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An optimization strategy for reliable Antarctic telescope control systems

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Abstract: Antarctic telescopes, especially those located at Dome A, face significant reliability challenges owing to the extremely harsh working environment, among which the reliability of the control system is critical in ensuring stable operation. This paper describes various factors affecting the reliability of Antarctic telescopes, as well as the challenges of reliability improvement. Combined with the development of Antarctic telescopes and the experience of Antarctic scientific expeditions, we introduce, in detail, the optimization strategy for reliability enhancement, including the hardware layer, software layer, modular design to facilitate maintenance, and reliability management. The current status of the Antarctic Survey Telescope (AST3) is also briefly introduced, along with future development plans. We aim to provide ideas for the reliability design of Antarctic telescopes and provide technical support for the development of future Antarctic telescopes.

Keywords: Antarctic telescope; Control system; Reliability; Optimization strategy

1. INTRODUCTION

For favorable observing conditions, such as good seeing and low light pollution, telescope sites tend to be located in adverse environments, such as cold, high-altitude, and sparsely populated areas. In recent years, the interior of Antarctica has become an important site for astronomical research undertaken by various countries. The highest point of the Antarctic inland ice cap, Dome A (at an elevation of 4096 m), is currently the best astronomical site on Earth in terms of seeing[1], with observing conditions comparable to those in space.

The extreme environment of Antarctica is a double-edged sword for telescopes. The unique geographic location of Dome A is an excellent observatory location, with good visibility combined with a 3-month-long polar night observing window. However, the high altitude, ultra-low temperature, ground-blown snow, and long polar night all pose a threat to the stable operation of the telescope over long periods. The entire body of the telescope may be encased in snow during the polar night (see Fig. 1), mainly because of ground blowing snow. Accumulated snow will increase the driving load of the telescope and may even cause axis seizure. Simultaneously, it can cover the window and impose an additional burden on the mirror heating system.

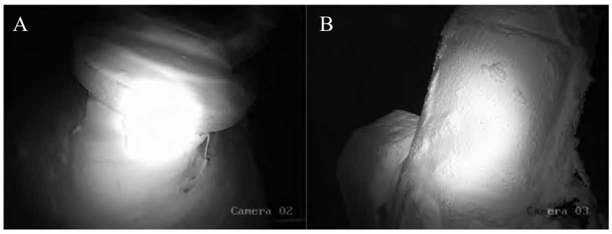

Fig. 1. Extreme environmental circumstances during polar night at Dome A in Antarctica, showing snow cover on the AST3-2 right ascension (A) and declination (B).

Three telescopes are actively operating at Kunlun Station in Antarctica: the Chinese Small Telescope ARray

(CSTAR)[2], Antarctica Survey Telescope (AST3)[3–4], and near-infrared optical telescope[5] developed by Nanjing Institute of Astronomical Optics & Technology, Chinese Academy of Sciences (NIAOT). The China Antarctic Observatory plans to build a 2.5-m large-aperture optical/infrared telescope, the Kunlun Dark Universe Survey Telescope (KDUST)[6], and the 5 m Dome A Terahertz Explorer (DATE5)[7–8] at Kunlun Station, also proposing a long-term plan for other facilities including 6–8-m optical/infrared telescopes and 15-m terahertz telescopes as initial projects in a subsequent construction program[9]. The existing optical telescopes at Dome A are shown in Fig. 2. In the upper left of the Fig. 2 is AST3-1 (operating from 2012 to 2017), the first telescope in the Dome A that can be pointed and tracked. In the upper right is CSTAR (operating from 2007 to 2012), which took the first historic step in Chinese astronomical exploration in Antarctica. In the lower left is Near-infrared Telescope (operating since 2024), which effectively fills the observational gap in the 1.1–1.4-µm band at Dome A. In the lower right is AST3-2 (operating since 2015), the largest currently operating optical telescope in Antarctica. AST3 is a series of antarctic survey telescopes, with AST3-1 being the first and AST3-2 being the second.

Fig. 2. Optical astronomical telescopes at Dome A in Antarctica. AST3-1, the first optical telescope in Antarctica with automatic pointing and tracking function. CSTAR, the first independently developed Chinese Antarctic optical telescope. The Near-infrared Telescope, filling the observational wavelength gap of 1.1−1.4 µm, installed in 2024. AST3-2, the largest aperture optical telescope operating at Dome A in Antarctica, installed in 2014.

