CTA Observatory ERIC Scientific & Technical Description

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Scientific Technical Committee is invited to provide a recommendation for this document.
1. Purpose and Scope of this Annex

This document provides a description of the key aspects of the CTA Observatory, and summarizes the scientific and technical goals that the Members and Strategic Partners of the project aim to achieve. In particular, the present document covers the scientific objectives, the performance requirements of the Observatory, as well as the design and architecture of the CTA Observatory. The document also provides a summary of the project’s development and intended lifecycle.
2. Overview of the CTAO ERIC

The purpose of the CTA Observatory European Research Infrastructure Consortium (CTAO ERIC) is to construct and operate the Cherenkov Telescope Array Observatory (CTA), the international observatory for ground-based gamma-ray astronomy that will produce ground-breaking science in the next decades. CTAO ERIC will be one of the first intergovernmental organizations specifically dedicated to the field of astro-particle physics. Given its trans-disciplinary nature, CTAO will strengthen bridges between the particle physics and the astrophysics communities, enabling disruptive scientific breakthroughs. Jointly with other new facilities, from gravitational waves experiments to observatories operating at lower frequencies (from radio to high-energy gamma rays), CTAO will be driving the emerging field of multimessenger astronomy that will be constitutive of science in the XXIst century.

The preceding gamma-ray instrumentation pioneered the research of the Universe at the highest-energy electromagnetic radiation including ground-based telescopes - H.E.S.S., MAGIC, VERITAS – and space instrumentation – INTEGRAL, Swift, FERMI, AGILE – each of which has produced new and outstanding scientific discoveries. However, gamma-ray astrophysics now necessitates a large-scale higher sensitivity observatory that can provide high-energy data to the extended scientific community. Of this global community, CTA's Consortium already includes around 1500 scientists and engineers from more than 150 Institutes distributed over 25 Countries. The future user community is anticipated to expand well beyond the current Consortium, involving astrophysicists, particle physicists and plasma physicists in Europe and all over the world, in an open and competitive environment. The CTA Observatory and the CTA Consortium have in close collaboration, over the last decade, developed and established the science case of the CTA Observatory, and developed a technical implementation that relies upon the proven technique of Cherenkov imaging of gamma-ray induced particle cascades in the atmosphere, yet pushes the performance envelope in every direction, providing an up to 5-10 fold increase in sensitivity, as well as in the source localization, over current instruments, up to a 100-fold increase in the speed with which the sky can be surveyed, and coherent full-sky coverage from two locations, in the Northern and Southern hemispheres.

Figure 1 gives an artist impression of the Southern CTAO Array Site in Northern Chile, showing the central region of the telescope array, which in its ultimate configuration includes Cherenkov telescopes of three different sizes, covering overlapping bands in gamma-ray energies. CTAO ERIC will include the two Array sites in the Canary Islands and in Chile, its Headquarters in Italy and its Science Data Management Centre in Germany, with three of the four locations in EC Member states.

Figure 1: Artist impression of the CTAO Southern Array site, showing the array combining three different sizes of Cherenkov telescopes, covering a multi-km² area. The combination of a large number of telescopes of different sizes gives the CTA Observatory tremendous flexibility of operation as well as unprecedented sensitivity and energy range.
CTAO ERIC meets the requirements for European Research Infrastructures under Article 4 of the Regulation (EC) 723/2009 on the Community legal framework for a European Research Infrastructure Consortium (ERIC). CTAO has a long history as European project; it has been an ESFRI emerging project since 2006 and a regular project in ESFRI roadmaps from 2008, resulting among the first group of research infrastructures having a perspective as European initiatives for consolidation of multilateral scientific programs. It was recognized an ESFRI Landmark in the ESFRI Roadmap 2018. The wide and complex technical and scientific scope of the CTA project requires a multi-national approach to infrastructure implementation and exploitation, with EU member countries and countries associated to the framework programme playing a central role in driving the field. As the largest, most advanced, and world-wide unique infrastructure in this field, based on expertise from formerly competing predecessor projects, CTAO ERIC will strengthen, structure and focus the European Research Area (ERA) and will provide a significant step in the relevant scientific and technological fields at international level. CTAO ERIC will allow EU scientists to preserve and reinforce the leadership established with the European-driven H.E.S.S. and MAGIC experiments, and the participation in the US experiment VERITAS. At the same time, CTAO ERIC will attract the best resources from non-European scientists active in the field. It will create unique opportunities to carry out advanced research and is expected to attract the best researchers from across the world and train highly qualified engineers and students.

