Research in Astronomy and Astrophysics

RESEARCH PAPER

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To cite this article: Zhi-Fei Wang *et al* 2026 *Res. Astron. Astrophys.* **26** 075014

Research in Astronomy and Astrophysics, 26:075014 (12pp), 2026 July
https://doi.org/10.1088/1674-4527/ae520f
CSTR: 32081.14.RAA.ae520f

Design and Implementation of the Operational Control Platform for the CART 40 m Radio Telescope

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Received 2025 November 5; revised 2026 February 11; accepted 2026 February 20; published 2026 April 28

Abstract

The China–Argentina Radio Telescope (CART) has a diameter of 40 m, which was funded by the Ministry of Science and Technology of China. It is a milestone project between China and Argentina. As the largest single dish and Very Long Baseline Interferometry unit in South America, CART 40 m bears China's advanced technology in the manufacturing of large radio telescopes and is the first large aperture facility built abroad for carrying out astronomical co-investigations. Here we present the design and implementation of the operational control software for the CART 40 m. We outline the design philosophy, technical framework, functional verification, and application prospects of the software platform. Based on an in-depth analysis of the project background, a novel distributed architecture design was proposed, along with a real-time interaction solution between the monitoring interface and backend service interfaces. Comprehensive functional testing has verified the effectiveness and stability of the software, providing reliable technical support for CART 40 m observations and operation. The successful design and implementation of this software platform have not only significantly enhanced operational efficiency and resource management but also laid a solid foundation for its precision and reliability. This achievement offers crucial technical support for realizing the long term stable operation abroad.

Key words: telescopes – site testing – reference systems

1. Introduction

The international cooperation project between the National Astronomical Observatories of the Chinese Academy of Sciences and the National University of San Juan, Argentina, for Very Long Baseline Interferometry (VLBI), known as the China–Argentina Radio Telescope (CART) 40 m project, is a significant "Going Global" initiative of the Chinese Ministry of Science and Technology. The CART 40 m project signifies the advanced level of China's independent research, development, and production of large-aperture radio telescopes. Upon completion, it will become the largest single-dish radio astronomical telescope and VLBI unit in South America, as well as the first large-aperture astronomical observation facility established by China overseas. It is of great importance for the long-term development of China's astronomical endeavors and deep space exploration activities. The project was initiated in 2010 December, with the goal of constructing the largest single-dish radio telescope in South America. Following project approval, the Chinese side undertook facility research and tender processes, with active participation from the Argentine side. The site selection process faced challenges, but after thorough evaluation and surveying, the site was finalized in 2015. Despite changes in the Argentine government and other challenges, the project has progressed with the joint efforts of both parties and support at various levels. Currently, the project is advancing smoothly and is expected to be completed and operational soon. It will not only promote astronomical research but also enhance scientific, technological, and cultural exchanges between China and Argentina, serving as a vital platform for bilateral cooperation (Li 2019, 2026).

The VLBI observation technology for radio telescopes initially evolved from the Field System (FS) control software developed by NASA (Himwich 2003; Xue 2011). Due to its universal nature, this software cannot meet the specialized requirements for controlling the unique equipment at our local station. Additionally, some specific functions of our local station system are not supported by FS. This compels us to develop a proprietary control system tailored to our station, in order to fulfill its specialized needs and enhance operational efficiency.

During observations, the FS software is responsible for reading SNAP commands from the observation schedule and accurately sending these commands to various devices within the observation station, thereby achieving precise control over the synchronized operation of each device. With its maturity and stability, the FS software has become an important tool in the field of VLBI observations for radio telescopes.

However, the FS software has certain limitations in its design and functionality. Since the software needs to be compatible with a variety of different devices, many of which are not necessary for the CART 40 m, this leads to resource wastage and reduced operational efficiency. To address this issue, it is necessary to redesign and develop a more tailored control software system based on the actual equipment requirements of the CART 40 m. This design aims to optimize resource utilization, improve operational efficiency, while ensuring the high precision and reliability of the control system. Through a customized software solution, the CART 40 m will be able to perform VLBI observations more efficiently, thereby promoting the in-depth development of astronomical observation research. To better adapt to requirements, the control system is fully based on digital technology.

The primary goal of the CART 40 m operational control system is to ensure efficient operation in accordance with the predetermined observation plan. This encompasses automated tasks such as target selection, tracking, data acquisition, and analysis to optimize observation efficiency. Consequently, this system guarantees the telescope's pointing accuracy, allowing for precise alignment with celestial objects, real-time acquisition of signals from the radio telescope, parsing and conversion of these signals into usable data formats, monitoring the status of system equipment, and detecting and predicting faults to ensure the telescope's long-term stable operation (Xue 2011).

2. Requirement Analysis of the Operational Control System

In designing radio telescope control software, requirement analysis is the cornerstone of system development. Through in-depth communication with the technical staff, operators, and researchers of the CART 40 m project team, coupled with extensive research on the development of operational control systems both domestically and internationally, and considering the system's functional and technical requirements, the overall structure of this software and the necessary functions for each module were designed.

2.1. Development Status

Internationally mainstream radio telescope control software systems possess significant advantages in terms of functional completeness and scalability.