Other Antarctic telescopes include the Italian 80-cm telescope International Robotic Antarctic Infrared Telescope-International Telescope "Maffei" (IRAIT-ITM)[10] and the American 10-m South Pole Telescope (SPT)[11] operating at radio frequencies. In addition, France and Italy have proposed the Kiloparsec Explorer for Optical Planet Search (KEOPS)[12]; Spain, the United Kingdom and Canada have proposed the Permanent All Sky Survey (PASS)[13] at Dome C (a prominent ice dome located inland in Antarctica); Australia and other countries have proposed the Pathfinder for an International Large Optical Telescope (PILOT)[14–15], a 2.4-m optical infrared telescope; the United States and Australia have proposed the Large Antarctic Plateau Clear-Aperture Telescope (LAPCAT)[16], an 8.4-m polarized optical infrared telescope to be constructed on Dome C.

An Antarctic telescope faces several significant challenges. The Antarctic continent exhibits significantly lower temperatures than any other region on Earth, because of the low solar elevation angle during daytime, and the three-month polar night. This is compounded by constant ice and snow cover, with a high reflectivity of solar radiation, causing less heat to be absorbed by the ground. This causes annual mean temperatures in the range of −30°C to −25°C[17]. The lowest recorded terrestrial surface air temperature of −89.2°C was measured at the Russian Vostok Station[18].

The average surface altitude on the continent of Antarctica is 2350 m. Geographically, the central region of Antarctica has a high surface elevation, with surrounding regions being lower. Coupled with extreme low temperatures, this means that many locations are prone to the formation of descending winds, with speeds potentially reaching up to hundreds of meters per second. Strong gusts of wind can carry a large number of snow particles, causing ground-blown snow, which poses a serious threat to equipment.

The extreme environmental conditions pose a great challenge to human activities in Antarctica. Consequently, facilities located in inland Antarctica operate without requiring direct human attendance. The Chinese National Antarctic Research Expedition (CHINARE) team arrives at Dome A only once a year, with limited time to perform any required tasks, so the equipment maintenance cycle is long.

Energy supply at Dome A has always been a significant issue, and workable solutions are urgently needed. There is no solar energy supply during polar night at Kunlun Station, and the placement of high-power energy storage devices in extreme environments is inefficient and costly. Fuel engines and wind turbines face significant reliability challenges and provide limited power output.

Antarctic communications are currently provided by low-bandwidth and high-cost satellite infrastructure. Low-orbit Iridium satellites provide excellent coverage for Iridium connectivity in the polar regions, with a maximum data transfer rate of 128 Kbps (i.e., up to 16 KB s^{-1}). This is a difficult situation for Antarctic telescopes at Kunlun Station, which need to interact remotely under such communication conditions.

Continued, long-term reliance on Iridium satellites for Dome A communications can no longer meet the timeliness requirements of remote telescope operations. Establishing coverage through an existing Chinese satellite constellation may present an optimal solution, while international cooperation could also be considered.

The drive control system of a telescope guarantees smooth operation during astronomical observations, and its reliability directly affects whether an observation can be carried out, as well as the efficiency and quality attainable. A stable and reliable drive control system not only ensures the precision of telescope pointing and tracking, but also effectively reduces the probability of telescope failure. The key to improving the operational efficiency of the telescope is to propose mechanisms to improve the reliability of the drive control system for different scenarios.

Here, we discuss factors affecting the reliability of the control system of Antarctic telescopes, aiming to provide optimal reliability for Antarctic telescopes, enrich the research of Antarctic astronomical techniques and methods, and guide the development of Antarctic astronomy. This can culminate in solutions and technical guidance for the development and operation of telescopes in extreme environments.

2. KEY RELIABILITY CHALLENGES FOR ANTARCTIC TELESCOPES

Kunlun Station in Antarctica has excellent astronomical observation conditions, but the harsh local environment places stringent requirements on the reliability of telescope control systems. The biggest concerns include the ultra-low temperature and ground blowing snow, causing low-temperature operating conditions for the telescope drive motors and other electrical parts. Temperature changes can cause deformation of mechanical structures, and pervasive snow drifts can cause snow to enter the drive mechanism, blocking gears, freezing the mechanism, and clinging to the mirror surface, requiring different considerations to conventional ground-based telescopes.

2.1. Electrical System

Compared with the wintering stations that are crewed all year round (such as Zhongshan Station and Great Wall Station), Kunlun Station is uncrewed, and has higher requirements for the stability of the Electrical system. Long-term automated operation is required, coupled with a harsher operating environment at lower temperatures and higher altitude. The power supply at crewed stations is stable, because any issues can be promptly detected and repaired by staff on duty.