The science topics and user community of the CTA Observatory cut across disciplines, including astrophysics, particle physics, plasma physics and fundamental physics. The Observatory aims for an intense interaction with the other most advanced facilities in these fields, in particular with gravitational wave observatories and neutrino observatories. At the same time, it will strongly interact with observatories in other electromagnetic wavebands, providing a synergistic view of our Universe, across wave bands, messenger particles, and science communities. The setting-up of CTAO ERIC as distributed infrastructure opens a great opportunity to enhance the circulation of these human resources, ideas and innovations with the driving force based on the common scope to be relevant and attractive at European and international level. The demonstrated involvement of a very large scientific community already generates a world-spanning network and exchange of both scientists and engineers, and it will allow to strengthen exchanges and to further enhance scientific and technical collaborations between researchers and technicians from all over the world.

With its technological innovations, CTAO ERIC will furthermore produce direct economic benefits to industries mainly in those countries supplying in-kind contributions to construction with significant part of investment for CTAO ERIC being spent in those countries, often supporting specialized small and medium sized enterprises, and training and expanding their expertise and capabilities. CTAO ERIC will produce benefits from an economic, labor, touristic and cultural perspective in the places where it will operate. Outreach and dissemination activities will enclose all aspects, from education to technology and technical training, and will involve the various stakeholders at European and international level.

A particular emphasis of CTAO ERIC is the efficient dissemination of CTA Observatory data using an open platform as well as the long-term archiving of data following the FAIR principles, allowing to reuse research results and promoting the efficient linking of CTA Observatory data with data from other observatories.

To quantitatively gauge its success and as a management tool, allowing monitoring of progress, and enabling evidence-based decision-making, CTAO ERIC will establish key performance indicators (KPIs). The KPIs will follow the general objectives behind the establishment of the Research Infrastructure, principally to enable the production of excellent science by ensuring the accessibility to all researchers in Europe and beyond through European Union support. Specific KPIs will be adapted to the observatory nature of the CTAO infrastructure. KPIs will in particular track the performance of the observatory, the use and impact of the facility, and its scientific and socio-economic return.
3. Scientific Objectives

Ground-based gamma-ray astronomy – imaging the Universe at very-high energies (VHE) above tens of GeV and covering several decades of the electromagnetic spectrum (see Figure 2) – is a young branch of astrophysics that has developed very rapidly since the detection of the first cosmic VHE source in 1989.

![Figure 2: The spectrum of electromagnetic radiation, characterised by its wavelength and the energy of individual photons, showing the spectral range covered by some of the major astronomical facilities are completed, planned or under construction.](image)

The CTA Observatory is envisaged as a general-purpose observatory for this VHE waveband; CTAO will be the first truly open VHE observatory, providing accessible data products and support services to a wide community.

The CTA Observatory will transform our understanding of the high-energy universe and will explore questions in physics of fundamental importance. CTAO aims at addressing a wide range of major questions in and beyond astrophysics, which can be grouped into three broad themes:

**Theme 1 - Understanding the Origin and Role of Relativistic Cosmic Particles:** The existence of highly energetic cosmic particles has been known for more than a century. CTAO observations will contribute providing answers to basic questions such as:

- 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:** VHE gamma rays can be used to explore environments of extreme energy density, as well as to probe another type of extreme environment, the cosmic voids that exist 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 also allow us to explore questions related to fundamental physics, reaching far beyond astrophysics. 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?