The control system exemplified by Atacama Large Millimeter/submillimeter Array features a middleware-free distributed control system, ensuring good maintainability. It successfully engineered and standardized complex distributed control systems. Through a meticulously designed, open standards-based architecture and toolchain, it ensures high performance and reliability while significantly enhancing development efficiency, system maintainability, and scalability. It effectively manages the software complexity inherent in large-scale international collaborative projects. Its component-based, layered, and decoupled design philosophy, along with developer-friendly high-level abstractions, is its most prominent strengths (Chiozzi et al. 2002). The Square Kilometre Array project employs the open-source distributed control system TANGO, which offers excellent scalability and processing efficiency (Chiozzi et al. 2002). In summary, these internationally advanced systems have evolved mature solutions in key technology domains such as modular design, distributed resource scheduling, and real-time data processing. However, its architectural complexity and resource dependencies precisely reveal the pitfalls of over-engineering and lack of flexibility when addressing specific observational requirements. Their technological advancements provide a crucial reference for the intelligent evolution of astronomical observation equipment. Nevertheless, their system architecture complexity and infrastructure reliance considerably vary from the actual operational requirements of the CART 40 m telescope—the latter necessitates a balanced approach that takes into account control precision, system stability, and engineering economy. This variance underscores the imperative for tailored control system development for regional astronomical observation facilities.

The NanShan 25 m radio telescope is deployed at the NanShan Observation Station of the Xinjiang Astronomical Observatory. It is the second VLBI-dedicated radio astronomical observation facility built in China following the 25 m radio telescope at the SheShan Observation Station of the Shanghai Astronomical Observatory. It features advanced characteristics such as multi-band, wide bandwidth, low noise, high efficiency, and high pointing accuracy. Based on the Windows XP system, it is implemented using Visual C++, Zhao et al. (2007). The FS computer issues commands to the control computer via the TCP/IP protocol.

In summary, currently, mainstream radio telescope control systems both domestically and internationally primarily adopt a distributed architecture and mainly rely on local area networks for communication. The CART system, referencing mainstream control methods from both domestic and international sources, combines the advantages of other systems with its own requirements. It has adopted a Browser-Server (BS) architecture, which differs from the traditional client-based control approach, and offers unique features such as cross-platform accessibility.

2.2. User Requirements

Automated Observation Control. Operators require software to facilitate automated control of the radio telescope, encompassing functions such as celestial object tracking, target selection, and equipment status monitoring.

Multi-device Coordination. Support for coordinated operation among multiple devices, including the telescope main unit/body, receiver, UDC, MARK6, etc., is essential to ensure communication and coordination between these devices.

Real-time Data Feedback. Operators need to monitor the telescope's status parameters in real-time (such as command position, actual position, position deviation, communication status, etc.) to promptly adjust observation strategies.

Data Acquisition and Processing. Researchers require software that can efficiently acquire radio wave signals and facilitate subsequent data analysis and processing. Flexible Observation Modes: The software supports various observation modes, including single-point observation and VLBI observation, to cater to diverse scientific research requirements.

Remote Monitoring and Maintenance. The system must support remote monitoring capabilities, enabling administrators to swiftly identify and resolve issues when they arise. Log Recording and Management: Maintain a record of system operational status and activity logs for subsequent analysis and troubleshooting of problems.

2.3. Functional Requirements

Task Scheduling and Execution. The software must be capable of receiving observation task instructions and scheduling them in accordance with the observation plan's priority.

Device Control. The software should achieve precise control of hardware, such as the telescope servo system and receiver, via shared memory (e.g., using the shm_addr module).

Data Transmission and Storage. The software must support the acquisition, transmission, and storage of radio wave signal data, ensuring the integrity and reliability of the data.

User Interface. The system offers a user-friendly graphical user interface (GUI) that enables operators to configure tasks and monitor the system status.

Multi-language Support. Given the international collaboration between China and Argentina, the software must support Chinese, English, and Spanish languages.

2.4. Performance Requirements

The operational control system of the radio telescope demands high real-time performance. The interface refresh time of the control system and the response time of the servo system must be kept at the millisecond level to ensure precise tracking of the telescope. The data acquisition and processing module must meet high throughput requirements to prevent data loss or delay.

The software must stably operate over the long term and maintain normal operation in complex environments. Comprehensive error detection and recovery mechanisms should be provided to ensure the system can quickly resume normal operation in the event of abnormal conditions.

Due to the need for technological upgrades of the radio telescope, the software design must have good scalability, for instance, support for adding new devices and observation modes.

2.5. Technical Requirements

System Architecture. The software employs a modular design for easy functional expansion and maintenance. Interprocess communication utilizes shared memory to enhance system efficiency.

Data Format and Interfaces. Unified data formats are defined to ensure efficient and reliable data exchange between modules. Standard API interfaces are provided for seamless integration with other astronomical observation systems.

Security. The system includes user permission management functions to prevent unauthorized operations. Sensitive data is encrypted during storage and transmission to ensure data security.

2.6. User Experience Requirements

User-friendly Interface. An intuitive graphical interface is provided to reduce the learning curve for operators. Support for hotkeys and batch processing functions is offered to improve work efficiency.

Help and Documentation. Detailed user manuals and technical documentation are provided to assist newcomers in quickly getting started. Real-time help tips are integrated within the interface to enhance the user experience.

3. Design and Implementation of the CART 40 m Operational Control System

3.1. Software Architecture Design

The distributed control software design for the radio telescope employs a layered architectural philosophy to ensure system flexibility and maintainability. The overall system architecture is divided into four layers: the Presentation Layer, Application Layer, Device Manager Layer, and Infrastructure Layer, as depicted in Figure 1. This layered approach assigns each layer distinct functional responsibilities while preserving low coupling and high cohesion among the layers.

The operation control system adopts a hierarchical and distributed architecture, which is vertically divided into four tiers, namely the presentation layer, application layer, device management layer, and infrastructure layer. Through the standardized design of inter-layer interfaces and the adoption of middleware to enable efficient interconnection and data exchange, this layered architecture not only endows the system with a distinct logical structure, but also lays a solid foundation for modular development and flexible scalability of the system.

