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The Cherenkov Telescope Array Observatory Comes of Age

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The Cherenkov Telescope Array (CTA) is the next-generation ground-based observatory for gamma-ray astronomy at very high energies. With up to 120 telescopes on two sites, CTA will be the world's largest and most sensitive high-energy gamma-ray observatory covering the entire sky. It will consist of a northern array located at the Roque de los Muchachos astronomical observatory on the island of La Palma (Spain) and a southern array near the European Southern Observatory site at Paranal (Chile). Three classes of telescope spread over a large area are required to cover all of CTA's very-high-energy range from 20 GeV to 300 TeV.

Conceived around a decade ago by a group of scientists, we are now on the cusp of constructing the largest observatory to study the gamma-ray Universe. Here we present a short look back at the evolution and recent maturation of the CTA project, as well as an outline of our expectations for the near future. A comprehensive introduction to CTA, including the detection technique, its history, the extraordinary improvements with respect to previous experimental facilities, and the scientific objectives has been provided by Werner Hofmann, Spokesperson of the CTA Consortium (Hofmann, 2017).

Conceiving the Cherenkov Telescope Array

Ground-based gamma-ray astronomy is a young field with enormous scientific potential. The possibility of astrophysical measurements at teraelectronvolt (TeV) energies was demonstrated in 1989 with the detection of a clear signal from the Crab nebula above 1 TeV with the Whipple 10-m imaging atmospheric Cherenkov telescope (IACT). Since then, the instrumentation for, and techniques of, astronomy with IACTs have evolved to the extent that a flourishing new scientific discipline has been established, with the detection of more than 150 sources and a major impact in astrophysics — and, more widely, in physics. The current major arrays of IACTs (the High Energy Stereoscopic System [H.E.S.S.], the Major Atmospheric Gamma Imaging Cherenkov Telescope [MAGIC], and the Very Energetic Radiation Imaging Telescope Array System [VERITAS]) have demonstrated the huge potential for studying the physics at these energies as well as the maturity of the detection technique. Many astrophysical source classes have

Figure 1. Distinguished guests and stakeholders in the LST project participate in a traditional Japanese ribbon-cutting ceremony at the inauguration of LST-1 on 10 October 2018.

A. Okumura

Figure 2. The CTA Observatory (CTAO) consists of two array site locations — one in Chile and one on La Palma — and three office locations — the CTAO Headquarters (interim) and Science Data Management Centre in Germany and the local office (and future site of the headquarters) in Italy.

been established, some of them now including many well-studied individual objects.

It was a little over a decade ago that a group of scientists first gathered to begin planning the next-generation gamma-ray instrument. And while CTA's instrumentation is very much an evolution of the proven IACT technology of its predecessors, it is vastly expanding the range and scale, enabling us to see the Universe at the highest energies with unprecedented accuracy and sensitivity. This will be accomplished with two arrays (one near ESO's Paranal Observatory in Chile and the other on the island of La Palma, Spain) of up to 120 telescopes of three different types: the Small-Sized Telescope (SST), the Medium-Sized Telescope (MST) and the Large-Sized Telescope (LST).

Between 2008 and 2018, a massive amount of work by collaborations around the world was carried out, both on the scientific and technical fronts. This covered, in particular, the development of the telescope prototypes, cameras and mirrors, and resulted in a virtual menu of finely built operating telescopes for CTA. During this time three different SST designs started to demonstrate their astronomical qualities:

– SST-1M: A single-mirror Davies-Cotton design prototype in Krakow, Poland — from a Czech, Irish, Polish and Swiss collaboration.
– SST-2M GCT: A dual-mirror Schwarzschild-Couder design prototype in Paris, France — from an Australian, Dutch, French, German, and Japanese collaboration.
– SST-2M ASTRI: A dual-mirror Schwarzschild-Couder design prototype on Mount Etna in Italy — from a Brazilian, Italian and South-African collaboration.

The MST prototype is a single-mirror Davies-Cotton telescope installed in Zeuthen, Germany, developed by a large collaboration involving scientists and engineers from Austria, Brazil, the Czech Republic, France, Germany, Italy, Poland, Spain and Switzerland. Meanwhile, an alternative mid-sized prototype, based on the dual-mirror Schwarzschild-Couder design, was conceived and developed by the US, Germany, Italy, Japan and Mexico. A prototype was inaugurated at the Whipple Observatory in Arizona in 2018.

