ASTRI Mini-Array On-Site ICT Infrastructure for High-Availability and Efficient SCADA Operations

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Outline

This presentation describes the Information and Communication Technology (ICT) infrastructure developed for the ASTRI Mini-Array and its system configuration.

The ICT has been specifically designed to support the Supervisory Control and Data Acquisition (SCADA) software and includes the hardware platforms and services required for the installation, commissioning, and operation of the nine telescopes of the array. Particular attention is given to the architectural solutions adopted to ensure high availability and reliability of the system.

- ASTRI Mini-Array Introduction
- ICT System Overview
- Virtual Telescope Control System
- Storage Architecture
- Network Architecture
- Kubernetes Architecture
- SCADA Architecture
- SCADA Deployment Across the ICT Infrastructure
- ICT Integration Timeline
- Conclusions

ASTRI Mini-Array

ASTRI (Astrofisica con Specchi a Tecnologia Replicante Italiana) is an international project led by INAF aimed at deploying a small array of Imaging Atmospheric Cherenkov Telescopes (IACTs) for very-high-energy gamma-ray astronomy.

Key characteristics

- Array of 9 dual-mirror Cherenkov telescopes
- 4-meter class Small-Sized Telescopes (SST-2M)
- Installed at the Teide Observatory (Tenerife, Spain)
- Designed to detect gamma rays above ~1 TeV

Scientific and technological goals

- Pathfinder for the Cherenkov Telescope Array Observatory (CTAO)
- Study of very-high-energy astrophysical sources

Operational requirements

- Coordinated array observations
- High-rate Cherenkov event acquisition
- Continuous monitoring and control of array subsystems

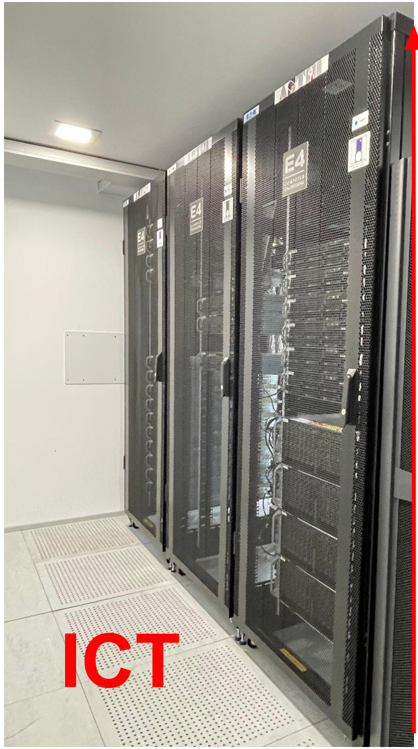
ASTRI Mini-Array

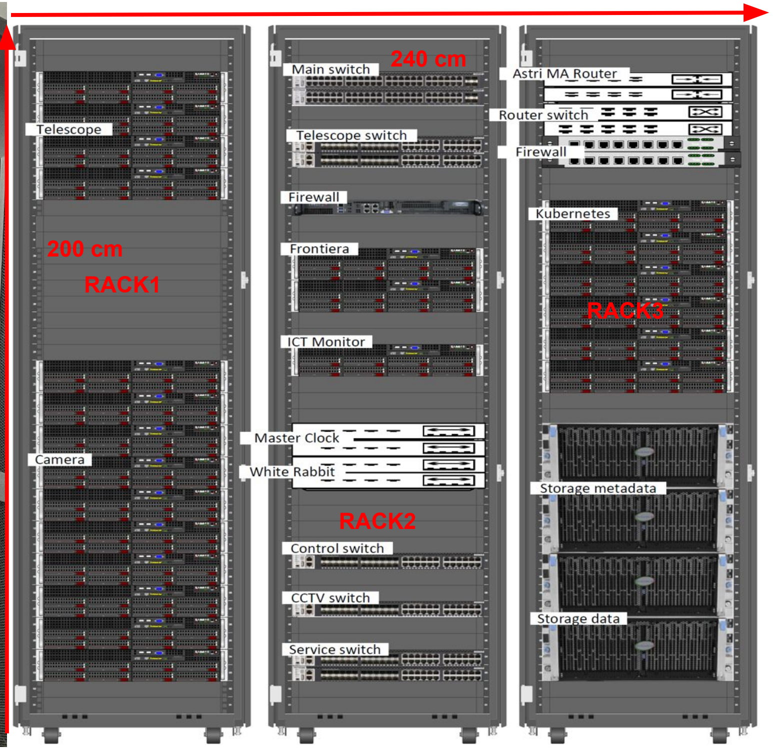
Seven telescopes have already been installed at the Teide Observatory in Tenerife, and two are currently acquiring Cherenkov events during the commissioning and science verification phase. **The array is supported by a dedicated on-site Information and Communication Technology (ICT) infrastructure that enables development, commissioning, and long-term scientific operations.**