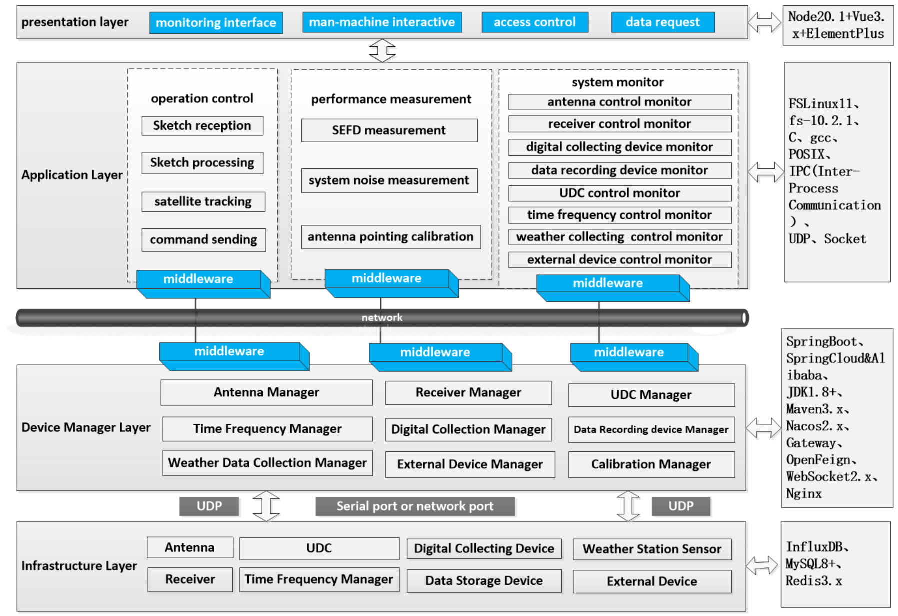

Figure 1. Operational control system architecture.

3.1.1. Presentation Layer

As the core interface for user-system interaction, the presentation layer undertakes critical functions including monitoring interface visualization, human-machine interaction enablement, access control implementation, and data request processing. To ensure efficient interaction and cross-platform compatibility, this layer is constructed based on the FSLinux 11 operating system, adopting a technology stack comprising Node.js 20.1, Vue 3.x, and ElementPlus. This technical combination offers distinct advantages: Vue 3.x significantly improves the efficiency and flexibility of user interface development through its reactive data binding mechanism and component-based development paradigm, enabling developers to conduct modular development at the component level, achieve high code reusability, and accelerate the interface iteration cycle. As a feature-rich and aesthetically consistent UI component library, ElementPlus provides a wealth of pre-built high-quality components for interface development, further enhancing development efficiency while ensuring interface uniformity and visual appeal. The Node.js runtime environment supports server-side execution of JavaScript code, which, when integrated with the Vue 3.x frontend framework, facilitates the construction of cross-platform user interfaces.

3.1.2. Application Layer

The application layer encapsulates the core business logic underpinning the operation and control of the radio telescope, integrating three primary functional modules to support the system's core operational capabilities. Specifically, the first module is Operational Control, which encompasses the reception and processing of observation task schedules, satellite tracking, and the transmission of control commands; the second is Performance Measurement, incorporating key functions such as SEFD measurement, system noise measurement, and antenna pointing calibration; the third is System Monitoring, which implements real-time surveillance of a suite of critical subsystems within the radio telescope system. Specifically, these subsystems include the Antenna Control Subsystem, Receiver Control Subsystem, Digital Acquisition Equipment Subsystem, Data Recording Equipment Subsystem, UDC Control Subsystem, Time and Frequency Control Subsystem, Meteorological Data Acquisition Control Subsystem, and External Device Subsystem. To guarantee the reliable implementation of these core functions while meeting real-time and compatibility requirements, the technical architecture of the application layer is constructed on a set of mature and efficient technical components, namely the C programming language, GCC compiler, POSIX standards, IPC, UDP protocol, and Sockets. From the perspective of real-time performance guarantee, the C programming language—owing to its inherent low-level control capability—in conjunction with the robust optimization capabilities of the GCC compiler, facilitates the generation of efficient and compact machine code while supporting low-level access to hardware resources, fully meeting the stringent requirements for high performance and low latency in radio telescope control scenarios. In terms of cross-platform compatibility, POSIX standards ensure the portability of the application layer software, enabling stable operation across diverse operating system environments. Additionally, IPC and Socket technologies lay a robust technical foundation for efficient data communication, both between internal modules of the application layer and between the application layer and other system layers. This integrated communication mechanism ensures the coordinated operation of all system components, thereby facilitating the real-time and precise monitoring and control of the entire radio telescope system.

3.1.3. Device Manager Layer

The device manager layer, dedicated to the centralized governance of all equipment within the radio telescope system, integrates a suite of specialized management modules, namely the Antenna Manager, Receiver Manager, UDC Manager, Time and Frequency Manager, Digital Acquisition Manager, Meteorological Data Acquisition Manager, External Device Manager, and Calibration Manager. Its fundamental objective lies in ensuring the coordinated and orderly operation of all system equipment. To fulfill this objective and guarantee the robustness and scalability of management functions, the technical architecture of this layer is constructed on a mature mainstream technology stack, encompassing Spring Boot, Spring Cloud Alibaba, JDK 1.8+, Maven 3.x, Nacos 2.x, Gateway, OpenFeign, WebSocket 2.x, and Nginx. To elaborate on the architectural advantages, Spring Boot and Spring Cloud Alibaba serve as the foundational frameworks for implementing a distributed microservice architecture, enabling each management module within the DML to be developed, deployed, and scaled as an independent microservice. This design not only significantly enhances system flexibility—facilitating the upgrade or optimization of specific modules in line with practical operational needs—but also effectively reduces the overall system maintenance costs. Meanwhile, Nacos 2.x assumes a dual role as both a service registration/discovery center and a configuration management center, which is crucial to the stable operation of the distributed microservice architecture. Specifically, it automates the processes of service registration and discovery to ensure that service consumers can accurately locate target services; concurrently, it enables centralized configuration management and dynamic configuration updates, thereby streamlining the service governance process and improving the stability and reliability of the entire system. From the perspective of real-time interaction requirements between the management layer and various devices, WebSocket 2.x is employed to support full-duplex real-time communication. This technology effectively meets the demands for real-time monitoring of device status and immediate issuance of control commands, ensuring that the system can promptly respond to changes in device states and achieve precise device control. Furthermore, Nginx, acting as a high-performance reverse proxy server, offers efficient load balancing and request routing capabilities. By evenly distributing user requests across multiple backend service instances, it significantly improves the operational efficiency of the system and strengthens the system's high availability to cope with fluctuating service loads.

