the image is.

in average although LST1 exhibits a lower threshold.

LST1 and MAGIC are at a short distance so one can combine data taken simultaneously. An additional study for these data will be the subject of a future publication. Preliminary results indicate that combining the three telescopes increases the sensitivity compared to the MAGIC-standalone array by roughly 50%.

2.2 LST1: first scientific results

Fig. 4 shows the spectral energy distribution (SED) of the Crab Nebula. It is consistent with previous measurements of MAGIC (shown in the same figure) and *Fermi*-LAT. The lowest energy point is at around 25 GeV.

As a subproduct of the Crab Nebula analysis, we have extracted the phaseogram of the Crab pulsar. Both P1 and P2 peaks are significantly detected and they have similar amplitude for the full data sample, which is consistent with an energy threshold well under 50 GeV. The calculation of the pulsar spectrum requires a more detailed analysis and will be the subject of a future publication

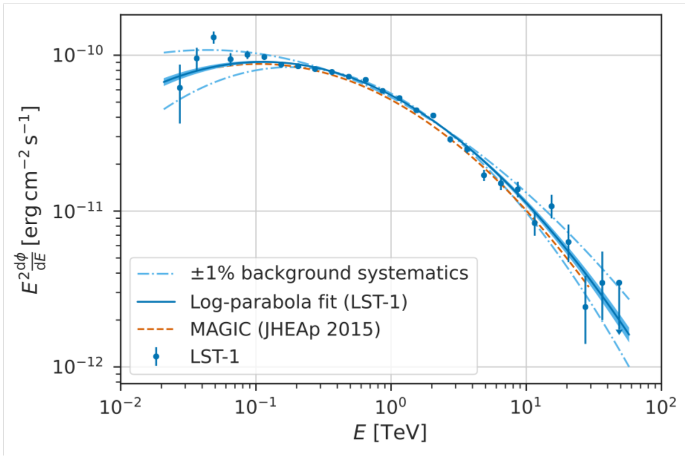

Figure 4: SED of the Crab Nebula as measured with LST1 (preliminary), in comparison with the same spectrum measured with MAGIC.

We observed RS Oph, the first nova detected at VHE, roughly 1 day after its onset. A clear detection, along with a spectrum and a light curve, have been reported at the conference[6]. LST1 is able to provide spectral points starting at the energy where the Fermi-LAT spectrum ends.

We have also studied the region around the PeVatron LHAASO J2108+5157 detected by LHAASO. This source is point-like in LHAASO and our goal was to use our significantly better angular resolution to identify a counterpart. An analysis of XMM data and 91 hours of LST1 observations shows no detection but upper limits point to hadronic acceleration. These results were presented at the conference[7] and have been submitted for publication.

The blazar BL Lac had been in a high emission state since 2020. LST1 observed it during the summer of 2021. A major flare of BL Lac was reported as an astronomical telegram (the first with a CTA telescope) in July 2021. On August 8th 2021, its gamma-ray flux was above 1 Crab unit for E<300 GeV. Its soft spectrum makes it possible to extract a spectral point at 30 GeV even for a <2 hour observation.

3. Next developments

3.1 Next three telescopes at CTAO-North

Essentially all parts for the three remaining LSTs to be deployed at CTAO-North (LST 2-4) are manufactured and ready for installation. Two of the cameras are going through verification tests, while the last one should finish production in March 2023. Only few other parts missing, e.g. the AMC actuators, which are now going through production and validation.

The installation at the site has been delayed because the local administration at the island have taken years to issue the construction permits, on one hand due to the introduction of a new administrative procedure and, on the other one, to the volcanic eruption. The permit was finally issued in September 2022. Civil works started in November 2022.

In the updated schedule, the mechanical installation should start in August 2023 and the last camera should be installed by mid-2025. The three telescopes should be validated at the beginning of 2026.

3.2 LSTs at CTAO-South

So far the construction of LST was limited to the northern array due to funding constraints. However Italy (INAF and INFN) is bringing additional funding to install two full LSTs in CTAO-South, with a possible extension to three LSTs if other funding sources are available in the short term. Adding LSTs in the south will widen the energy range down to few tens of GeV, thus increasing the reach in redshift of the array and the sensitivity to low-energy transients.

There is a significant funding constraint, namely that production of the telescope components should take place before the end of 2025. In these circumstances the telescopes in the south will follow a very similar design to the ones in the north. This may prove challenging because the telescope structure needs to be reinforced to withstand the accelerations expected for earthquakes at the specific location of the LSTs in the array.

3.3 Advanced SiPM cameras

CTA telescopes are required to operate for 30 years. However, since technology in photodetection and fast electronics evolves fast, the cameras are expected to be replaced in 15 years. This is not far into the future, considering that the first camera started to operate in 2018.

A significant effort is under way to replace PMTs with Silicon PMs as photodetectors. SiPMs would provide a significant increase in photodetection efficiency (PDE), i.e. lower energy threshold, and should show no degradation in performance with time even for high levels of night sky background (NSB). This advanced SiPM camera would probably be equipped with 4 times more pixels, which would improve its angular resolution. The specific SiPM model and camera architecture are currently being selected.

Acknowledgements

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