The LST prototype had a different evolution. Conceived and developed by a large collaboration of institutes — from Brazil, Croatia, Germany, France, India, Italy, Japan, Poland, Spain and Sweden — the prototype was constructed on the CTA-North site. The prototype, named LST-1, was inaugurated in 2018 and has since been undergoing commissioning. This is the first telescope to be installed on a CTA site for the moment and, as such, will eventually become the first "champion" of the CTA Observatory (CTAO).

After 12 years of gestation, it is evident that the CTA project is now passing through its adolescent phase; the time has arrived to make final decisions about what the observatory will look like for decades to come. It is now critical to transform all the brilliant ideas into a real observatory that is sustainable, consolidated and easy to maintain in the most cost-effective way. This, in short, is what the present management has been working on since it was installed about two years ago.

Finding the right home

The CTAO has found several locations to call home. Following a CTAO Council decision in 2016, its headquarters will be located in Bologna, Italy, at the Istituto Nazionale di Astrofisica (INAF) premises, in a new building shared with the Bologna University Department of Physics and Astronomy. This decision also made Berlin-Zeuthen the location for the Science Data Management Centre (SDMC) in a new building complex on the Deutsches Elektronen-Synchrotron (DESY) campus. The interim headquarters is located on the Max-Planck-Institut für Kernphysik (MPIK) campus in Heidelberg, Germany.

And to provide access to the entire sky, the CTAO has two array locations: one in the northern hemisphere and another in the southern hemisphere. In July 2015, CTA entered into detailed hosting agreement negotiations with the European Southern Observatory (ESO) for the southern array site near Paranal, Chile, and with the Instituto de Astrofísica de Canarias (IAC) for the northern array site in Villa de Garafía on the island of La Palma in the Canary Islands. The site selections were made after years of careful consideration of extensive studies of the environmental conditions, simulations of the science performance and assessments of construction and operation costs.

CTA's northern hemisphere site is located on the existing site of the IAC's Observatorio del Roque de los Muchachos on the island of La Palma. At an altitude of 2200 m and nestled on a plateau below the rim of an extinct volcanic crater, the site currently hosts the two MAGIC telescopes. The southern site of CTA is 11 km southeast of the location of the Very Large Telescope at ESO's Paranal Observatory in the Atacama Desert, and only 16 km from the construction site of ESO's Extremely Large Telescope.

Figure 3. This image illustrates all three classes of the 99 telescopes planned for the southern hemisphere at ESO's Paranal Observatory, as viewed from the centre of the array. This rendering is not an accurate representation of the final array layout, but it illustrates the enormous scale of the CTA telescopes and the array itself.

