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Methodology for the Integration of the Array Control and Data Acquisition System with Array Elements of the Cherenkov Telescope Array Observatory

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ABSTRACT

The Cherenkov Telescope Array Observatory (CTAO) is the next-generation atmospheric Cherenkov gamma-ray Observatory. CTAO will be constructed on two sites, one array in the Northern and the other in the Southern hemisphere, containing telescopes of three different sizes, for covering different energy domains. To combine and orchestrate the different telescopes and auxiliary instruments (array elements), the Array Control and Data Acquisition (ACADA) system is the central element for the Observatory on-site operations: it controls, supervises, and handles the data generated by the array elements.

Considering the criticality of the ACADA system for future Observatory operations, corresponding quality assurance provisions have been made at the different steps of the software development lifecycle, with focus on continuous integration and testing at all levels. To enable higher-level tests of the software deployed on a distributed system, an ACADA test cluster has been set up to facilitate testing and debugging of issues in a more realistic environment. Furthermore, a separate software integration and test cluster has also been established that allows for the off-site testing of the integrated software packages of ACADA and of the corresponding array elements. Here the software integration can be prepared, interfaces and interactions can be tested, and on-site procedures that are required later in the process can be checked beforehand, only limited by the simulation capabilities that are delivered as part of the software packages. Once preparations and testing with the off-site test cluster are completed, the integrated software can be deployed at the target site. The software packages and setup parameters are kept under configuration control at all stages, and deployment steps are documented to ensure that installations are reproducible. This methodology has been applied for the first time in the context of the integration of ACADA with the first CTAO Large-sized Telescope (LST-1) in October 2023.

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INTRODUCTION

1.1 The Cherenkov Telescope Array Observatory (CTAO)

The Cherenkov Telescope Array Observatory (CTAO) is the next-generation atmospheric Cherenkov gamma-ray Observatory[1]. CTAO will be constructed on two sites: One array in the Northern hemisphere that consists of 13 Imaging Atmospheric Cherenkov Telescopes (IACTs) located on the island of La Palma in the Canary Islands, Spain, at the Observatorio del Roque de los Muchachos, and the other one in the Southern hemisphere, consisting of 51 IACTs, located southeast of the Paranal Observatory in the Atacama Desert in Chile. Each array will contain telescopes of different sizes, for covering different energy domains.

1.2 The Array Control and Data Acquisition (ACADA)

To combine and orchestrate the different telescopes and calibration equipment (array elements), the Array Control and Data Acquisition (ACADA) system is the central element for the Observatory on-site operations: it controls, supervises, and handles the data generated by the array elements. ACADA comprises all software responsible for the high-level control of the array elements, for the environment monitoring at each CTAO site, for the efficient execution of pre-scheduled observations and of those triggered dynamically, for the data acquisition and volume reduction, and for the automated generation of science alerts. The ACADA system also provides a user interface for operators and astronomers.

1.3 CTAO Array Elements

The two CTAO arrays will be composed of the following array elements:

- Imaging Atmospheric Cherenkov Telescopes:
  - Large-Sized Telescopes (LST) with a 23m reflector (low-energy sensitivity)
  - Medium-Sized Telescope (MST) with a 12m reflector (CTAO's core energy range)
  - Small-Sized Telescope (SST) with a 4m reflector (high end of the CTAO's energy range)
- Calibration Equipment and Atmospheric Characterization Devices:
  - Raman Lidar
  - Wide-field Stellar Photometer
  - Moon/Sun Photometer
  - Illuminator
  - Weather Station
  - Ceilometer
  - All-sky Camera
  - Dust Counter
  - Lightning Sensor

INTEGRATION OF ACADA WITH CTAO ARRAY ELEMENTS

2.1 ACADA Quality Assurance Provisions

Considering the criticality of the ACADA system for future Observatory operations, at each stage within the ACADA software development lifecycle[2] provisions have been made to allow for corresponding Quality Assurance (QA) activities that accompany the different stages[3]. As shown in Figure 1, these consist of six stages, starting from the definition of specific quality objectives for the next release (stage 1), over supporting the internal review of the ACADA architecture and subsystem designs (stages 2 and 3), an evaluation of metrics

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and static code analysis results for subsystems (stage 4) and integration and verification of the system (stage 5), finishing the cycle with a quality-in-use evaluation (stage 6).