ICT System Overview

26 servers, 10 network switches, 2 White Rabbit (WR) nodes, 2 master clocks, 2 firewalls, 2 routers, and 200 TB of storage

a fully redundant and high-reliability infrastructure designed to operate ASTRI-MA continuously for at least 10 years.





ICT System Overview- Design

ICT Designed for SCADA Operations

- **Purpose-built infrastructure** – The ASTRI Mini-Array ICT is designed specifically to run the **SCADA system controlling, monitoring the telescopes and data acquisition**, rather than being a generic computing environment.
- **Resource optimization through virtualization** – The use of **Virtual Machines and containerized services** enables flexible deployment, efficient workload distribution, and simplified system management.
- **High availability by design** – Reliability is achieved through **carefully engineered redundancy and elimination of single points of failure**, ensuring service continuity across the infrastructure.
- **Efficient and sustainable design** – The architecture addresses constraints of **budget, limited on-site space, and energy efficiency**, ensuring reliable operations with optimized power consumption.
- **All these characteristics are achieved through a modular architectural design**, where the **infrastructure is organized into specialized subsystems**, each dedicated to a specific function, built using the most appropriate technologies and properly interfaced with the others.

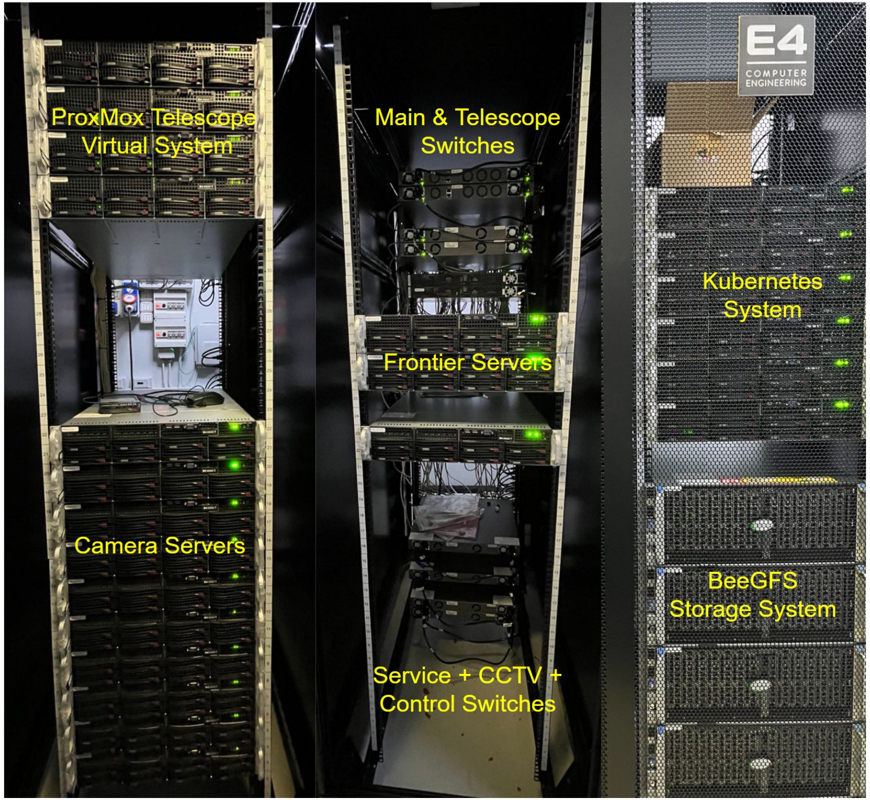
ICT System Overview - Modules

Main subsystems

- **Virtual Telescope Control System (TCS):** Proxmox-based virtual environment hosting SCADA control services and operational software.
- **Data Acquisition System (ADAS):** Dedicated camera servers receiving data streams from the Cherenkov cameras and auxiliary instruments.
- **Distributed Storage System:** BeeGFS parallel file system used for temporary on-site storage and data sharing.
- **Computing Platform:** Kubernetes cluster supporting monitoring, data-quality services, and distributed applications.
- **Timing System:** GPS-synchronized master clock and White Rabbit network for sub-nanosecond time distribution.