As critical components of the electrical system, power supply and communication face severe challenges in Antarctica's extreme environment. The Plateau Observatory for Dome A (PLATO-A), currently the primary observation support platform at Dome A, provides essential power and communication support for telescope operations. During polar day, energy is supplied by solar panels, while fuel-powered generators provide power during polar night. Communication is via Iridium satellites. PLATO-A is broadly composed of an engine module, solar panel arrays, and an instrument module (as shown in Fig. 3). The engine module and solar panels provide energy for telescope operations during polar night and day respectively, while the instrument module maintains a thermally regulated environment for telescope control cabinets and enables satellite communications.

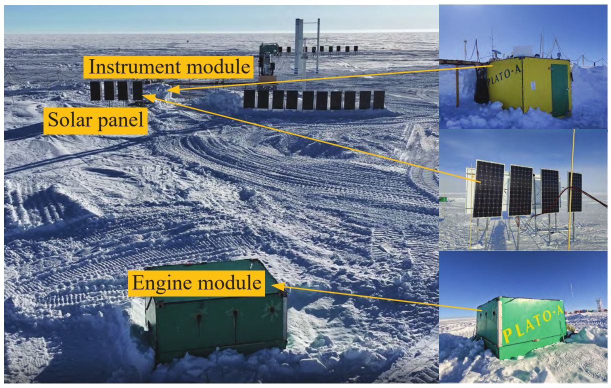

Fig. 3. Photographs of the PLATO-A facility at Kunlun Station.

2.2. Mechanical Structure

The mechanical structure of an astronomical telescope serves as the operational foundation for a precision motion system that integrates interdependent optical, mechanical, and electrical subsystems. The electrical system provides operational support for the optical system which ultimately determines overall performance. In the unique operating environment of Antarctica, mechanical structures must meet higher reliability requirements, imposing stricter standards on material selection, design, manufacturing, and assembly.

A mechanical structure undergoes deformation as temperatures vary, and any given material will have a distinct coefficient of thermal expansion (CTE), with more pronounced structural deformation occurring in materials possessing higher CTEs. An Antarctic telescope operates in an environment with annual temperature variation spanning a range of up to 50°C. Such mechanical deformations may alter the preload force in moving component assemblies, consequently inducing variations in driving torque and impairing drive performance. Additionally, thermal deformation of the mirror support structure causes positional shifts of optical elements with temperature fluctuations, compromising optical alignment and ultimately degrading image quality.

Taking the AST3 as an example, the key mechanical components of the telescope are constructed from materials with low CTEs, while the structural design has been optimized to better adapt to the Antarctic environment. Snow and frost ingress into the gear mechanism, leading to blockage, has been identified as a common issue in Antarctic telescopes and a primary cause of tracking failure during observations. To address this, the mechanical design of AST3-3 was further improved by implementing a fully enclosed gearbox (shown in Fig. 4), which has effectively resolved this problem.

Fig. 4. Photographs of the fully enclosed gearbox used for AST3-3.

3. STRATEGIES FOR RELIABILITY OPTIMIZATION

3.1. Hardware Layer Optimization

Antarctic telescopes work in an open-air environment, meaning that motors, encoders, reading heads, and other related electrical accessories inevitably suffer from low temperatures, wind, and snow, so hardware optimization is indispensable. In the case of the AST3, its spindle control program is a dual-motor gear backlash elimination, that is, the equinoctial axes are equipped with two drives and two servo motors, providing a redundancy backup while also eliminating gear backlash. The gear drive design solution also minimizes the energy consumption of the motors. This solution has been successfully applied to the AST3-2 and AST3-3 telescopes, with favorable results. The AST3 spindle dual motor design principle is shown in Fig. 5.

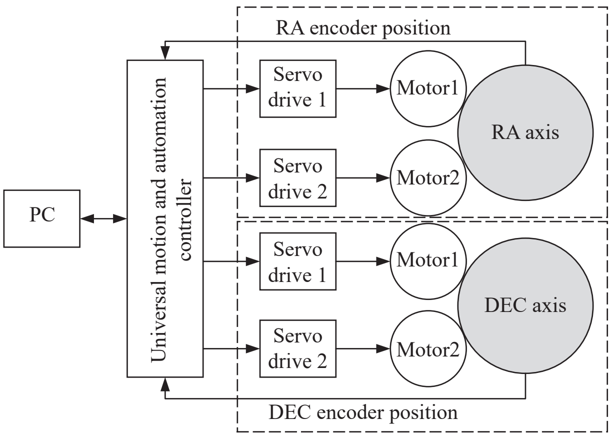

Fig. 5. Design scheme of the AST3 spindle drive system, with two motors and two drivers on both the right ascension and declination axes.