CTAO science needs have evolved over many stages of their development, resulting in a defined set of science cases that fall under each of these themes. Many of these science cases will strongly benefit from coordinated observations with other facilities operating at different wavelengths or based on the detection of different messengers, i.e., neutrino telescopes, cosmic ray detectors or gravitational waves instruments. Therefore, to maximize its scientific return, the CTA Observatory is conceived as a key player in the fundamentally new domain of astronomy and astrophysics: the multi-messenger astrophysics.
Some of the above-presented open questions imply the definition of large science programmes to ensure that a large amount of observations and their subsequent data analysis are addressed in a coherent fashion. This led to the definition of the Key Science Projects (KSPs) requesting hundreds to thousands of hours of observations, and, in turn, producing legacy data sets and data products, i.e., catalogues, for the use by the scientific community. Some potential KSPs are:

- Probing Dark Matter
- Exploring the Galactic Centre
- Galactic Plane Survey
- Large Magellanic Cloud Survey
- Extragalactic Survey
- Transient Phenomena
- Cosmic Ray PeVatrons
- Star Forming Systems
- Active Galactic Nuclei
- Clusters of Galaxies

4. Performance Requirements and High-Level Specifications of the CTA Observatory

The following high-level characteristics define the main features of the CTA Observatory to be constructed, as required to address the science topics outlined in Section 3. Characteristics concern (i) the design specifications of the telescope arrays, (ii) the requirements regarding their science performance, (iii) the ability to react to alerts from other instruments, and to issue alerts, (iv) the observation time made available to observers, and management of this observation time, and (v) the management of the resulting data.

(i) High-level design characteristics for the two telescope arrays:

- Number of observation sites: Two, one in each hemisphere to cover the full sky.
- South site location: latitude -20 to -40 degrees, altitude 1500 m to 2500 m.
- North site location: latitude 20 to 40 degrees, altitude 1500 m to 2500 m.
- Number of telescope types to cover the 0.02 TeV to 300 TeV energy range: Three, referred to as Large-Sized, Medium-Sized and Small-Sized Telescopes (LST, MST, SST).
- Operation: The LST, MST and SST subsystem should be operable both independently as well as part of the complete system.

(ii) Primary performance requirements for the two telescope arrays and their subsystems:

Performance requirements are defined separately for the LST, MST, and SST subsystems, each of which governs overall system performance over a specific energy range. The number of telescopes on each site and for each subsystem are listed for the configuration at the end of the initial Construction Phase ("Alpha configuration"), with a total of 64 telescopes, and for the potentially ultimate configuration targeted in the Operation & Enhancement Phase ("Omega configuration"). Already the Alpha configuration ensures transformational science, but implies a temporary specialisation of array sites, with a focus of the northern array site on extragalactic targets and the range of low to medium gamma-ray energies, whereas the southern array is optimised for Galactic targets and medium to high gamma-ray energies.

The performance requirements listed in Table 1 refer to the best ("peak") performance characteristics within a subsystem’s energy range.

Additional key performance requirements include:
- System deadtime where the system is operational but unavailable for recording events: less than 2%.
- Energy scale uncertainty: less than 10%.
- Knowledge of effective gamma ray detection area: to better than 10%.

(iii) Science alerts
- Connection to international networks to allow automatic response to external science alerts.
- Science alerts based on CTAO data must be produced within 90 seconds from the CTAO detection, but the sensitivity may be degraded with respect to the sensitivity of the full processing pipeline.

(iv) CTAO observing time

- Annual science observing time per site: 1150/1000 hours/year (prime time, moon below horizon, for the Southern and Northern array, respectively) or 1600/1400 hours/year (including moon time).
- Time allocation of the observing time is the responsibility of the Director General, advised by a Time Allocation Committee (TAC), who will rank proposals based solely on scientific merits.