3.1.4. Infrastructure Layer

The infrastructure layer acts as the hardware foundation of the system, comprising essential components such as antennas, receivers, UDC, digital acquisition equipment, weather station sensors, and external devices, supported by data storage and communication interfaces. To meet the diverse storage and management requirements, this layer is built upon a tripartite data management strategy utilizing InfluxDB, MySQL 8+, and Redis 3.x. Specifically, InfluxDB is selected for its high-performance handling of time-series data, effectively addressing the storage and analysis needs of radio telescope observations. MySQL is utilized for its robust relational management capabilities, which are essential for handling data with complex associations. Finally, Redis serves as an in-memory cache to provide exceptional read/write speeds, thereby significantly boosting the overall system responsiveness.

3.2. Monitoring Interface Design and Implementation

During the observation process, operators primarily interact with the system through the visual graphical interface provided by the operation control system. The front-end interface of this system is developed using Node.js 20.1 + Vue 3.x + ElementPlus. This technology stack offers several advantages: richer component support, high development efficiency through componentization, and support for hot reloading. Adopting a Browser/Server (B/S) architecture enables cross-platform access, as the web application can be accessed via a browser without requiring any client installation. As an international collaborative project, the CART 40 m telescope has fully considered the diverse needs of its users during the development of its operation control system. This design approach not only enhances user experience but also improves overall system usability, as depicted in Figure 2.

During antenna operation, the interface presents real-time operational status information for various modules, including the antenna, receiver, UDC, MARK6, time–frequency, and meteorological station. Furthermore, the interface offers parsing of the schedule file and displays details about the current and pending sources.

When the user opts for the manual control mode, the system directs them to the manual control interface. Within this interface, the user must manually enter the required antenna azimuth and elevation values. Upon entering these values, the user should click the start button on the interface, allowing the system to process these parameters and execute the corresponding antenna pointing operation. Additionally, users can

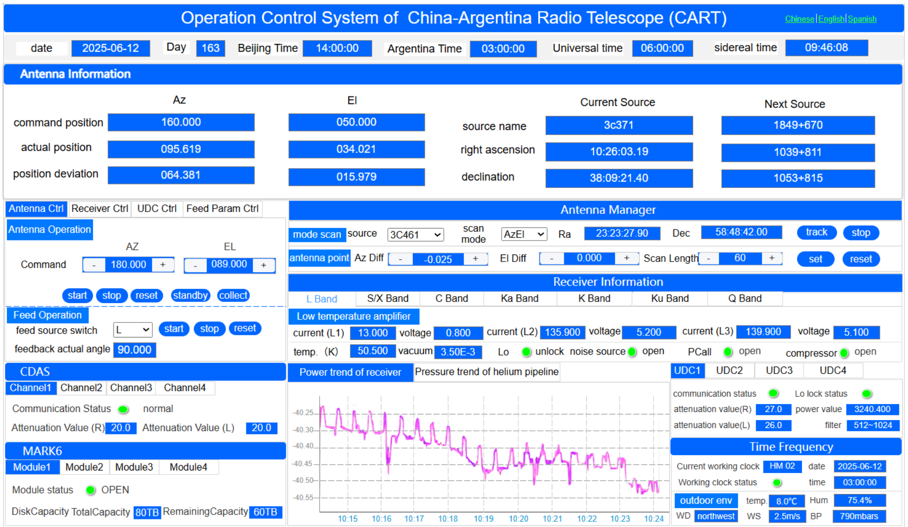

Figure 2. Interface display.

perform operations such as switching command modes and feed switching control for the antenna through the interface.

On the other hand, when the user selects the program observation mode, the system automatically transitions to the program observation control interface. On this interface, users can choose various observation types as required, such as pulsar observation. In some instances, after selecting the observation type, the system initiates the observation process immediately. However, for certain specialized observation tasks, such as single radio source observation, users must specify the particular source that they wish to observe.

On the single radio source observation interface, users can choose their desired observation source from a file that contains detailed information about various radio sources. This file not only allows users to select from existing observation sources but also enables them to add new sources or remove unnecessary ones as needed. When users add or delete observation sources, the corresponding storage file is updated in real-time, ensuring data consistency and accuracy. This feature makes the program's observation control interface both flexible and user-friendly.

The operational control system's layout is divided into several display areas: time display, antenna information display, control area (including antenna, receiver, UDC, and feed switching parameter control), antenna manager, receiver information display, CDAS information display, MARK6 information display, receiver power trend real-time display, hydrogen pipeline pressure trend real-time display, UDC information display, and time–frequency meteorology real-time display modules.

3.3. Monitoring Real-time Display Module

The monitoring real-time display module encompasses the time display module, antenna information display module, receiver information display module, CDAS, MARK6, UDC, time–frequency meteorology, receiver power trend analysis, and hydrogen pipeline pressure trend analysis information display modules.

The Time Display Module presents the current date and time. The Antenna Information Display Module showcases the antenna's azimuth and elevation in real-time (including command position, actual position, position deviation), the name of the current source and the waiting source, along with their R.A. and decl. coordinates.