An encoder is a key component for a telescope to achieve accurate closed-loop control, and the grating hub and reading head work at ambient temperature, so the reading head needs to be equipped with a temperature control device. Two reading heads are equipped for each axis of AST3-2, and four for each axis of AST3-3, which plays the role of redundancy. Each reading head is fitted with a platinum resistance temperature sensor, and the average value of the sensor is taken. When the temperature value is less than the lower limit of the set value, the programmable power supply is turned on and heating begins; when the temperature is greater than the upper limit of the set temperature value, the programmable power supply is turned off and heating stops. The AST3-2 reading head and the heating unit are shown in Fig. 6.

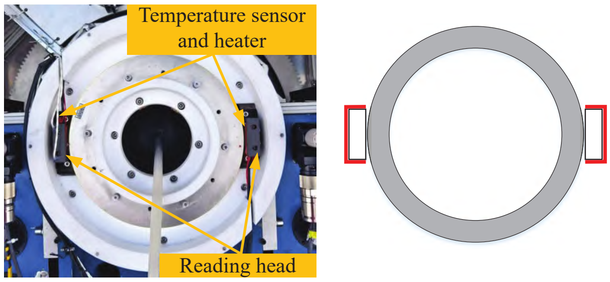

Fig. 6. Photograph and diagram of the AST3-2 reading head and heating unit.

In addition, the window snow removal system is also an important part of the telescope, ensuring unobscured observation. Snow can easily block the window of the telescope, causing it to be “blinded”. The window design, created using Indium Tin Oxide (ITO) conductive film provides a solution for electric defrosting. The window heating of AST3-2 adopts a special multi-terminal saturated contact design scheme, with a spring flexible support structure behind each terminal. This design ensures good contact between the terminals and electrodes, and avoids hard contact problems caused by deformation. The conductive electrodes are supplied with a three-way independent power supply, ensuring the redundancy of the power supply to the conductive film and improving reliability. The telescope window and mirror heating electrode are shown in Fig. 7.

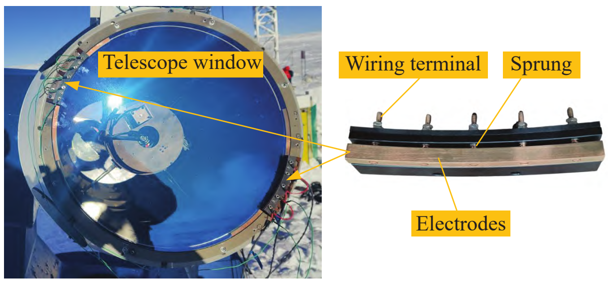

Fig. 7. Telescope window and mirror heating electrode.

Telescope temperature maintenance can be achieved using encoder read-head heating and window defrosting, using the closed loop formed by the heating pad or heating film and the temperature sensor to achieve temperature regulation. At Dome A, where energy is scarce, high-power temperature maintenance methods are not feasible. Therefore, most telescope components, such as mechanical structures, motors, and cables, are custom-designed for extreme low-temperature operation.

3.2. Software Layer Optimization

Antarctic telescope control software uses a combination of distributed soft real-time and hard real-time, giving high precision, distribution architecture, real-time operation, reliability, security, and openness design. Its core function is to control the actuator for precise pointing and tracking of targets, while calculating system error and compensating for it, to achieve high-quality target images.

Antarctic telescope control software runs on a computer between the user layer and the equipment layer, allowing information interaction with the equipment layer through the network interface, and achieving information interactions between the different types of user layer through the human-computer interface and software interface protocol. The architecture of the control software for an Antarctic telescope is shown in Fig. 8.