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>LST Subsystem (South)</th>
<th>LST Subsystem (North)</th>
<th>MST Subsystem (South)</th>
<th>MST Subsystem (North)</th>
<th>SST Subsystem (South)</th>
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<tr>
<td>Energy range (TeV)</td>
<td>0.02-3</td>
<td>0.02-3</td>
<td>0.08-50</td>
<td>0.08-50</td>
<td>1.3-00</td>
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<td>Alpha configuration, at the end of the Construction Phase</td>
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<td>4</td>
<td>14</td>
<td>9</td>
<td>37</td>
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<tr>
<td>Omega configuration, targeted in the Enhancement Phase</td>
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<td>4</td>
<td>25</td>
<td>15</td>
<td>70</td>
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<tr>
<td>Optical field of view of telescopes (deg.)</td>
<td>&gt; 4.3</td>
<td>&gt; 7.0</td>
<td>&gt; 7.0</td>
<td>&gt; 8.0</td>
<td></td>
</tr>
<tr>
<td>Gamma ray field of view diameter (deg.)</td>
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<td>&gt; 6.0</td>
<td>&gt; 6.0</td>
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<td></td>
</tr>
<tr>
<td>Peak gamma ray detection area (km²) *</td>
<td>&gt; 0.13</td>
<td>&gt; 0.8</td>
<td>&gt; 0.8</td>
<td>&gt; 2.0</td>
<td></td>
</tr>
<tr>
<td>Gamma ray flux sensitivity at subsystem energy lower edge ($10^{-13}$ erg/cm²s) for 50 h, 0.2 DEX *</td>
<td>&lt; 110</td>
<td>&lt; 20</td>
<td>&lt; 30</td>
<td>&lt; 5</td>
<td></td>
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<tr>
<td>Peak gamma ray flux sensitivity ($10^{-13}$ erg/cm²s) for 50 h, 0.2 DEX *</td>
<td>&lt; 3.0</td>
<td>&lt; 1.3</td>
<td>&lt; 1.7</td>
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<td>&lt; 0.04</td>
<td>&lt; 0.04</td>
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<td>Peak gamma ray energy resolution (%)</td>
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<td>&lt; 10</td>
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<tr>
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<tr>
<td>Time resolution for gamma-ray events (ns)</td>
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<td>&lt; 100</td>
<td>&lt; 100</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Primary characteristics and performance requirements for the different subarrays for fully dark conditions and 20 degree zenith angle. The characteristics indicated with * refer to the Alpha configuration; performance approximately scales with the number of telescopes and is correspondingly enhanced for the Omega configuration arrays.
(v) Data management

- Data format: CTAO science data products are provided in IVOA (International Virtual Observatory Alliance) compliant data formats aiming to guarantee global electronic access to the broadest astronomical community. CTAO will provide open-source science analysis tools allowing users to derive high-level science data products such as gamma-ray sky maps, light curves, or energy spectra. CTAO follows the FAIR principles.

- Archive: Access to all CTAO science data products and the required supporting information will be publicly available, after a proprietary period of 12 months for the Principal Investigator (PI) of the proposal. In exceptional cases, a modified proprietary period may be decided by the Director General to maximize the scientific impact of the CTA Observatory.
5. CTA Observatory

The CTA Observatory is a distributed infrastructure including the Northern and Southern observation stations, the Headquarters and the Science Data Management Centre. The core scientific elements of the observatory are the arrays that include telescopes, calibration instruments and the supervisory control system. From detailed studies the need emerged for three telescope sizes and two sites to efficiently cover the wide energy range of the CTA Observatory and to address all of the major science questions. These three telescope sizes are referred to as the Large-Sized, Medium-Sized and Small-Sized Telescopes (LSTs, MSTs and SSTs), with approximate primary reflective surfaces diameters of 23 m, 12 m, and 4 m respectively, see Section 4 for specifications. The CTAO arrays in their Alpha configuration will consist of a total of 64 telescopes of the three types; for the Operation & Enhancement Phase, the goal is to roughly double the total number of telescopes. 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. Based on CTA Observatory requirements for performance, reliability, availability, maintainability and safety, detailed designs and prototypes have been developed for these different telescope types. Figure 3 shows the telescope prototypes installed in different locations and used for verification against requirements. The different telescopes have rather different design drivers. For example, the main drivers for the LSTs are the huge light-collection power and rapid re-positioning requirements, while for the SSTs the large number of elements implies tight constraints on unit cost, reliability and maintenance cost.