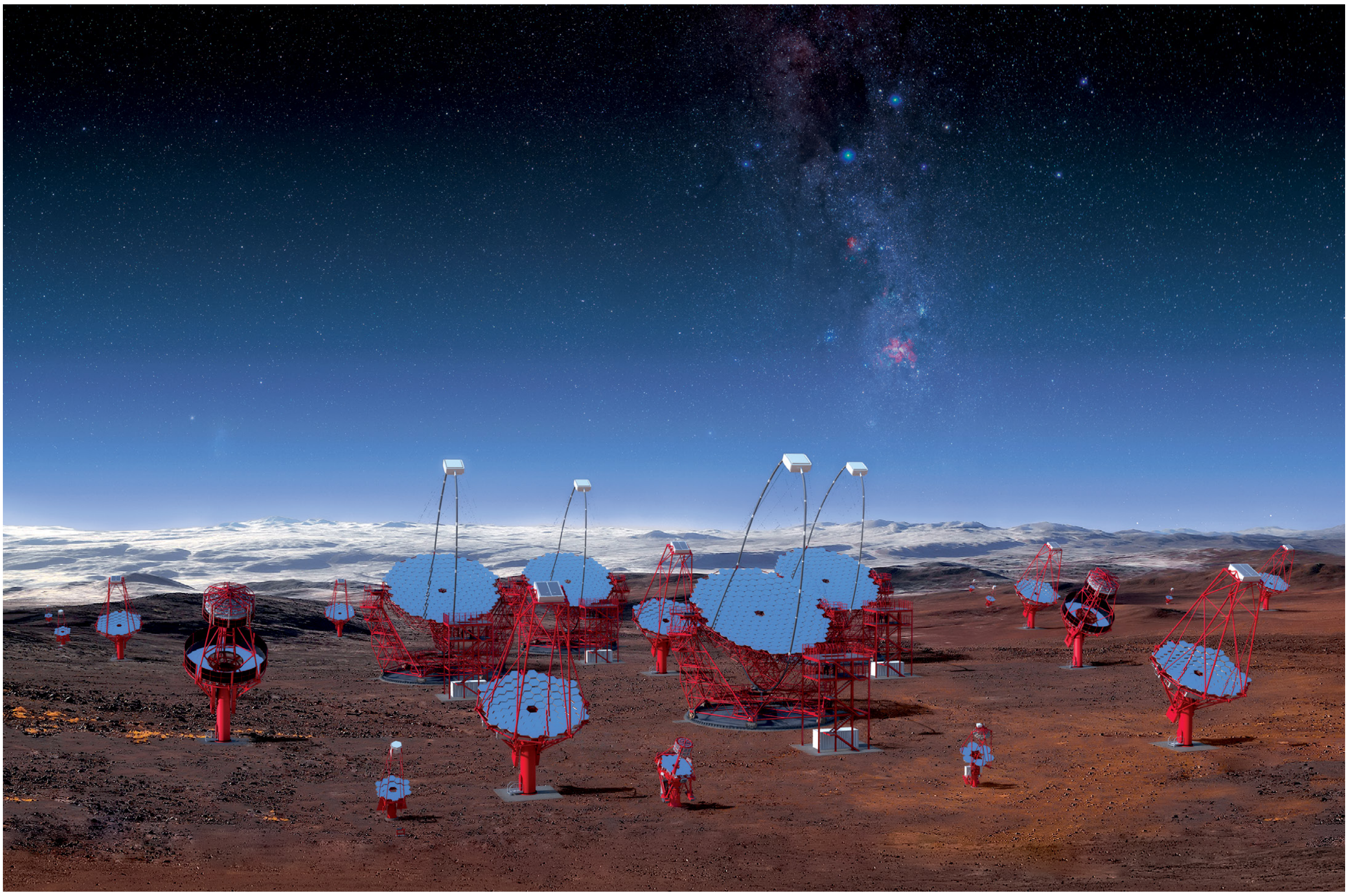
The road to formalising a hosting agreement with the IAC for the northern site, while intricate — owing to the extensive requirements to integrate the CTA structures into the existing complex of astronomical instrumentation — was relatively short. The agreement was signed in 2016 with the Director of the IAC, taking advantage of the fact that Spain is a shareholder in the CTA project.

For the southern site, the negotiation was more complex, considering the region is a Chilean territory, ESO is responsible for any astronomical infrastructure installed on their land and the Chilean scientific community should benefit from astronomical facilities on their (extraordinary) land. The three negotiations had to be handled in parallel and, thanks to the excellent synergies with the ESO Director General, they were successfully concluded in December 2018. Soon after, the participation of ESO in the CTA project was fully formalised when ESO officially became a shareholder in the CTAO in March 2019.