The Receiver Information Display Module facilitates real-time monitoring of the current, voltage, temperature, and vacuum level for the cryogenic and room temperature amplifier stages of each band, as well as the status of the local oscillator, noise source, PCal1 status, and compressor status.

The CDAS Information Display Module enables real-time monitoring of the communication status of each channel and the left/right circular polarization attenuation values.

The MARK6 Information Display Module provides real-time monitoring of the status of each module and disk capacity (including total capacity and remaining capacity).

The UDC Information Display Module offers real-time monitoring of the communication status, local oscillator lock status, attenuation value, power value, and filter status for each UDC device.

The Time–Frequency Meteorology Information Module presents the working status and time of the hydrogen maser, along with real-time environmental temperature, humidity, wind direction, air pressure, etc. The Receiver Power Trend Analysis Chart displays trend analysis monitoring of the power for receivers in each band over the current period.

The Hydrogen Pipeline Pressure Trend Analysis Chart presents trend monitoring of the high and low pressure in the hydrogen pipeline over the current period.

3.4. Equipment Control Module

The equipment control module encompasses the antenna control, receiver control, UDC control, feed switching control, and feed switching parameter control modules.

The Antenna Control Module facilitates functions such as maneuvering the antenna to a specified azimuth/elevation position, stop control, homing (return to zero), standby mode, and managing position faults. Operators can manually manipulate the antenna by entering the desired azimuth and elevation values and clicking the "Start" button to direct the antenna toward the target position. In the event of an abnormal emergency during antenna movement, clicking the "Stop" or "Standby" button can avert safety incidents. Upon completion of the observation task, the "Homing" operation can be utilized to realign the antenna with its original position.

The Receiver Control Module manages functions including band switching, toggling the noise source, PCal activation/deactivation, and compressor control. The UDC Control Module oversees functions such as setting UDC power, controlling attenuators, and configuring filters. The Feed Switching Parameter Control Module executes band switching for feed positions *L*, *C*, *S*/*X*, *Ku*, *K*, *Ka*, and *Q*.

The Antenna Manager module enables tracking scan functionality and the configuration of antenna pointing deviation parameters.

The Tracking Scan Function Module conducts tracking scans by selecting a radio source from the source list under various scan modes, such as the AZEL cross-scan mode.

The Antenna Pointing Deviation Parameter Setting Module is employed post-pointing model completion. This function establishes azimuth deviation, elevation deviation, and scan length parameters to enhance the antenna's pointing precision.

3.5. Implementation of Backend Service Interfaces

The backend service interfaces for the antenna encompass antenna status monitoring (including high-speed reporting and status reporting), antenna operation mode control (command mode instruction, manual speed mode instruction, standby mode instruction, and favorite mode instruction), data recording instructions, remote switching instructions, feed switching operation mode control, feed switching control, and feed switching parameter control.

Data interaction between the Monitoring and Control System (MCS) computer and the Antenna Control Unit (ACU): As depicted in Figure 3, the ACU actively sends the high-speed report command information frame to the MCS every 50 ms; the status information report command information frame is actively transmitted by the ACU to the MCS every second. Commands for antenna operation mode control (command mode instruction, manual speed mode instruction, standby mode instruction, favorite mode instruction), data recording instructions, remote switching instructions, feed switching operation mode control, feed switching control, and feed switching parameter control are issued by the MCS and received by the ACU.

In this system architecture, the MCS computer and the ACU computer utilize the UDP network protocol for efficient data interaction. Here, the MCS computer assumes the role of the upper computer, primarily responsible for sending various control commands to the ACU computer, which acts as the lower computer. These commands precisely guide the ACU computer to execute corresponding operations, thereby driving the antenna to perform precise movements according to preset requirements, including but not limited to changing azimuth, adjusting elevation angle, and controlling movement speed. Simultaneously, the ACU computer also undertakes a crucial feedback task. It reports key status data, such as the antenna's current azimuth information, elevation status, and real-time movement speed, to the MCS computer in a high-speed reporting manner, ensuring timely and accurate updates. Through this tight and efficient collaboration mechanism between the upper and lower computers, the entire system can achieve precise control and real-time monitoring of antenna movement, thereby ensuring stable and reliable system operation. This meets application requirements in various complex scenarios, provides a solid foundation for subsequent tasks such as signal transmission and data acquisition, and strongly supports the efficient operation and functional realization of the entire system.

To ensure communication reliability, the following measures were implemented:

Data Integrity Checks. Each UDP packet includes a data segment length field for verifying data integrity.

Sequence Numbering. Packets are sequentially numbered to detect loss and enable reordering.

Acknowledgment and Retransmission. Critical commands use a simple ACK mechanism with retransmission after timeout (200 ms).

Heartbeat Mechanism. MCS and ACU exchange heartbeat packets every 5 s to confirm liveliness.

These mechanisms ensure that the UDP-based communication meets the reliability requirements of the control system, even in the presence of occasional packet loss or network delays.

This antenna control software, which integrates the monitoring capabilities of the MCS, can calculate the antenna's position in real-time with precision and quickly transmit accurate instructions to the ACU. This ensures that the antenna accurately targets the desired object and meets complex observation requirements, as depicted in Figure 4. The MCS is highly intelligent and adaptable. It can not only process various instructions from the FS computer to successfully complete automated observation tasks but also swiftly and accurately relay the antenna's real-time status information to the remote monitoring system. This enables operators to remotely and in real-time monitor the antenna's operational status and make timely adjustments and decisions. Consequently, the MCS is an indispensable core component of