![Figure 3: Prototypes for the three types of CTAO telescopes. a) LST prototype on La Palma (Spain) b) MST prototype in Berlin (Germany) c) SST prototype in Sicily (Italy).](image)

Simulation studies showed that best performance is obtained by deploying the arrays at altitudes between 1500m and 2500m above sea level. The optimised telescope arrangements, i.e., the arrays’ layouts, are illustrated in Figure 4. The LST, MST and SST subsystems of the CTA Observatory are specified to be operable independently as well as part of the complete system. It is envisioned that a significant fraction of the observation time will be spent in sub-system mode, allowing optimised simultaneous observation of soft and hard spectrum gamma-raysources.

In addition to the telescopes, various calibration and monitoring instruments are installed at the array sites. These instruments relate to the overall calibration, monitoring and characterisation of the arrays and the environmental conditions on-site during regular operations. The latter includes LIDARs (Light Imaging, Detection, And Ranging), that are used for atmospheric characterization purposes as the atmosphere can be considered as an integrated element of the instrument, and its transparency must be constantly measured with high accuracy. Environmental alarms may be raised by the environmental monitoring devices, in cases where these may have implications for array operation.
Figure 4: Layout of the two CTAO Arrays in their Alpha configuration on the two array sites in the Southern hemisphere (right) and Northern hemisphere (left). The final layouts may slightly deviate from those here illustrated. The Southern Array site contains more telescopes and covers a larger area, to allow the study of highest-energy sources within our Galaxy. The SST array has a large footprint to provide a very large gamma-ray collection area, but with a relatively high-energy threshold due to the smaller telescope size. The LSTs have large individual light-collection power to reach low gamma-ray energies but need only a modest footprint due to the much higher fluxes of lower energy gamma-rays. The Northern Array layout shows also the positions of the two MAGIC telescopes (cyan circles) that are still in operations, at the moment of writing.

In order to handle the complexity of the CTA Observatory, a model-based and formal approach towards the CTA Observatory architecture has been adopted. Figure 5 illustrates the function of the Observatory and its main interactions with the outside world and the environment.

The CTA Observatory is internally composed of a set of key systems that each provide defined functionality and have well defined interfaces. The aggregation of these systems and their interplay cover the full functionality of the CTA Observatory necessary to reach the objectives. The main systems include:

**Telescopes**: instruments that can indirectly detect VHE gamma rays by imaging the few nanoseconds timescale flashes of Cherenkov radiation generated by the cascade of relativistic charged particles produced when a VHE gamma ray strikes the Earth atmosphere.

**Array Control and Data Acquisition System**: the supervisory control and data acquisition system of the Array. It will also perform the dynamic scheduling, the monitoring of the Array performance, as well as the automatic generation of science alerts.

**Array Common Elements**: instruments responsible for the calibration of the array and the monitoring of the environmental conditions at the array site during regular operations.

**Infrastructure**: the system of fundamental facilities, installations, equipment, and services, such as telescope foundations, roads, buildings, and utilities that form the basis and are needed for the operation of CTAO.

**Data Processing and Preservation System**: a software system responsible for reducing the raw data and producing low-level data products appropriate for science analysis. Includes also the production of simulated data, (re)processing and long-term preservation of data products, as well as data transfer from the on-site to the off-site ICT centres.

**On-site ICT centre**: facility, located at the Array Site, including the hardware elements necessary to temporary store and analyze all the data collected, both scientific and monitoring data.

**Off-site ICT centre**: facility, geographically distributed, including the hardware elements necessary to permanently store and analyze all the data collected, both scientific and monitoring data.

**Science & Technical Operation Support Systems**: a collection of software systems supporting the CTA Observatory operations, including, for instance, configuration management, issue tracking, and maintenance planning.

**Science User Support System**: a software system providing the user the point of access to the Observatory for proposal submission, user support, and retrievability of high-level CTAO science data products and of the CTAO science analysis tools. Provides support for proposal evaluation, for generation of the observation schedule and for user support.
Management and Administrative System: a collection of software systems associated with the administration of the CTA Observatory. Includes, for example, procurement, logistics, human resources management, and systems supporting the generation of performance/status reports for external stakeholders.