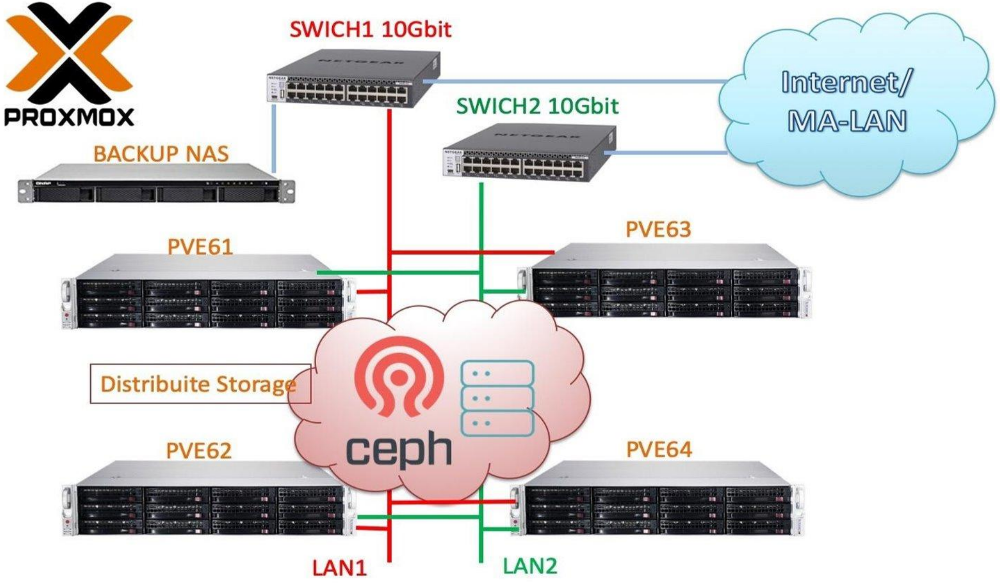
Design goals

- High availability (no single point of failure)
- Support for telescope array operations
- High-throughput data acquisition and processing



Virtual Telescope Control System

- **Professional virtualization platform based on Proxmox Virtual Environment**, providing management of virtual machines, software-defined storage and networking, and high-availability clustering.
- The platform hosts the virtual machines used for the **Telescope Control System (TCS)**, the **ALMA Common Software (ACS) components**, and **general infrastructure services**, including the **General Network Services VM**.
- The **Virtual TCS implementation** leverages the experience developed within **INAF** in the deployment and operation of complex scientific infrastructures.
- The system is implemented as a **hyperconverged high-availability cluster** composed of **4 physical servers**, interconnected through **dual 10 Gbit/s switches**.
- This architecture allows the TCS infrastructure to **tolerate the failure of a server and/or a network switch**, ensuring continuous operation.



160 physical CPU cores 320 threads
1 TB RAM
48 TB gross SSD storage

Storage Architecture

The storage system acts as the central data repository for the ASTRI Mini-Array, storing operational data and **buffering scientific data** before transfer to the off-site data center in Rome. Built on a **distributed BeeGFS architecture**, it enables parallel access by acquisition, monitoring, and processing systems, while ensuring data protection through **RAID6 disk redundancy** and **server-level data replication**, allowing continued operation even in the event of a server failure.

Key characteristics

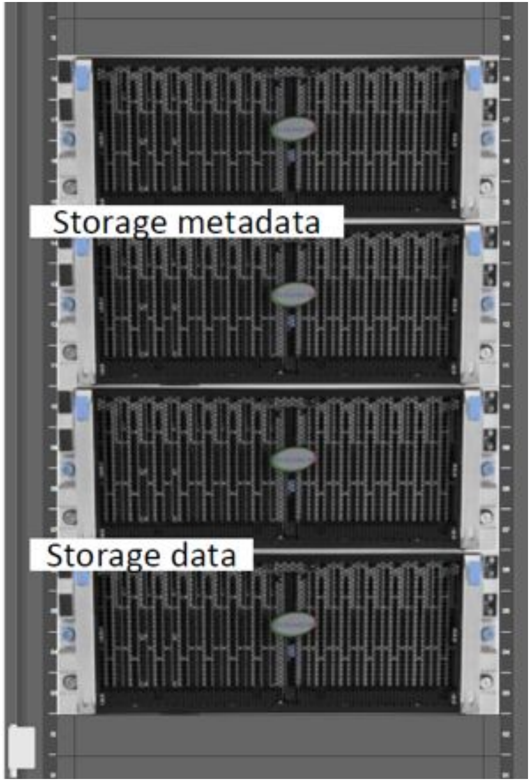
- **Distributed parallel file system:** BeeGFS
- **Storage cluster:** 4 storage servers
- **Dual-role nodes:** two servers acting as metadata servers
- **Data replication:** server-level replication enabling continued operation in case of a storage server failure