The definition of quality objectives and specifications evolves with each ACADA release, both by adding further quality criteria and metrics, and by tightening the target values of the already established criteria. This activity is performed during the Requirement Analysis phase of the ACADA development lifecycle. The goal is to reach the complete, envisioned scope of quality criteria and metrics with the last, planned ACADA release, so allowing to prioritize the early development of functionality while paving the way for progressively also improving the code quality.

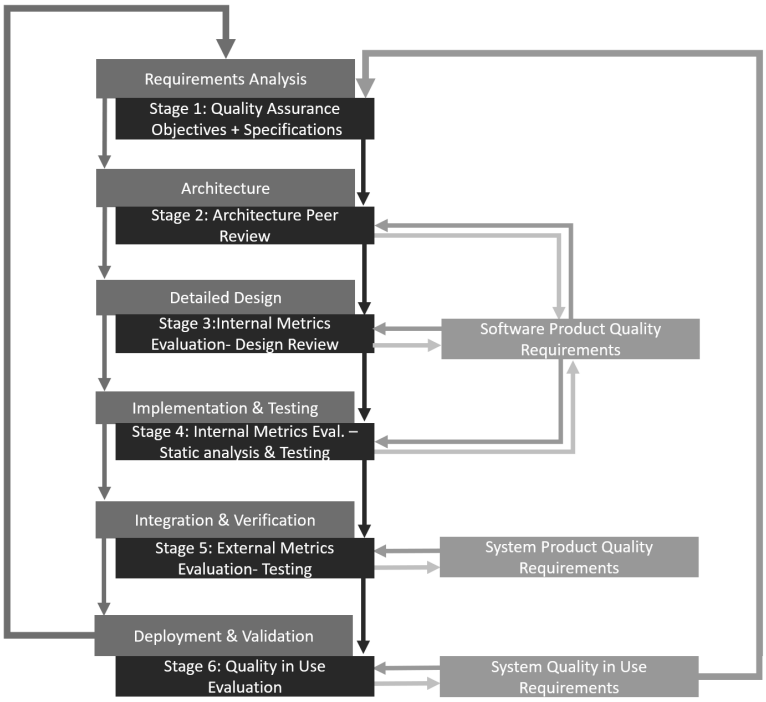


Figure 1: Stages of QA provisions foreseen within the ACADA software development lifecycle.

The architecture- and design review is the process where the ACADA architecture and the specific sub-system designs are checked and updated, in response to issues detected in the previous release, to changes of requirements, and to incorporate further details as these unveil. After the design review the Implementation & Testing phase begins.

During the development, ACADA sub-system developers can obtain quick feedback on their code quality via the static code analysis, which is implemented using the SonarQube[7] tool and where a customized quality gate has been defined. Even when throughout the development it is not required to meet the quality gate all the time, this becomes mandatory at the time of final integration. Furthermore, all quality metrics defined at sub-system level (internal metrics) also shall meet their corresponding targets at the time of integrating the release. There is however still work to be done to set up the infrastructure for obtaining and monitoring the internal metrics results.

Metrics related to the ACADA system level (external metrics) are evaluated once the system has been integrated and verified successfully. Like the internal metrics, also here still more work must be done to establish the

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framework to develop, obtain and monitor the respective metrics. System verification is based as much as possible on automated use-case tests, which are then linked to their corresponding, underlying requirements. The quality-in-use evaluations are envisioned to be included at a later stage of the construction phase of the CTAO.

Following this quality assurance approach, at an outcome it is expected that a corresponding ACADA release is sufficiently complete and tested to proceed with its integration with the other Observatory systems, specifically, with the CTAO array elements. The process has been validated and further improved during the development of ACADA Release 1[5], which was intended to be integrated with a CTAO telescope for the first time.

2.2 ACADA Test & Integration Environment

For the development of ACADA, a dedicated Continuous Integration (CI) infrastructure based on Jenkins[6] has been set up[2]. This allows for the automated integration and testing of the system via corresponding pipelines, providing quick feedback on the quality of the submitted code. This CI environment is however limited to a single machine, so does not fully represent the distributed nature of ACADA. Therefore, a separate ACADA Test Cluster has been set up to facilitate testing and debugging of issues in a more realistic environment, to enable higher-level tests of the software deployed on a distributed system. Furthermore, a separate Software Integration and Test Cluster has been established that allows for the off-site testing of the integrated software packages of ACADA and of the corresponding array elements, i.e., beyond the scope of just ACADA. Figure 2 shows a summary view of the different parts of the ACADA/CTAO software integration and test infrastructure.