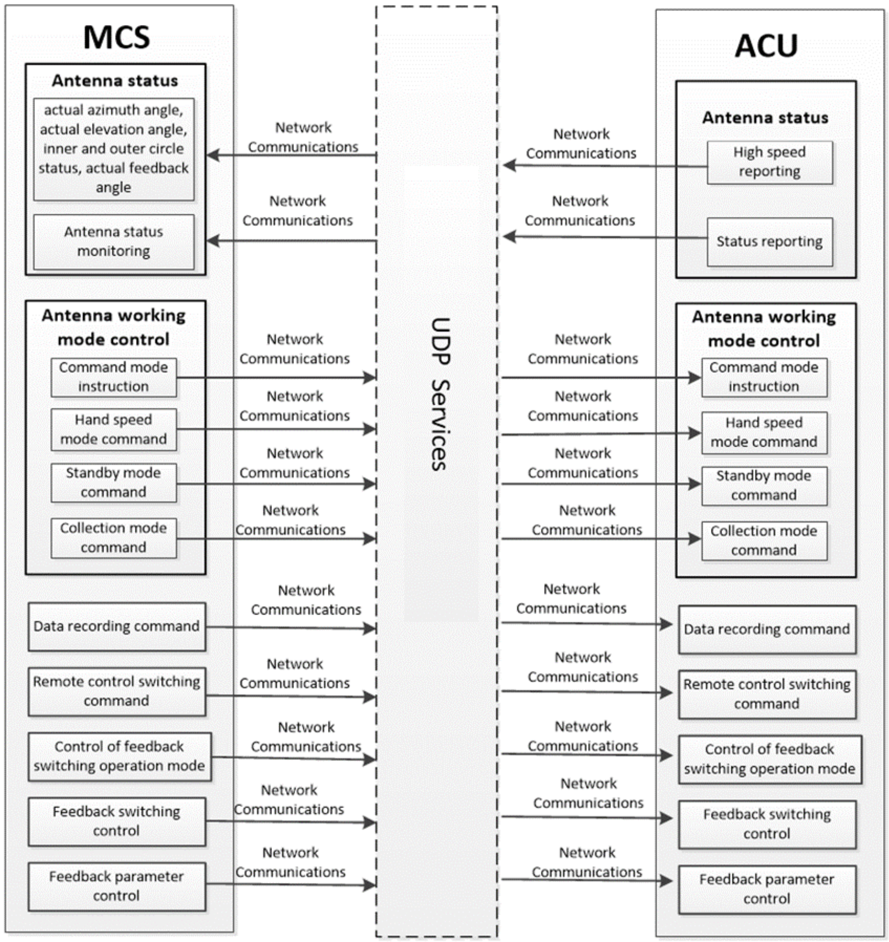

Figure 3. Data interaction block diagram between MCS and ACU.

the entire system. It functions like the human brain: on one hand, it receives "instruction information" from the FS computer, processes this data, and issues precise commands to the ACU computer, akin to how the brain processes external stimuli and task directives; simultaneously, it sends back the antenna's status information to the remote monitoring system, simply as the brain controls bodily movements and feeds back its own state to the external environment. This facilitates the efficient and stable operation of the entire antenna control system and the execution of intelligent automated observation tasks, strongly ensuring the system's reliability and functionality, and providing robust technical support for various application scenarios that depend on antenna observations (Hu et al. 2008).

3.6. Implementation of Data Storage and Analysis

When selecting a data storage solution, the CART 40 m operational control system opted for the InfluxDB time-series database. InfluxDB exhibits significant differences and holds unique importance when contrasted with relational databases, such as MySQL, SQL Server, or Oracle. Relational databases are founded on a tabular structure, organizing data into a two-dimensional format of rows and columns. They feature mature transaction processing mechanisms, strict data consistency constraints, and robust multi-table join query capabilities. These databases are well-suited for general business scenarios that are transactional, structured, and demand high data integrity. Their strength lies in accurately managing complex business logic and data relationships. In contrast, InfluxDB is specifically engineered for time-series data. It employs a time-series data model, using timestamps as the primary index, and can efficiently store and process vast quantities of data that are generated in chronological order (Figure 5). For the CART 40 m, the volume of data produced by a single observation is just right. Additionally, scholars analyzing observation data often choose data from specific timeframes, which is more convenient and faster with InfluxDB. It better fulfills the requirements for data storage and real-time insights, offering robust data support for related applications.

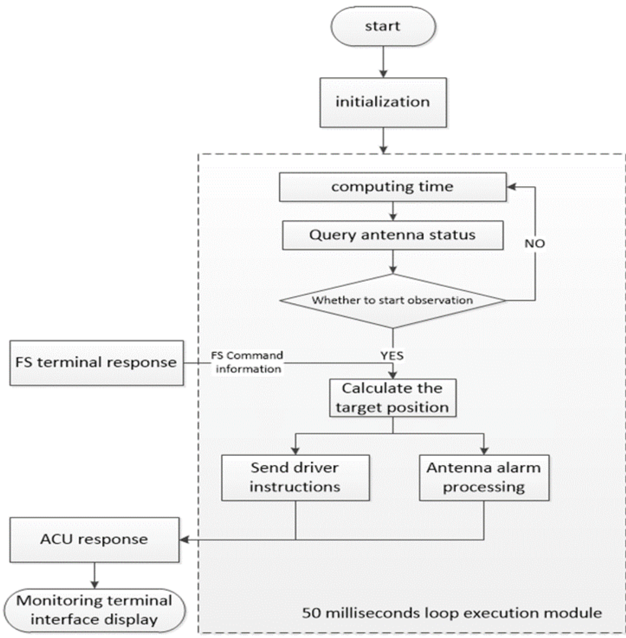

Figure 4. FS-MCS-ACU interaction flow.

The data acquisition program stores the collected data into the database. It necessitates setting the URL, token (or username and password), organization name, and bucket name, and initializing the InfluxDB client, as shown in Figure 6.

By configuring the InfluxDB connection information as described above, we can successfully store the collected data into the InfluxDB database and display it through the Grafana visualization analysis solution, as shown in Figure 7 below.