Stored data

- **Raw data** from Cherenkov cameras and interferometer instruments
- **Data from monitoring and alarm systems**
- **Online observation quality data**
- **AIV Data**

Performance requirements

- **~200 TB** total storage capacity
- **~2 GB/s** write throughput
- **~1 GB/s** concurrent read throughput



Network Architecture

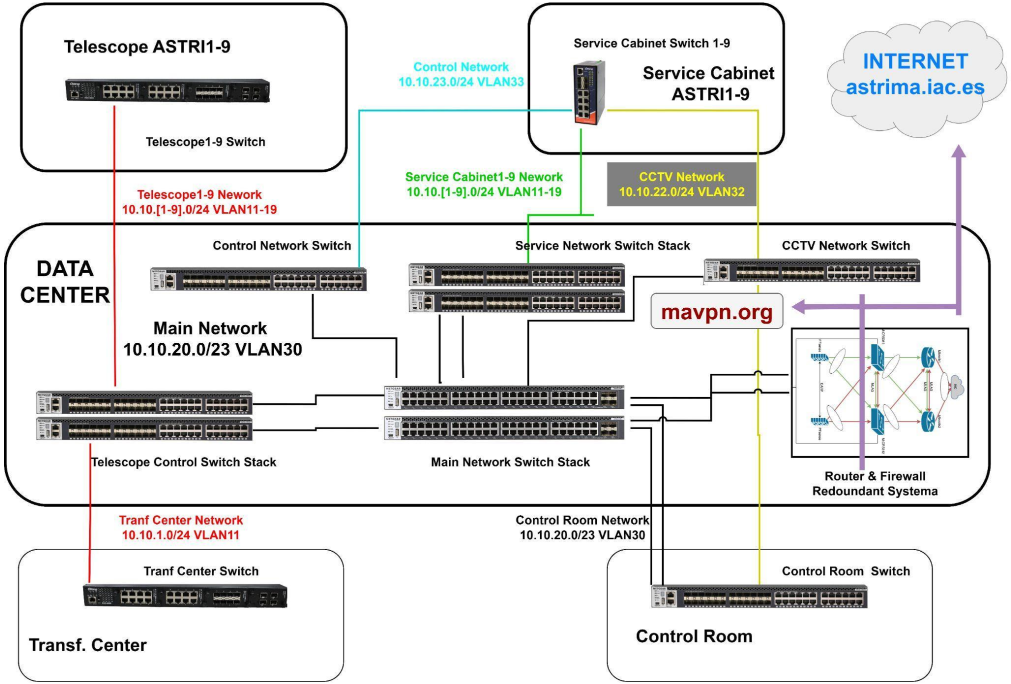
The ASTRI ICT infrastructure relies on a high-performance and redundant network designed to guarantee reliable communications between telescopes, data center systems, and external facilities

Main network components

- **Main Network**: Core network connecting computing systems, storage, acquisition servers, and services.
- **Telescope Network**: Dedicated fiber connections linking telescopes with the data center and control systems.
- **Service Network**: Infrastructure network for management interfaces, sensors, and hardware monitoring.
- **Control and Safety Network**: Dedicated network connecting PLC safety systems and telescope control devices.
- **CCTV Network**: Independent network for surveillance cameras.