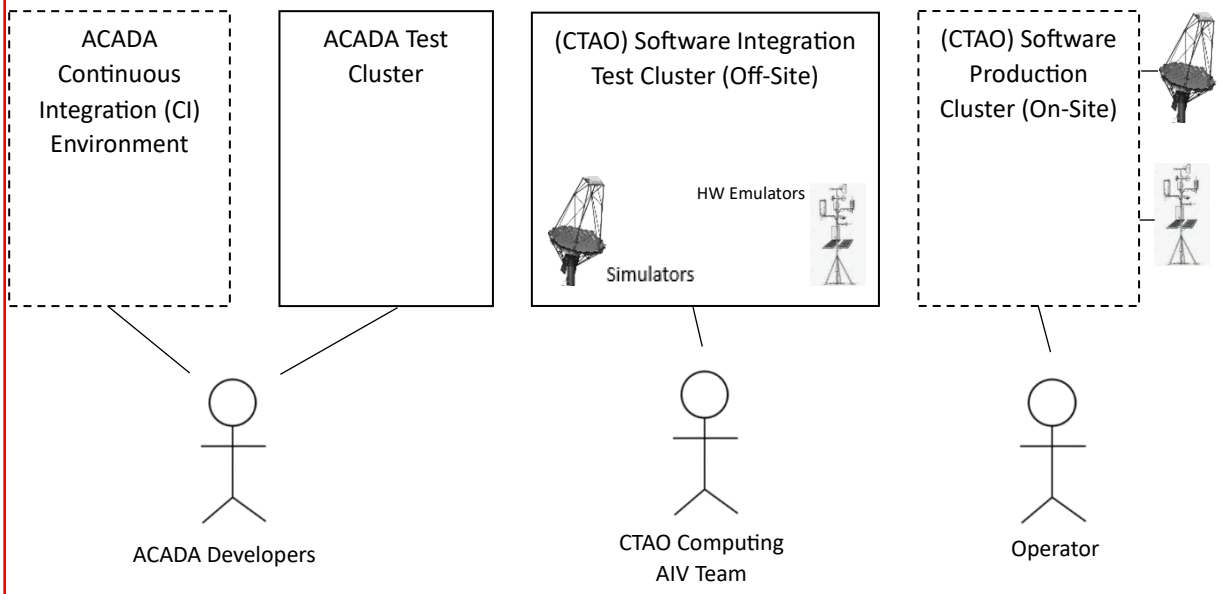


Figure 2: Sketch of the ACADA/CTAO software integration and test infrastructure.

The ACADA Test Cluster currently consists of four nodes, number that can be expanded as the need arises. Four nodes already allow for the setup of a small distributed system where the different ACADA components can be deployed. Developers can access these nodes from remote, and the allocation of use of the nodes is coordinated by the ACADA AIV Team.

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In addition, a separate Software Integration Test Cluster has been set up for the off-site integration of ACADA with the lower-level control- and data acquisition software of the different CTAO array elements: on this multi-node computing cluster it is possible to make use of available simulators and hardware emulators to mimic the production system as close as possible. At this stage of the CTAO construction the production- and off-site test environments are still not sufficiently standardized and simulation capability is just being built up, meaning that the added value of the off-site tests remains somewhat limited. However, the goal is to keep developing these aspects in the coming years to allow for the effective off-site integration and test of ACADA with most if not all CTAO array elements. Systematic and automated interface, integration and deployment tests are also envisioned to be developed in the longer term.

2.3 Deployment and Testing with CTAO Array Elements

Once preparations and testing at the off-site test cluster are completed and the respective deployment procedures are established, the integrated software can be deployed at the respective target site. The target site can be one of the Observatory array sites, or it could be a laboratory setup at a partner institute or company that builds CTAO array elements or their key subsystems. During this process, the software packages and setup parameters are kept under configuration control at all stages, and deployment steps are documented to ensure that installations are reproducible.

Once the integrated software has been deployed, a first set of interface tests are foreseen, which focus on the specific interfaces between ACADA and the integrated array element, mainly related to the monitoring of the element's subsystems, to sending commands and to receiving feedback on status, to log and alarm notifications, to the data acquisition, and to the time synchronization between both subsystems. For the interface tests only those parts of the system are started up that are required to test the interface to avoid the potential interactions from other subsystems that could mislead the tests. The goal is to check and confirm that the defined interfaces have been correctly implemented on both sides.