4. Testing of the CART 40 m Operational Control System

4.1. ACU Server Implementation and Simulation Testing with MCS and FS

The communication method (UDP) and data transmission method between the CART 40 m operational control system and the ACU adhere to the CART 40 m monitoring protocol. Devices involved in the operational control system data interaction include the FS, MCS, and ACU.

Simulation testing of the CART 40 m operational control system requires extensive preparation:

First, write the simulation programs for the ACU and FS, as well as the MCS operational control system; Second, deploy the FS program, MCS program, and ACU simulation program on three test servers respectively; Third, establish the necessary network environment. During the development and testing phase of the operational control system, considering that the actual hardware is not yet fully deployed, providing a realistic operating environment for communication between

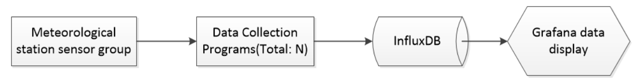

Figure 5. Data flow architecture diagram.

the ACU as the core equipment and the MCS and FS is particularly important.

The MCS receives commands from the FS computer to perform automated observation tasks and sends the antenna status reported in real-time by the ACU to the remote monitoring system. The interaction information between the ACU end and the MCS end consists of three parts: frame header, data segment, and frame tail, where the frame header and frame tail are composed of fixed information. The ACU parses the messages sent by the MCS system and executes the corresponding type of command code to complete related actions.

The high-speed report information (0×30) consists of six components: actual azimuth angle, actual elevation angle, inner/outer ring status, azimuth deviation, elevation deviation and actual feed switching angle. Apart from the inner/outer ring status, which takes up 1 byte, all other data types are floating-point and occupy 4 bytes each. This information is dynamically reported by the ACU to the MCS every 50 ms. Each transmitted message must contain a frame header, data segment, and frame tail, summing up to 42 bytes in total.

The MCS parses the content that includes the current timestamp, sender identifier, receiver identifier, a data segment length of 21 bytes, and the command code (0×30). The results of the data parsing are illustrated in Figure 2.

The ordinary status report information frame (0×41) comprises a data segment with nineteen primary components: antenna operation mode, command azimuth angle, command elevation angle, command azimuth speed, command elevation speed, azimuth rotation mode, equipment and limit status, antenna fault status, actual azimuth angle, actual elevation angle, actual azimuth speed, actual elevation speed, inner/outer ring status, feed switching operation mode, actual feed switching angle, feed switching running speed, command feed switching angle, feed switching running status, and the currently operating feed source. Including the frame header and frame tail, it occupies 81 bytes of memory. It is actively reported by the ACU (every 1 s) to the MCS. Upon reception, the MCS decodes the data into recognizable information, as depicted in Figure 2.

The antenna operation mode control command is sent by the MCS and received by the ACU, along with parameters. The operation mode indicated by 0×32 is the command position instruction, which contains 22 bytes of data. The backend program assembles the message and sends it to the ACU in real-time for processing. As shown in Figure 2, the user can input specified angles in the azimuth and elevation boxes, then

```python
self.acu_add = acu_add
self.acu_port = acu_port
# InfluxDB 连接参数
self.token = "-jfsLJX2LxxhY-9eBwvhsh4AFcgoyl-zBVWGes9fVbYVwPY0zER1vAeOHTu2w_LnTXRYkclw8oxHB97jpLj9uA=="
self.url = "http://localhost:8086"  # 请根据你的实际 InfluxDB 地址修改
self.org = "CART"  # 设置组织名
self.bucket = "CART"  # 设置目标 bucket 名称
self.client = InfluxDBClient(url=self.url, token=self.token, org=self.org)
# 使用同步写入方式
self.write_api = self.client.write_api(write_options=WriteOptions(batch_size=5000, flush_interval=10000, retry_interval=5000))
```

Figure 6. InfluxDB connection configuration.

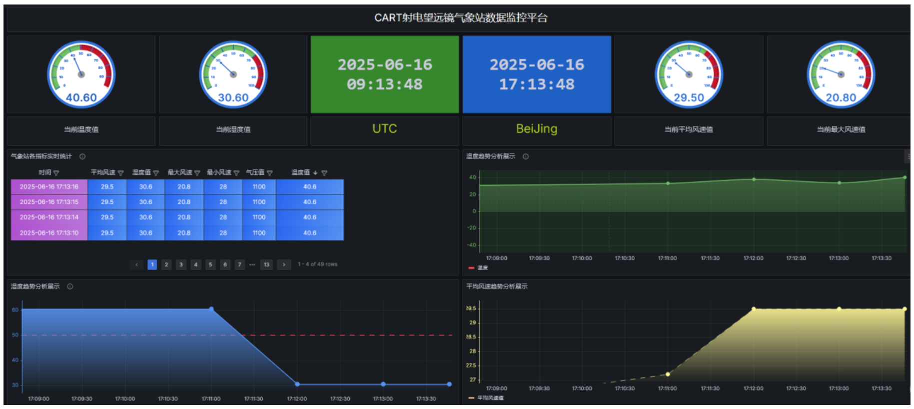

Figure 7. Grafana meteorological data analysis display chart.

click the start button to control the antenna movement, and can also perform remote control.

Communication Reliability Test Results:

Packet Loss Rate: <0.1% under normal network conditions.

Command Response Time: <10 ms for non-critical commands; <50 ms for critical pointing commands.

Heartbeat Stability: No missed heartbeats over 24 hr continuous test.

Data Integrity: 100% integrity verified through checksum validation.