Some of these systems act across CTA Observatory locations and interconnect Headquarters and Science Data Management Centre with the observation stations, or between the stations, for coordinated scheduling of observations. Central management functions are located at Headquarters. The Science Data Management Centre coordinates the processing of data, in distributed computing facilities, the archiving of the data and the interfacing with the users.

Figure 5: Schematic representation of the observatory architecture, illustrating the flow and processing of data and information, the interaction with the outside world, and the observatory governance.

For users, access to CTA observing time will be possible through:

Standard Proposals: observation proposals responding to Announcement of Opportunity calls, typically requesting in the range of few h to 100 h of observing time, either for direct scheduling or in response to external or internal triggers (Targets of Opportunity, TOOs). Standard Proposals can request for Open Time, and are reviewed by the Time Allocation Committee (TAC).

Key Science Projects (KSP): large (often multi-year) scientific programs requesting more than hundreds of hours that have the potential to lead to a major advance or breakthrough in the field of study for CTA and that will produce
legacy data sets and data products to be delivered to the open CTA Science Archive. KSP proposals are reviewed by the TAC.

**Director General’s Discretionary Time (DDT) proposals:** scientifically outstanding proposals not subjected to the standard time allocation process. Their execution is time critical and/or offers the possibility of anticipating important discoveries which may be missed if subjected to the time delay introduced by the TAC evaluation.

Figure 6 shows as an example the approximate sharing of observing time between categories; the definitive sharing will be decided by the ERIC Council and may be adjusted over time. It is anticipated that, once excluded the Guaranteed Time Observations (GTOs) arising from contractual obligations of CTAO, the remaining observing time is assigned to scientists from Member & Strategic Partner countries (Member Time), except for a small fraction, the International Community Observing Time (ICOT), that serves to provide access to CTAO for outstanding proposals from all scientists regardless of their affiliation, to maximize the science reach and science impact of CTAO. GTOs are currently arising from CTAO obligations with the Host Countries/Organizations and correspond to 25/20% of the total observing time of the two CTAO Northern/Southern arrays.

![Figure 6: An example of the sharing of the categories of observing time, including Guaranteed Time Observations arising from contractual obligations of CTAO ERIC. The exact sharing of observing time remains to be decided by the CTAO ERIC Council.](image)

### 6. Project Development and Lifecycle

The CTA Consortium (CTAC) formed in 2008 to develop a concept for the first major open observatory for this waveband, motivated by the success of existing imaging atmospheric Cherenkov telescopes (IACTs) such as H.E.S.S., MAGIC and VERITAS. The CTA Observatory is much larger than current instruments (a factor of ~15 more telescopes), resulting in vastly improved performance but also specific challenges in design, construction and operation.

CTA was supported in its Preparatory Phase by an EU Framework Programme 7 grant (2010–2014) and features globally on major roadmaps, including the ESFRI roadmap. In 2014, the CTAO gGmbH was founded as an interim legal entity to prepare for CTA Observatory implementation. Under H2020, CTAO is supported under Infradev2014-2015 G.A. 676134 (CTA-DEV) and H2020 Infraeosc2018-2020 G.A. 824064 (ESCAPE)

A comprehensive programme of site search and evaluation was conducted from 2010 - 2013, resulting in a short list of suitable sites, joining to the decision on best location: the Paranal site in Chile hosted by the European Southern Observatory (ESO) and the Roque de los Muchachos Observatory in La Palma, Spain hosted by the Instituto de Astrofísica de Canarias (IAC). In June 2016, the CTAO Council selected Bologna (Italy) and Zeuthen (Germany) to host the CTAO Headquarters (HQ), and the CTAO Science Data Management Centre (SDMC), respectively.

The CTA-DEV grant served to further refine the definition of the infrastructure and of the plans for its implementation, defining the Business Plan of the facility and deriving the technical requirements definition. Towards infrastructure
deployment, a Generic Infrastructure Technical Design Report was generated, and site-specific plans for site development.