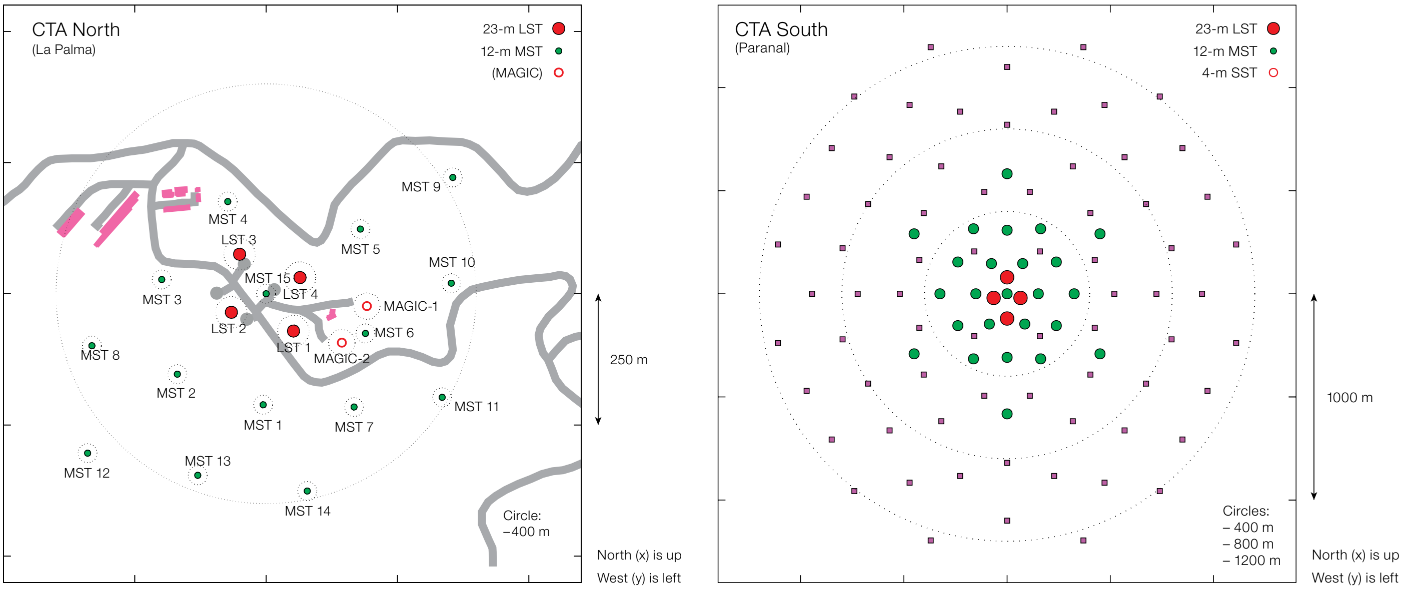
Getting organised

Building an infrastructure as big and complex as CTA takes a lot of organisation, people and funds, not to mention a governing body that can fully support the diverse and complicated landscape of CTA's multinational investments and business locales.

The CTAO gGmbH, a non-profit limited liability company under German law, *ad interim*, was created in 2014 and is the current legal entity in charge of the preparations to construct the CTAO. However, to manage the construction and then the operation of the CTAO, it will transition to a European Research Infrastructure Consortium (ERIC) as defined by the European Commission. This status will deliver several advantages,



CTA/M.-A. Besel/IAC (G. P. Díaz)/ESO



Baseline layout: 4 LSTs, 15 MSTs (status: 2017-12-04)

Baseline layout: 4 LSTs, 25 MSTs, 70 SSTs

Figure 4. The site maps for the northern and southern CTAO sites.

from both a political and a financial point of view. The process, led by a Board of Governmental Representatives, toward the application and final recognition of the ERIC status began in the spring of 2018 and, in March 2019, the first part of the application was presented to the European Commission. The process is progressing at a steady pace and we are confident that it will conclude before the end of 2020.

There will be a fundamental consequence of this process: those Members agreeing to participate in the CTAO ERIC will be in a position to unfreeze the funds assigned by their respective governments to the construction of the observatory. A critical constraint to starting construction will start to unravel after the ERIC is in place!

The CTAO is actively preparing for this crucial milestone by finalising the Cost Book (set for approval in June 2020), boosting the CTAO staff (which has more than doubled since 2018, to 37), establishing an administrative structure, preparing the necessary basis for a construction project (for example, construction, safety, integration and verification plans, a unique documentation management system, interface definition and control and software standards), completing system designs for the array sites by the end of 2020 and holding technical reviews, such as Critical Design Reviews, to move from the design phase to the construction phase.

The structure of the CTAO, once the ERIC legal entity is in place, will be organised on four sites: the headquarters in Bologna (Italy), the Science Data Management Centre in Zeuthen (Germany), the CTA-North site on La Palma (Spain) and the CTA-South site near Paranal (Chile).

Strategising and harmonising

As mentioned above, the path from CTA's "adolescence" to full maturity requires a lot of decisions based on funding and the feasibility of execution while not compromising our ability to achieve our exceptional science goals. The full CTA baseline configuration consists of up to 120 telescopes of three types, covering different energy ranges, and distributed over two sites to ensure full sky coverage. Each individual telescope is a functional scientific instrument whose performance can be tested, verified and integrated into a large-scale array consisting of many telescopes.