4.2. Field Testing at the 13 m Radio Telescope of SheShan Station, Shanghai Astronomical Observatory

Tests and experimental verification of the monitoring software were conducted using the 13 m radio telescope at the SheShan Station of the Shanghai Astronomical Observatory. The MCS monitoring system successfully established real-time communication links with devices such as the FS, ACU, wide dual-band receiver, compressor, UDC, and meteorological instrument. It correctly parsed parameters and controlled the antenna to stop. If the observation task ended, the operator could click the homing button to return the antenna to its original position. After clicking the standby button, the antenna would automatically run according to the schedule parsed by the FS. If it was not in standby mode, it would reject commands issued by the FS. The favorite button could save the antenna's current azimuth and elevation (current source) for later calibration use.

Table 1
System Key Performance Indicators Test Results

Performance Indicator	Test Result	Requirement
GUI Response Time	<50 ms	<100 ms
Command Execution Delay	15 ± 5 ms	<50 ms
Data Acquisition Rate	15 frame s^{-1}	>10 frame s^{-1}
Uptime (Continuous)	240 hr	>168 hr

Log records are maintained, and the correct operation of the antenna is controlled. The effectiveness of this communication ensured that parameters could be accurately transmitted, thereby guaranteeing the smooth operation and precise control of the antenna. The functions of this operational control system mainly include the following aspects: First, it is responsible for the operational control of the antenna, ensuring that the antenna can point and track precisely according to predetermined instructions. Second, the system status monitoring function allows operators to monitor various performance indicators and system status of the antenna in real-time, in order to promptly discover and handle possible abnormal situations. Finally, the data recording function is responsible for collecting and storing key data during the antenna operation process, which is crucial for subsequent analysis and research. The key measurement data of the system performance are detailed in Table 1.

Upon completion of testing, a systematic evaluation of system accuracy was conducted under consistent conditions to quantitatively assess performance. The assessment comprehensively

Table 2
Pointing Accuracy Test Results

azCommendAngle	azActualAngle	azDeviation	elCommendAngle	elActualAngle	elDeviation
175.0	175.0	0.0	85.008	85.007	0.001
180.003	180.003	0.0	88.996	88.989	0.007
180.0	179.999	0.001	89.008	89.008	0.0
180.0	180.0	0.0	70.0	69.999	0.001
185.0	185.002	−0.002	75.0	75.002	−0.002
190.0	190.0	0.0	80.0	80.005	−0.005
160.0	160.0	0.0	80.0	79.998	0.002

covered static pointing accuracy, dynamic tracking capabilities, and system stability, with detailed results presented in Table 2.

The test results indicate that the CART 40 m radio telescope operation control system demonstrates excellent precision performance in static pointing, dynamic tracking, and environmental adaptability. The measured accuracy of all test items either meets or exceeds the system design specifications, reflecting the effectiveness of the system's hardware-software co-design and real-time control algorithms.

The data transmission interface of the ACU is RJ45, transmitting via UDP communication. The data is transmitted in data frame format, consisting of a frame header, frame count, time, data field length, information classification code, information field content, and frame tail. The high-speed reporting of the antenna involves the ACU actively reporting the antenna's real-time angle information to the station control (MCS) at a frequency of 50 ms intervals.

From the outset, this operational control system was designed with the potential future need to add various personalized devices and applications on telescopes of different scales in mind. It adopted an independent design philosophy for each control module unit during system construction. This ensures that the code modification workload can be minimized for equipment of different scales, guaranteeing code usability while also possessing strong extensibility. This solution was also tested module by module at the 13 m radio telescope of the SheShan Station of Shanghai Astronomical Observatory. Finally, the system's accuracy and control precision were verified through complete system testing. Simultaneously, extensive sub-item tests and integrity tests were conducted using this system on the CART 40 m workstation.

This further proved the system's scalability and universality, indicating that the system not only has the capability to be tested successfully on small antennas but also has the potential to be applied on larger-scale antennas.

4.3. Data Validation Test between the Hexapod Subreflector Feed Switching Unit and the ACU

The data transmission interface between the CART 40 m hexapod subreflector feed switching unit and the ACU is also an RJ45, which transmits data via UDP communication in a data frame format. The data transmission format comprises a frame header, command work mode, data field length, information field content, and frame tail. The hexapod subreflector feed switching unit's high-speed reporting involves the unit actively sending its real-time status information to the ACU at intervals of 50 ms.

5. Conclusion and Outlook

This research successfully designed and implemented the operational control software for the China–Argentina CART 40 m. By adopting a layered architecture design and optimizing the monitoring interface and backend service interfaces, the system successfully overcame the limitations of existing technology, significantly improving resource utilization, operational efficiency, and the system's precision and reliability. Field test results fully verified the functional completeness and performance stability of the MCS monitoring system, fully meeting the practical needs of radio telescope observations.

Future research could focus on further improving software performance and stability, and further enhancing antenna pointing accuracy and observation efficiency through algorithm optimization. Simultaneously, with the in-depth development of astronomical research and continuous technological progress, deeply exploring the application potential of artificial intelligence technology in equipment fault diagnosis and prediction will be of great significance. These research directions will further promote the development of radio telescope observation technology and provide more powerful and reliable technical support for innovative research in the field of astronomy.

Acknowledgments

The CART 40 m project was funded by the Key International Cooperation Project of the Ministry of Science and Technology of China through grant 2010DFA02710. It is contributed also by the National Natural Science Foundation of China via grants 11503035, 11573036, 11373009, 11433008, 11403040, 11403041, etc. Additionally, this project has been supported by the Chinese Academy of Sciences, the National Astronomical Observatories of the Chinese Academy of Sciences, the National Scientific and Technical Research Council of Argentina (CONICET), the Ministry of Science, Technology and Innovation of Argentina, the Province of San Juan, Argentina, and the National University of San Juan (UNSJ), Argentina.

Here, we extend our sincere gratitude to all members of the 13 m project team at the SheShan Station of the Shanghai Astronomical Observatory, as well as to government departments at all levels in China and Argentina, for their sustained, enthusiastic, and generous contributions to this milestone project between China and Argentina.

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