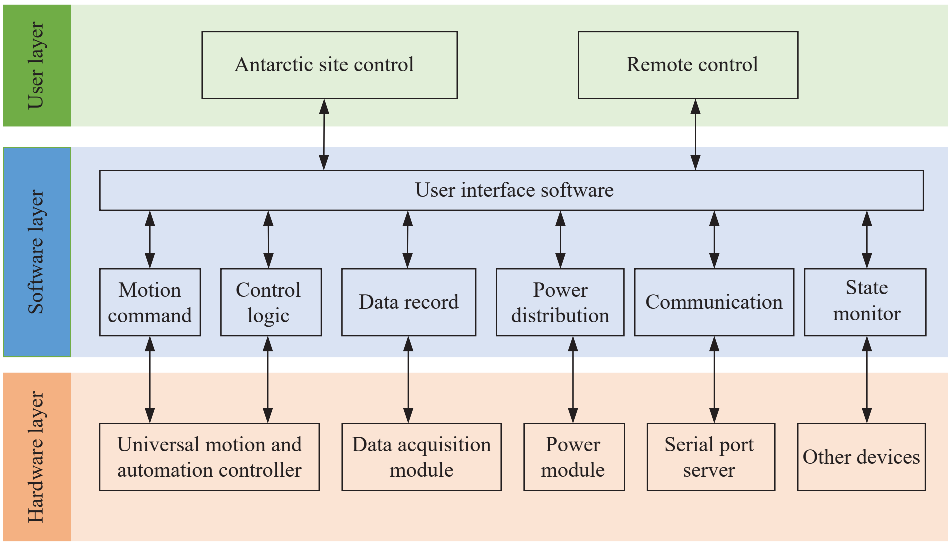

Fig. 8. Three-layer structure design scheme for AST3 control system software, showing the hardware layer, software layer, and user layer.

The telescope master control host uses a dual-machine operation mode, with dual network card binding for each host, and automatic load balancing. Communications between the host and each node are unified using TCP/IP-based socket protocol, and the master control host is responsible for coordinating the work between each node. The master control host parses, encodes and redistributes the commands coming from the communication host, while being responsible for re-encoding, compressing, and packaging the information fed back from each node to upload to the communication host. Through this control method, the work of each telescope can be effectively coordinated to improve the observation efficiency and increase scientific output.

3.3. Modular and Maintainable Design

The maintenance cycle of a telescope at Dome A is long, with only one on-site opportunity per year, lasting less than 20 days. The limited number of Antarctic research team members cannot meet the demand for professional personnel of various disciplines, and the combination of modularization and easy maintenance of the control system design is particularly important. Researchers of different specialties can be competent in the maintenance and upgrading of the telescope control system after simple training. For example, the hardware component of the control system of the Antarctic Sky Survey Telescope adopts a layered cabinet design, with each drawer control box responsible for the unit function module, facilitating upgrade and maintenance activities. The modular design of the AST3-3 cabinet is shown in Fig. 9.

3.4. Reliability Management

Reliability management, based on knowledge and data, is currently a widely adopted approach in Antarctic telescopes. The fault diagnosis and self-healing expert system is a reliability management tool, developed using existing knowledge, which is an intelligent computer program with automatically execute and possess logical reasoning capabilities. This system integrates operational knowledge and expert experience from Antarctic telescopes, such as AST3 and CSTAR, using this information to identify, locate, and even autonomously resolve system faults. By implementing complex problem-solving processes such as logical reasoning and linguistic description through computer programming, the expert system simulates human cognition to address telescope malfunctions with expert-level capability and analytical thinking. Expert systems store a large amount of human knowledge bases and are equipped with logical reasoning and decision-making mechanisms, thereby playing an important role in telescope reliability management.

The expert system contains a host computer, a knowledge acquisition machine, a knowledge base, a comprehensive database, a reasoning machine, a diagnostic log. Its design principle is shown in Fig. 10.

Data-based reliability management uses telescope condition monitoring data to analyze operational status, providing critical support for on-site maintenance personnel. This can improve work efficiency while serving as a refer-