Apart from the interface tests also a second test suite is prepared that focuses on using the whole system, thus considering tests that require the interaction of several or all parts of the system, and which culminates with an end-to-end test of the available system capabilities. It is noted that at this stage no formal verification of requirements is envisaged yet, so the tests remain at the level of checking the general functionality of ACADA with a CTAO array element subsystem, retiring risks related to the overall system architecture, design, and interfaces, and obtaining early feedback on its functionality and usability.

2.4 First Trial with the CTAO LST-1 Telescope

This methodology has been applied for the first time in the context of the integration of ACADA with the first CTAO Large-sized Telescope (LST-1), which started performing astronomical observations in late 2019[4]. The planning of this exercise began in late 2021, bringing together the core developers and management teams from the LST-1 and ACADA sides. The methodology outlined in this paper was presented and discussed with all participants, and the related activities were collected and described in an Integration & Test Plan. This plan resulted to be an effective tool to converge on details and decisions within a large group of people, who worked on this plan collaboratively, and which ultimately was reviewed and signed off by the corresponding management in October 2022.

During the first half of 2023 the development ACADA Release 1[5] was completed and the defined quality criteria were checked at ACADA sub-system and system levels. Some observed non-conformances were recorded, reviewed, and corresponding dispositions were agreed upon, and it was concluded that Release 1 was of satisfactory quality to proceed with the integration and test with the LST-1 telescope.

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Consequently, off-site integration and test activities were performed using the test clusters and the available simulators, and detailed test procedures were prepared and tested. In support of preparing and consolidating the on-site software deployment, also two hosts of the telescope's computing cluster were made available for use by the ACADA Team.

The dates for the tests of the integrated ACADA and LST-1 software were then confirmed for October 2023, split into a first campaign on site focusing on the interface tests, and a second one focusing on the end-to-end tests of the system. Both campaigns were planned to be separated by one week to allow for the debugging and fixing of the issues that likely would be encountered during the first test campaign. In addition, prior to the on-site campaigns some interface tests that were believed to have a higher technical risk were anticipated, including tests of the data acquisition system and its related time synchronization, checks of the monitoring system, and preliminary telescope interface tests.

Having followed the steps of the methodology presented in this paper, having retired higher technical risks ahead of time and having had a good portion of luck with the weather conditions on site, both test campaigns could be performed according to the plan and following the detailed test procedures. Naturally, a significant number of issues were detected during these campaigns and recorded for future follow-up, but all identified ACADA key functionalities could be successfully executed in the on-site environment. The outcome is that ACADA worked effectively with a CTAO telescope (LST-1) for the first time.

CONCLUSIONS

The methodology that is applied to integrate the ACADA system with other CTAO array elements starts with the planning of the detailed integration and test activities, assures a satisfactory quality of the ACADA software for integration, makes use of off-site test clusters for more realistic testing and for preparing the software integration and deployment, it considers the development of detailed test procedures for interface and end-to-end tests and for deploying the integrated software on site, and it culminates with the execution of the tests with the respective array element.

We acknowledge that at this stage of the CTAO construction the production- and off-site test environments are still not sufficiently standardized, and simulation capability is just being built up, meaning that the added value of the off-site tests remains somewhat limited. However, the goal is to keep developing these aspects in the coming years to allow for the effective off-site integration and test of ACADA with most if not all CTAO array elements. Systematic and automated interface, integration, and deployment tests are also envisioned to be developed in the longer term.

As can be expected, many issues were identified and need to be worked off, but the successful integration and test with the first CTAO Large-Sized Telescope (LST-1) in La Palma gives sufficient reassurance that this methodology can also be applied to other telescope types and to calibration equipment. It is anticipated that for each CTAO array element, and at least for the first-time integration and test activities, specific variations of this integration methodology will have to be tailored that consider the available software, simulators, hardware, and human resources in each case.

Even when still at a very early stage, the methodology that has been established for the integration of ACADA with the different CTAO array elements appears to be effective for structuring and performing the first-time integration of new telescope types and calibration equipment, thus allowing to retire related risks at an early stage of the construction of the Observatory, while paving the ground for an increasingly powerful software test infrastructure in support for the upcoming commissioning and operations phases.

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