Recognizing that the founding members of the ERIC may initially not be able to commit to the full cost of CTAO construction, Alpha configuration of the arrays were defined as target of the initial Construction Phase (see Table 1). Despite the initially reduced numbers of telescopes, the Alpha configuration arrays offer a scientifically highly viable implementation, that satisfies the top-level science performance requirements in most of the energy ranges. It defines the funding baseline for the start of CTAO construction with a temporary specialization of the CTAO observation stations: the Northern one will focus on the extragalactic science cases (typically lower energies), and while the Southern one on Galactic science targets (typically higher energies). It is anticipated that additional contributions to go beyond the Alpha configuration will be raised during the Construction phase, resulting in a continuous deployment of telescopes beyond the Alpha configuration in the Operations and Enhancement Phase, rather than in a less efficient staged deployment. The highest priorities for deployment beyond the Alpha configuration include:

**LST telescopes on the southern site:** the Alpha configuration does not include LST telescopes on the southern site. Their addition will enable detection of gamma rays in the 20-100 GeV domain, and rapid follow-up of transient sources, significantly enhancing time-domain astronomy with CTAO. To reduce civil construction at the center of the array, the Construction Project will include works for the LST foundations.

**Additional SST telescopes on the southern site:** recent results from northern air shower arrays have strengthened the case for PeV-domain gamma-ray astronomy; the SSTs will open this domain for the southern sky. To increase array area and energy reach, it is desirable to early deploy 10-15 additional SST telescopes. Three extra SST foundations that are needed to complete the array symmetry are included in the Construction Project budget.

The full lifecycle of CTAO consists of phases of design, construction, operation and enhancement, possible upgrades, decommissioning. The design phase is basically concluded. The remaining aspects are:

**Construction:** The start of the construction phase is defined by the beginning of activities required to build the observatory with two arrays in their Alpha configuration, including the necessary infrastructure. These activities include the definition, preparation, formalization and execution of all the tasks (as In-Kind contribution or by contractors) as laid down in the CTAO Work Breakdown Structure (WBS). Activities include in particular construction of infrastructure, hardware, software, system integration, commissioning and science verification activities, practicing and demonstrating the entire observatory workflow up to the generation and distribution of science data products. The construction phase ends with the deployment and commissioning of the last alpha-configuration telescopes. Council will review the criteria for ending the construction phase and agree on the formal end of the Construction Phase.

**Operation & Enhancement:** Regular operations will start after the end of the Construction Phase as defined by Council. The arrays or partial arrays will be regularly operated. As additional resources will become available, observatory components and in particular additional telescopes beyond the Alpha configuration will be deployed and made available to observatory users.

**Upgrades:** Scientific use of a facility like the CTA Observatory will go through several phases: an initial discovery phase, where the large improvement over previous-generation facilities allows premium science with relatively short exposure times; a consolidation phase of in-depth follow-up to initial discoveries and of targets which are more demanding in terms of required observation time, understanding of the instrument, and analysis techniques; finally a phase of diminishing returns, where required observation time reaches plausible allocations, and the understanding of systematic errors limits the achievable performance. Before entering this phase, given the significant cost of operating the Observatory, an upgrade, or else decommissioning, should be considered. The expected timescale for a major upgrade is 10-15 years, roughly coinciding with the timescale over which obsolescence will create maintenance problems, in particular for cameras. Upgrade proposals will be prepared by CTAO in interaction with the community, and upgrade projects approved by Council.

**Decommissioning:** At the point when the CTA Observatory is no longer sufficiently attractive to the community, and when further upgrades are not scientifically motivated, technically feasible or affordable, on the basis of a Council decision, observatory operation will be terminated and the Observatory will be decommissioned, implying the restoration of the array sites to their natural state.

**Data Preservation:** The CTA Observatory data archive should remain available for at least 10 years after CTAO decommissioning. On the scale of the then available technology, data storage and network access requirements will be modest. Analysis tools should be mature enough to require minimal maintenance.