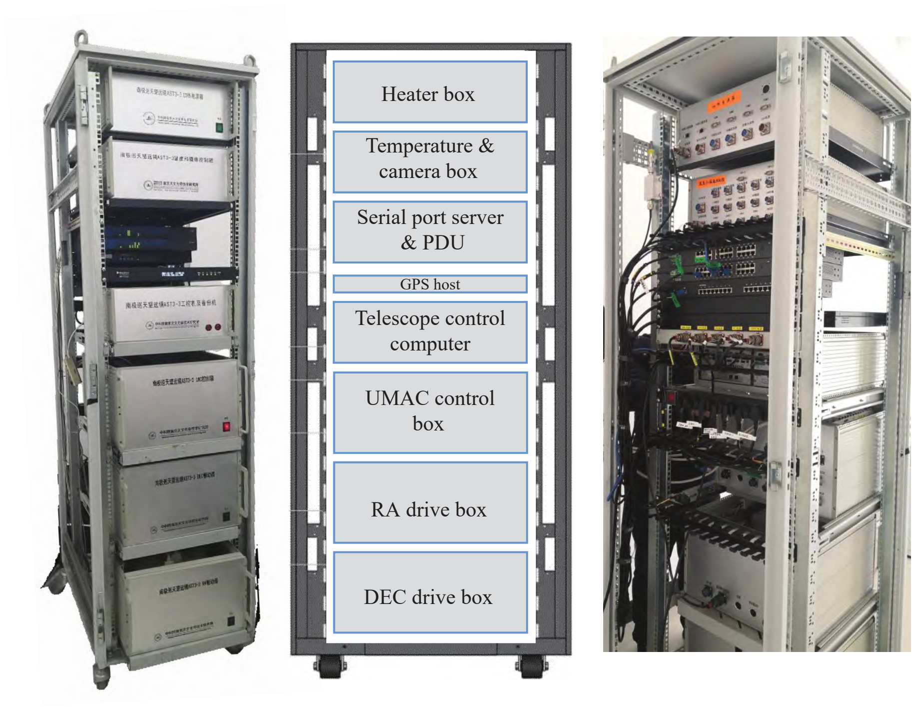

Fig. 9. The modularly designed telescope control cabinet, consisting of multiple modules with different functions, such as a controller module, driver module, and power supply module.

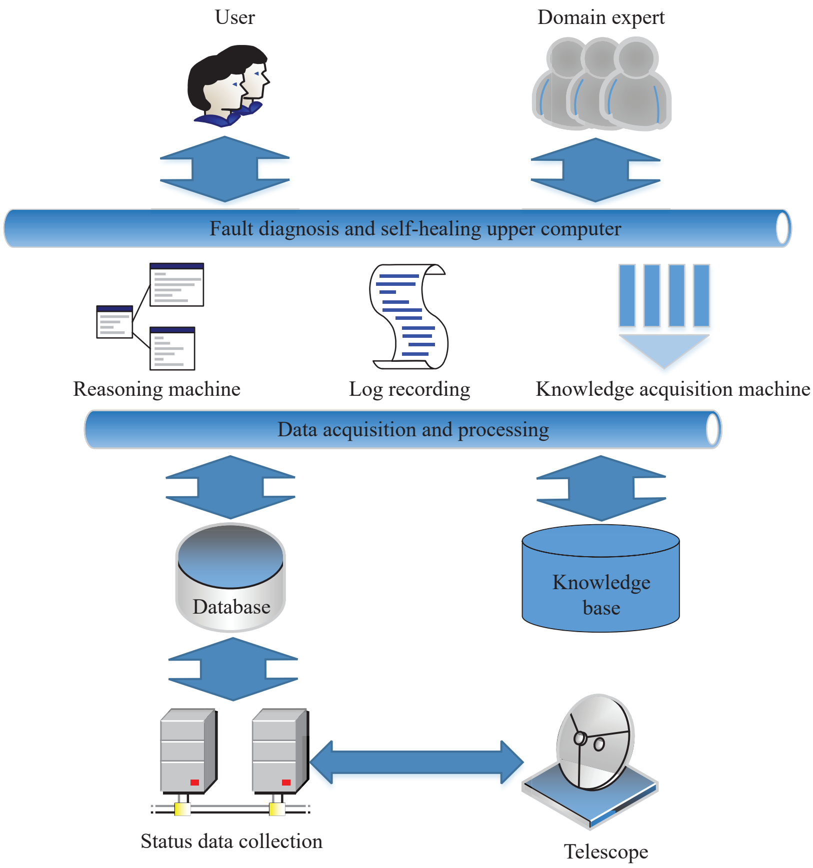

Fig. 10. Principles of fault diagnosis and self-healing expert systems for an Antarctic telescope, showing a three-layer architecture consisting of a user layer, function layer, and data layer.

ence for remote maintenance teams to assess real-time conditions at the Antarctic site. Telescope status data consists of three primary categories: operational data, observational data, and environmental data.

Operational data comprises real-time operational parameters and performance metrics, including tracking error, loop current, voltage, and temperature rise in heating systems. Observational data involves the analysis and evaluation of final output data quality, with key assessment criteria including stellar Full Width at Half Maximum (FWHM), atmospheric extinction levels, and energy distribution profiles. Among these, FWHM is a parameter that measures the observational quality of the telescope, reflecting its resolution, but is limited by seeing conditions. Atmospheric extinction is the phenomenon of intensity attenuation due to absorption and scattering when light passes through Earth's atmosphere. The extinction coefficient can be measured using either photometric or all-sky camera methods. Energy distribution profile is a key measure of the energy distribution of a telescope system, covering the Point Spread Function (PSF). The energy distribution of an Antarctic telescope is less affected by the atmosphere than ground-based telescopes constructed elsewhere on the planet. Finally, environmental data, collected by on-site meteorological stations, provides critical external condition measurements such as ambient temperature and wind speed.