Connectivity

- Optical fiber links (1–10 Gbit/s) between telescopes and data center
- 10 Gbit/s switching infrastructure inside the data center
- **Redundant router and firewall system for Internet connectivity**



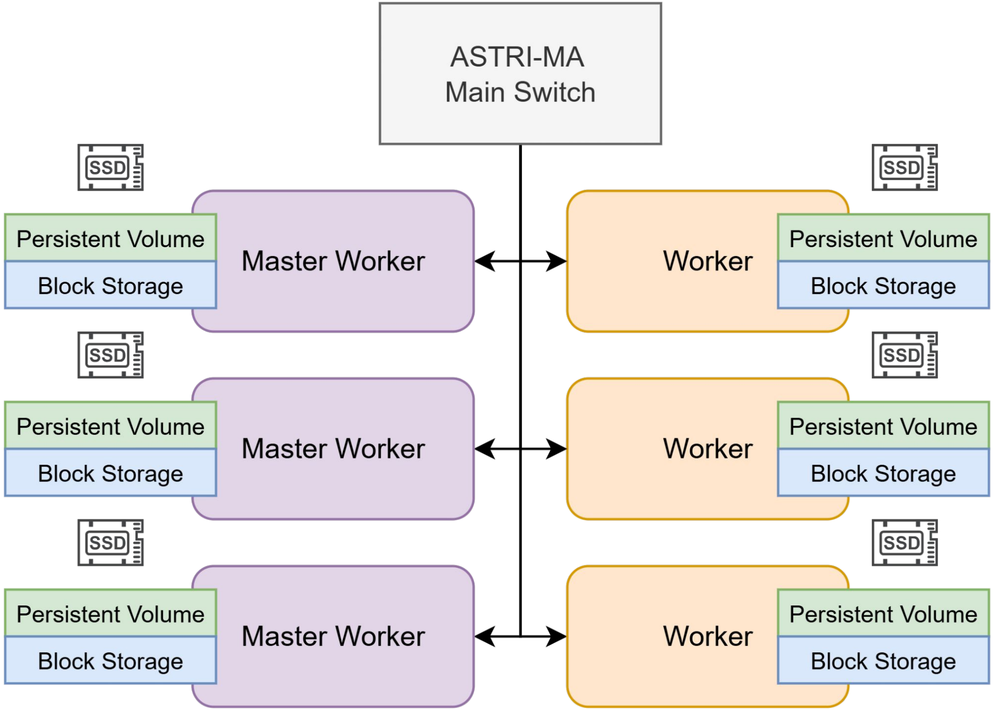
Computing Architecture

The computing system is based on a Kubernetes cluster, designed to execute all compute-intensive operations of the ASTRI Mini-Array software infrastructure.

The platform is engineered for high availability, scalability, and automated orchestration, ensuring reliable operations without on-site intervention.

The Kubernetes cluster consists of 6 physical compute servers:

- Control Plane Nodes
  - 3 Master-Worker nodes
  - Host Kubernetes core services (API Server, Scheduler, Controllers, etcd)
  - Can also run application workloads
- Worker Nodes
  - 3 Worker nodes
  - Dedicated to running application pods and distributed services



SCADA Architecture

The SCADA software system supervises telescope operations, monitoring, and data services across the ASTRI Mini-Array through a distributed software architecture.

1. Observatory Control Layer

- Startup-System and Human-Machine Interface: coordinates the entire array operations and executes observation plans.
- Manages Scheduling Blocks / Observing Blocks and orchestrates subsystems.

2. SCADA Core Services

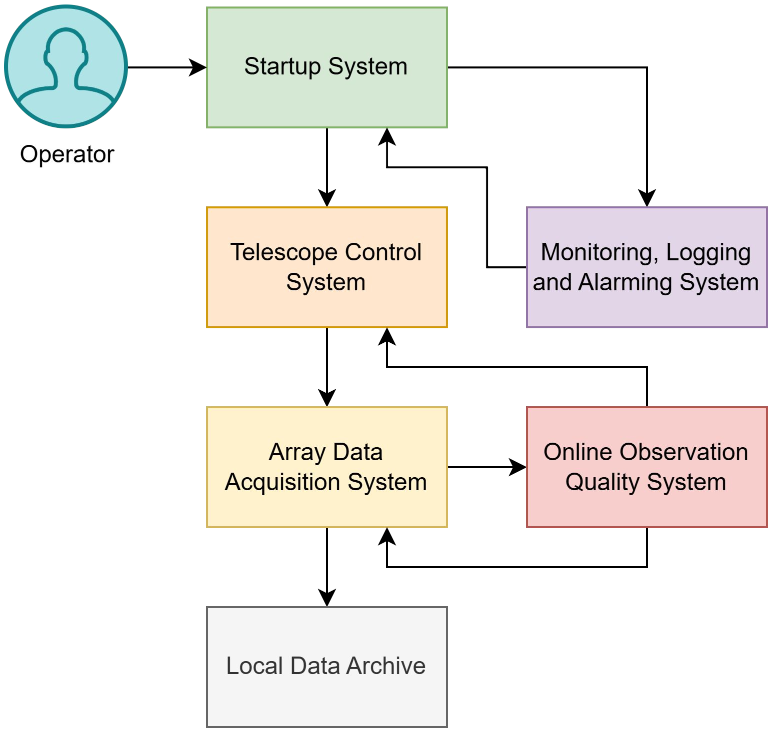
- Supervisory control of all subsystems and site infrastructure
- State management and configuration of assemblies
- Alarm handling and health monitoring
- Telemetry collection and command distribution