For widely usable energy coverage, it is desirable for the effective gamma-ray detection area to increase with gamma-ray energy, compensating for the rapid drop of gamma-ray flux with increasing energy (for typical sources, the gamma-ray flux drops with energy, E, like $dN\gamma/dE \sim E^{-2}$ or faster). Hence, rather than deploying one type of Cherenkov telescope on a regular grid, the CTA arrays use a graded approach:

- The lowest energies (20 GeV – 3 TeV) are covered by an arrangement of four 23-m LSTs at each site, capable of detecting gamma rays as low as 20 GeV.
- The middle of the range (80 GeV – 50 TeV) is covered by larger arrays of 25 (CTA-South) and 15 (CTA-North) 12-m MSTs.
- The highest energy gamma rays (1–300 TeV) are detected by a multi-kilometre square array of 70 4-m SSTs in the south.

The small telescopes are only foreseen for the southern array since the highest energies are most relevant for the study of Galactic sources. The use of three different sizes of telescope proved to be the most cost-effective solution, and it allows each telescope type to be optimised for a specific energy range.

Access to the full sky is necessary as many of the phenomena to be studied by CTA are rare and individual objects can be very important. For example, the most promising galaxy cluster, the brightest starburst galaxy and the only known gravitationally lensed TeV source are located in the north. The inner Galaxy and the Galactic centre are key CTA targets and are located in the south.

The baseline configuration foresees 19 telescopes on CTA-North (4 LSTs and 15 MSTs) and 99 on CTA-South (4 LSTs, 25 MSTs and 70 SSTs). However, the present funding situation demands a phased approach, reducing the initial objective to a threshold configuration for the next five years. The optimal distribution of telescopes that is well defined and affordable is the installation of nine telescopes on CTA-North (4 LSTs and 5 MSTs) and between 55 and 65 telescopes on CTA-South (15 MSTs and 40/50 SSTs). The quality of science will be outstanding and far beyond what can be attained with current instruments even in this reduced configuration. The ambitious objective of implementing the full configuration is expected over the following five years.

Overall, CTA is a large science infrastructure with many individual units and a high degree of complexity. There are many good reasons to design and implement the simplest and most harmonised system possible. In fact, a high degree of simplification will be a crucial factor for success, during both construction and operation. This need for harmonisation applies to many subsystems and components of the array. One prominent area concerns the SSTs, where harmonisation is particularly important owing to the large number of units that need to be built, operated and maintained.

Based on the findings and recommendations of a year-long review, and taking into account funding considerations, the CTAO Management formulated its proposal for a unified SST design (called the CTA-SST). The CTA-SST Consortium has now taken responsibility for delivering the SST telescopes based on the ASTRI structure and the Compact High-Energy Camera (CHEC) designs. As for the MST, the newly formed CTA-MST Consortium is proposing a sustainable solution for the provision of telescopes, including structures, cameras and mirrors, for the two sites. Finally, for the LSTs, the situation is more straightforward as only one design exists; their production is being arranged.

Finding CTA's Place in the Multi-messenger Universe

After August 2017, the paradigm for the astronomical world changed and the new mantra is "multi-messenger astronomy". Indeed, the extraordinary sequence which began with a gravitational wave signal, followed after ~ 1.5 seconds by a gamma-ray flash and then by all the electromagnetic detections that could be observed, has modified our approach of studying the sky.

In May 2019, the First CTA Science Symposium "Exploring the High-Energy Universe with CTA" ratified the important role that the CTAO will play in the landscape of new, highly-sensitive observatories becoming operational in the next decade. The CTAO is going to be one of the pillars of multi-messenger astrophysics, which will rely heavily on the detection of gamma rays to pinpoint the sites of activity at extreme energies in the Universe. It will also be the first ground-based gamma-ray observatory open to the worldwide astronomical and particle physics communities as a resource for data from unique, high-energy astronomical observations.

The detection technique adopted by the Cherenkov ground-based telescopes is a perfect integration of frontiers regarding both astronomical and particle physics technologies: the need to reveal a very weak optical signal — just a few photons — within an extremely short timescale — a few nanoseconds — coupled with the best instrumentation from the two branches of physics. This is, at the same time, translated into scientific objectives that are a mixture of unsolved problems for astrophysics and particle physics, spanning the origin of cosmic rays, catastrophic collapse, and the nature of dark matter. Do not underestimate the fact that CTA detectors could reach particle energies some 20 times higher than present CERN collision limits.

The scientific themes that will be the principal objectives of the scientific production of the observatory are summarised. A detailed description can be found in CTA's description of Key Science Projects (CTA Consortium, 2018).