By integrating and analyzing these status datasets, the current operational performance of the telescope can be evaluated in real time, enabling proactive maintenance and optimization. The data acquisition system is shown in Fig. 11.

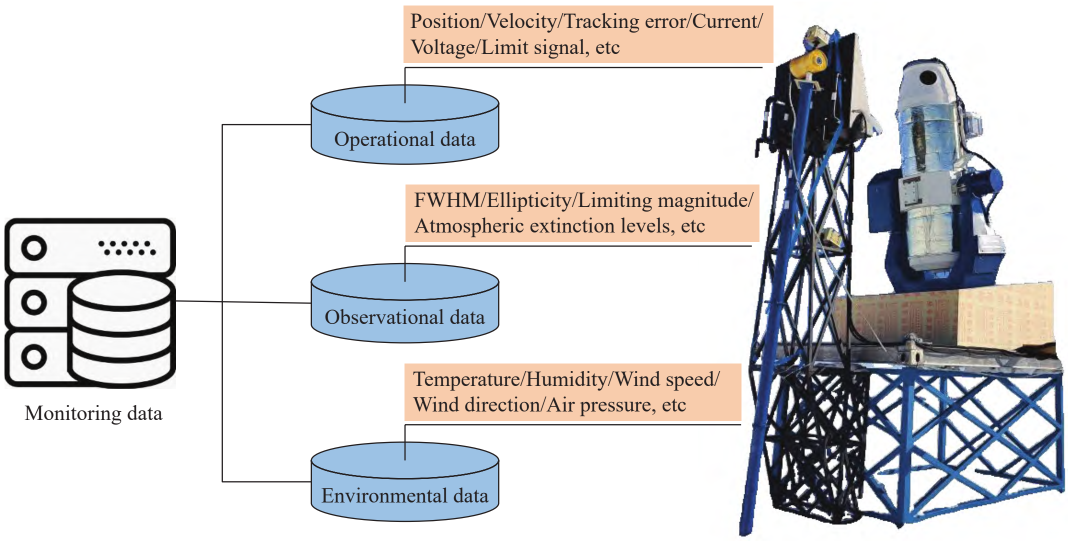

Fig. 11. Antarctic telescope data acquisition system able to record operational data, observation data, and environmental data.

4. CURRENT STATUS AT DOME A

Astronomical research at Dome A commenced in 2008, during China's 24th Antarctic Scientific Expedition. After years of infrastructure development, multiple astronomical instruments have been successfully deployed and operated at Dome A. Some of these, such as CSTAR and AST3-1, have already yielded valuable results and been subsequently decommissioned[19–23].

The astronomical instruments currently operating at Dome A include AST3-2, the Near-infrared Telescope, PLATO-A, the Kunlun Automatic Weather Station-2 Generation (KLAWS-2G), and the Kunlun Differential Image Motion Monitors (KL-DIMM). The Dome A astronomical site is shown in Fig. 12.

AST3-2 was installed at Kunlun Station in 2013 and has been in operation for more than 12 years, with scientific data still being produced. During the 40th Chinese Antarctic Scientific Research Expedition in 2024, researchers at Kunlun Station conducted comprehensive upgrades and maintenance on AST3-2, successfully restoring it to full functionality. Upgrade and maintenance tasks for AST3-2 included modification of the focusing system, replacement of the camera, enhancement of the mirror heating system, and software upgrades.

In 2025, during the 41st Chinese Antarctic Scientific Research Expedition, the crew of Kunlun Station performed further maintenance on AST3-2. Currently, the telescope is operating normally and conducting scientific observation tasks. The status of the AST3-2 can be acquired using a camera at Dome A, with an example shown in Fig. 13.

The AST3-3 was developed in 2020 and installed at the Yao'an Observatory in Yunnan Province in the same year, for trial operation. In June 2021, an expert panel comprising representatives from the Purple Mountain Observatory (PMO), NIAOT, the Yunnan Observatories (YNAO), the Nanjing Astronomical Instrument Co., Ltd. (NAIRC), and Tsinghua University conducted comprehensive performance testing and acceptance evaluation of the AST3-3 system. Designed for infrared observation missions at Kunlun Station, the telescope is currently awaiting the completion of its infrared camera, which is under active development. AST3-3 is scheduled for installation at Kunlun Station in the near future. AST3-3, in operation at Yao'an Observatory, is shown in Fig. 14.