3. Subsystems Integration

Main subsystems controlled by SCADA:

- Telescope Control System (TCS)
- Array Data Acquisition System (ADAS)
- Online Observation Quality System (OOQS)
- Environmental and calibration systems

Communication between components is based on distributed services and event streaming.



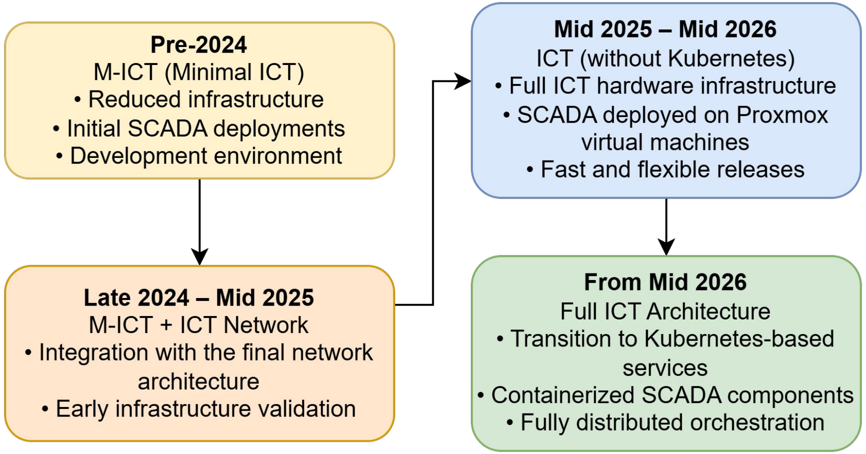
SCADA Deployment Across the ICT

The ASTRI ICT infrastructure was designed not only to host the final operational system, but also to **support different deployment strategies during the evolution of the software stack**.
This approach allows the infrastructure to remain stable while the software progressively transitions toward a fully distributed and containerized architecture.

The ICT infrastructure supports **multiple execution environments**.

SCADA services can currently run on **virtual machines deployed on the Proxmox virtualization platform**, which simplifies deployment, debugging, and software iteration.
At the same time, the infrastructure already includes a **Kubernetes cluster**, originally designed to host distributed services such as **Kafka, Cassandra, OOQS, and monitoring systems**.

This dual capability allows the system to **adapt the deployment strategy to the maturity of each software component**.



ICT Integration Timeline 1/2

Birth of m-ICT & First Telescope Operations

2022

- m-ICT is installed (initial computing + storage + network environment).
- ASTRI-1 (first telescope) is deployed.
- AIV begins mechanical tests on ASTRI-1 using m-ICT.

Mid 2023
- AIV Team test the mechanics of ASTRI-1
- Arrival of Camera 0, the first optical camera.
- It is mounted on ASTRI-1, enabling combined mechanical + optical tests.

End of 2023
- The SCADA team releases the first core services (Kafka, Cassandra, InfluxDB, etc.) These components are deployed entirely on m-ICT.
- AIV continues manual telescope operations through m-ICT.

2023

First SCADA Components & Early Optical Integration

First Full SCADA Deployment / ICT Installed / First Light

2024

- March: first complete SCADA deployment on m-ICT.
- ADAS software linked to the optical camera and used for data processing.
- October: the new ICT is installed (new compute, storage, cameras, network).
- m-ICT remains operational but becomes secondary.
- November: first light of ASTRI-1.
- All operations still run on m-ICT during this phase.

ICT Integration Timeline 2/2

Infrastructure

- Several AIV virtual machines are moved to the ICT.
- New camera servers on ICT replace the old m-ICT camera workstation.
- m-ICT activity decreases progressively.