Theme 1 – Understanding the origin and role of relativistic cosmic particles: The existence of highly energetic cosmic particles is known since more than one century. In our Galaxy and beyond, the energy density of such particles is comparable to the energy contained in motions of interstellar gas and in magnetic fields, implying a tight coupling between these carriers of energy in the cosmos and a potentially significant impact of energetic cosmic particles on cosmic evolution. However, a range of basic questions remain:

- *What are the sites of high-energy particle acceleration in the universe?*
- *What are the mechanisms for cosmic particle acceleration?*
- *What role do accelerated particles play in feedback on star formation and galaxy evolution?*

Theme 2 – Probing extreme environments: Acceleration of particles to high energy requires environments of extreme energy density, that are generally characterised by a complex nonlinear interplay of different forms of energy. Very-high-energy (VHE) gamma rays can be used to explore these environments. Gamma rays are also used to probe the other type of extreme environments, the cosmic voids in the space between galaxies. Specific questions concern:

- *What physical processes are at work close to neutron stars and black holes?*
- *What are the characteristics of relativistic jets, winds and explosions?*
- *How intense are radiation fields and magnetic fields in cosmic voids, and how do these evolve over cosmic time?*

Theme 3 – Exploring frontiers in Physics: VHE gamma rays serve to explore questions of fundamental physics, in scope reaching far beyond astrophysics. Relic particles left over from the Big Bang – such as dark matter particles – can potentially be detected in gamma rays. In their billion-year journey from distant extragalactic sources to Earth, gamma rays furthermore probe subtle effects predicted in many theories, but beyond *the reach of laboratory experiments. Topics addressed include:*

- *What is the nature of dark matter?*
- *How is dark matter distributed?*
- *Are there quantum gravitational effects on photon propagation?*
- *Do axion-like particles exist?*

The investigation of the full spectrum of electromagnetic radiation is going to improve in a dramatic way in the next decades. CTA will cover the highest frequencies on a timescale during which other international projects will start operation: for example, the ELT in the infrared/optical and the Square Kilometre Array (SKA) in the radio. Synergies among the large astronomical infrastructures are going to become the most natural way to develop multi-wavelength and multi-messenger astrophysics; the relationship with ESO instrumentation is obvious now that CTA is an ESO project. The interaction with the SKA has a clear framework since the SKA Organisation and the CTAO signed a Cooperation Agreement, sanctioning their future collaboration in science, technology and management.

In due course, collaboration agreements will be established to make the contribution of this large-scale telescope system as effective as possible in measuring transient phenomena in close coordination with other astrophysical instrumentation, such as gravitational wave interferometers and large-scale neutrino detectors.

Progressing Towards Construction

CTA is currently in pre-construction with some construction activities already begun. While the design and prototyping of subsystems, such as telescopes and cameras, calibration equipment and software elements, are quite advanced, the system-related aspects (for example, system interfaces, an array-wide alarm system and overall integration and verification) are currently being addressed by the CTAO Project Office. At the same time, a simplification of the overall CTA and the harmonisation or choice among different design solutions are being addressed. As previously mentioned, this resulted in a unique SST design for the telescope structure and camera. Other subsystems will undergo a similar exercise.

On the CTA-North site, preparations for the first stage of infrastructure design and construction are well under way for a further three LSTs and the first MST. An agreement between the LST team and the CTAO has been created to provide the framework for CTAO staff to support the LST-1 commissioning and to get better acquainted with the telescope. Moreover, a low-elevation office space has been rented and its refurbishment is being finalised with a local architect.

For CTA-South, the first step in preparing the site is to develop the overall layout of the site's supporting facilities (buildings, power substation, warehouse, etc.) and the required infrastructure, as well as to conduct an analysis of the current telescope positions by marking them in the field and re-evaluating their construction feasibility. The first preparatory procurements (vehicle, generator set, refurbishment of office containers) have been completed or are in preparation. In addition, the road access and the power connection to the public electricity grid are being investigated to find the correct strategy and technical solution. It is the CTAO's intention to begin building the CTA-South access road, data and power connections to the array as soon as the funding becomes available.

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An artistic rendering of CTA's northern hemisphere site located on the existing site of the Instituto de Astrofisica de Canarias's (IAC's) Observatorio del Roque de los Muchachos on the island of La Palma. This rendering does not reflect the final layout of the array, but serves to illustrate the scale of the array.