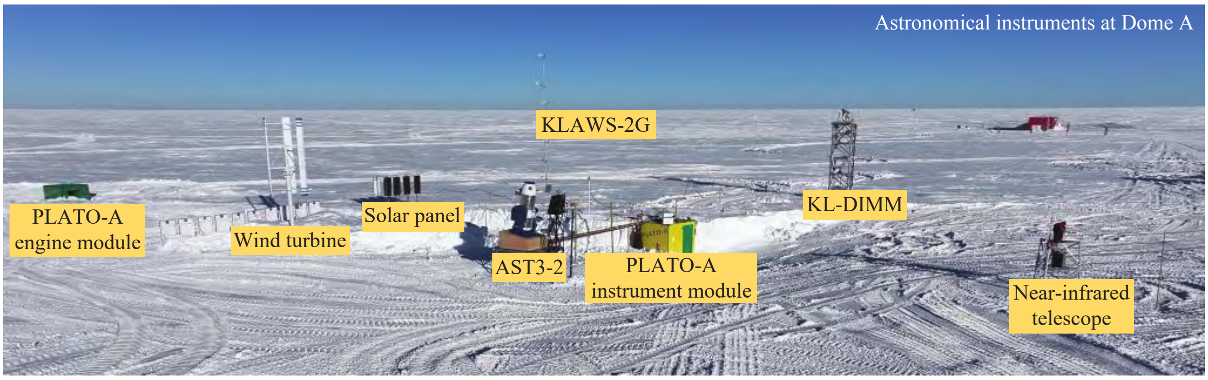

Fig. 12. Photograph of the Dome A astronomical site, showing currently operational instruments.

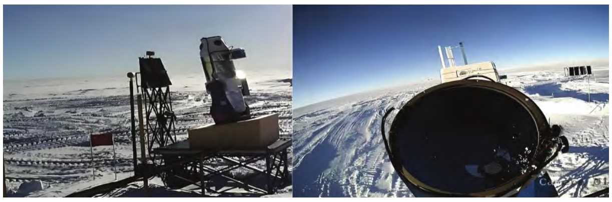

Fig. 13. Status of the AST3-2 near the beginning of 2025.

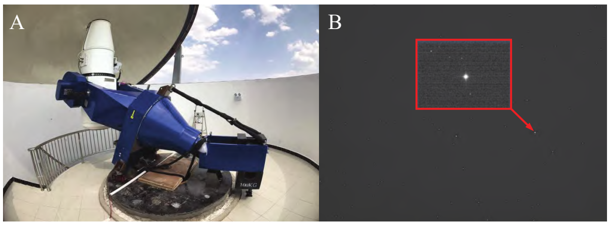

Fig. 14. AST3-3 in operation at Yao'an Observatory (A) and an example obtained image (B).

5. CONCLUSION AND OUTLOOK

The efficiency and scientific output of an Antarctic telescope are directly influenced by its control system, making it imperative to design systems optimized for reliability. Here, we analyze the factors affecting the reliability of Antarctic telescopes from various aspects and describe how this was applied in the development of AST3. We also summarize the development of existing Antarctic telescopes, which can provide technical accumulation and direction for enhancing reliability in the development of future Antarctic telescopes.

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AI DISCLOSURE STATEMENT

AI-assisted technology is not used in the preparation of this work.

AUTHOR CONTRIBUTIONS

Yun Li performed experiments, analyzed data, and wrote the original draft of the manuscript. Shihai Yang and Xiaoyan Li conceived the ideas. Zhenshuai Yan contributed to the study design and corrected the language. Yanpeng Guo, Zhuangzhuang Deng, and Cong Pan, as members of the Antarctic project team, contributed to the preparation of this manuscript. Zhengyang Li and Bozhong Gu administrated and supervised the project. Michael Ashley provided developed PLATO-A, which provides energy and communication support for the operation of the Antarctic telescope. All authors read and approved the final manuscript.

DECLARATION OF INTERESTS

Zhengyang Li is the Executive Editor-in-Chief and Michael Ashley is an editorial board member for Astronomical Techniques and Instruments. They were not involved in the editorial review or the decision to publish this article. The authors declare no competing interests.

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