SCADA

- SCADA reaches v3.2.0, still fully hosted on m-ICT.
- Deployment of SCADA v4.0.0 begins:
  - First version running on the ICT, though only partially using Kubernetes.

Telescopes

- March: installation of Telescopes 2 to 7.
- October: first light of ASTRI-3.

AIV

- Achieves simultaneous mechanical control of all telescopes
- using a combination of m-ICT + ICT resources.

Optics

- July: delivery of Optical Camera 1 (second optical unit).

2025

Transition Year: Migration Toward ICT

2026

Full ICT Operation / SCADA and AIV Transition Completed

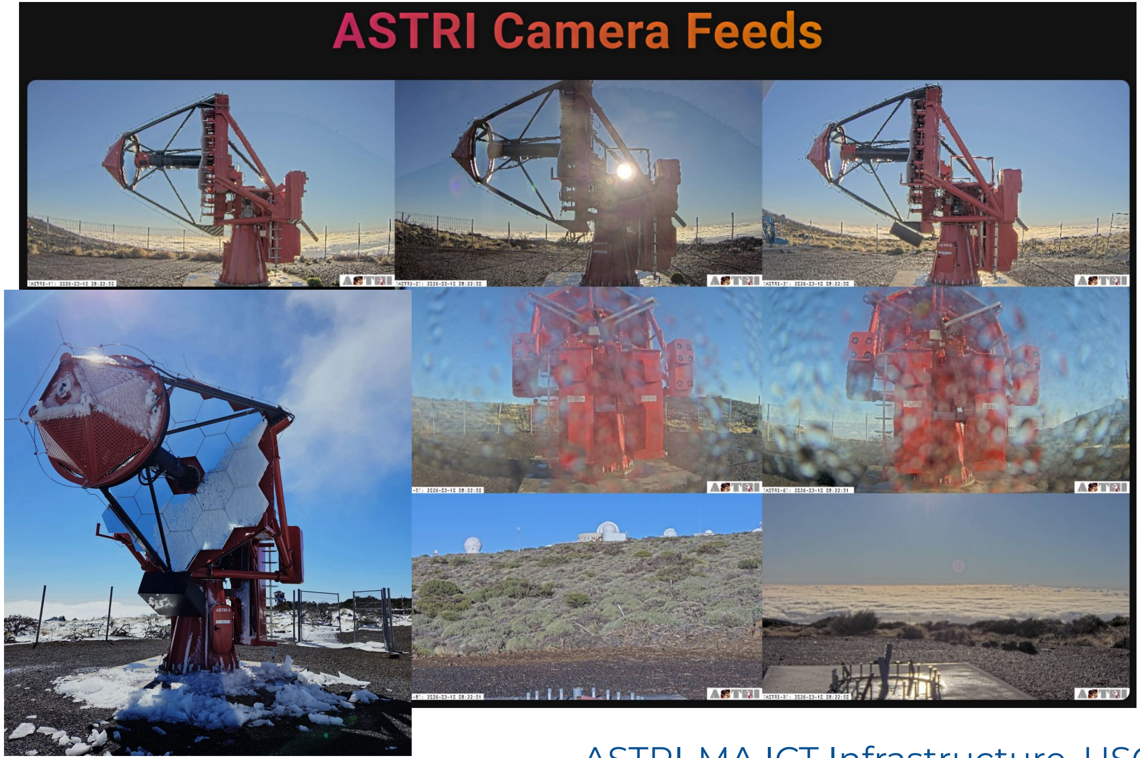
- SCADA migrates all its components to the appropriate ICT clusters (services distributed across Kubernetes and dedicated hosts).
- Delivery of all remaining optical cameras.
- AIV reaches full operational capability: complete control of all telescopes with their optics.
- m-ICT is decommissioned.

CONCLUSIONS

Purpose-built ICT for SCADA operations – The ASTRI Mini-Array infrastructure demonstrates the effectiveness of designing the ICT platform specifically around the requirements of the SCADA control system rather than adopting a generic IT environment.

Efficient and resilient architecture – Virtualization, containerization, and carefully engineered redundancy enable efficient resource utilization, high availability, and continuous multi-telescope operations.

Modular and sustainable design – A modular architecture based on specialized subsystems allows the use of the most appropriate technologies while meeting constraints of space, budget, and energy efficiency.



Thank you for your time

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