Construction and Operation of International Scientific Regional Centers for Large Astronomical Facilities: Postprint

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Abstract

With the continuous deepening of astronomical research, the construction and operation of international large-scale astronomical facilities have become increasingly important factors driving scientific progress. This review summarizes the construction status and operational mechanisms of scientific regional centers for international large-scale astronomical facilities, and explores their roles in data management, scientific collaboration, and user support. It first introduces the definition of scientific regional centers and their importance in astronomical research, then analyzes several typical regional centers for large-scale astronomical facilities, including the Low-Frequency Array (LOFAR) and the Atacama Large Millimeter/submillimeter Array (ALMA), emphasizing the impact of infrastructure, technical investment, and management architecture on their success. On this basis, it further discusses current challenges such as resource allocation, data sharing, and collaboration mechanisms, and looks forward to future development directions and trends, providing reference and guidance for the construction and operation of future scientific regional centers for large-scale astronomical facilities.

Full Text

Preamble

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Establishment and Operation of Scientific Regional Centers for International Astronomical Mega-Facilities

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Abstract

With the continuous deepening of astronomical research, the construction and operation of international astronomical mega-facilities have become increasingly important drivers of scientific progress. This paper reviews the current status and operational mechanisms of scientific regional centers for international astronomical mega-facilities, examining their roles in data management, research collaboration, and user support. We first introduce the definition of scientific regional centers and their importance in astronomical research, then analyze several representative centers associated with major facilities including the Low-Frequency Array (LOFAR) and the Atacama Large Millimeter/submillimeter Array (ALMA), emphasizing how infrastructure, technological investment, and management architecture contribute to their success. Building on this foundation, we further discuss current challenges such as resource allocation, data sharing, and cooperation mechanisms, while outlining future development directions and trends. This analysis provides valuable reference and guidance for the construction and operation of future scientific regional centers for astronomical mega-facilities.

Keywords: radio astronomy; astronomical mega-facilities; regional centers

1 Introduction

Astronomy, an ancient yet ever-mysterious discipline, has witnessed humanity' s continuous exploration and understanding of the universe. From ancient stargazers interpreting celestial mysteries to modern astronomers employing sophisticated instruments to probe every corner of the cosmos, astronomy has consistently advanced alongside human progress. Modern breakthroughs such as precise measurements of cosmic microwave background radiation, direct detection of gravitational waves, and in-depth studies of distant galaxies all depend on the construction and operation of large-scale astronomical facilities. International astronomical mega-facilities—including the Atacama Large Millimeter/submillimeter Array (ALMA) [1-3], the Square Kilometre Array (SKA) [4, 5], the Low-Frequency Array (LOFAR) [6], the Laser Interferometer Gravitational-Wave Observatory (LIGO) [7, 8], and the Large Synoptic Survey Telescope (LSST)—have become essential tools driving astronomical advancement. These facilities require not only massive investment and complex technology but also international cooperation and coordination.

Scientific regional centers (variously called science centers, data centers, or branch centers, hereafter unified as “scientific regional centers”) have emerged under these circumstances and play crucial roles in these international facilities. They provide researchers with data storage, processing, and analysis support; concentrate resources and expertise to improve data utilization efficiency and accelerate scientific discovery; and offer user support, education, and training services to promote public understanding of astronomy. Therefore, studying the construction and operation of these centers is vital for understanding the complexity of international astronomical cooperation, improving research efficiency, and advancing scientific knowledge dissemination.

This paper examines the establishment and operation of scientific regional centers for international astronomical mega-facilities, including organizational structures, operational models, challenges, and key success factors, to provide reference for China’ s future leadership or participation in international astronomical mega-projects and contribute to sustainable astronomy development. We analyze planning, construction, and daily operations of several representative centers and explore how they support scientific research and educational activities. The paper is organized as follows: Section 2 defines scientific regional centers and their functions; Section 3 analyzes the construction and operation of representative international mega-facilities (ALMA, LOFAR, LSST, SKA); Section 4 discusses challenges and solutions while offering recommendations for future research.

2 Concept and Functions of Scientific Regional Centers

As astronomical data volumes surge and observational technologies advance, the concept of scientific regional centers has emerged to provide centralized support for research from multiple perspectives. A scientific regional center is a data processing and analysis facility established within a specific geographic region to support data management, analysis, and sharing for international astronomical mega-facilities (or large scientific projects). These centers, typically co-invested and managed by participating nations, perform multiple functions to promote collaboration and efficient data utilization. Figure 1 [Figure 1: see original paper] illustrates a simplified regional center architecture, where different nodes provide varying computational elements, architectures, storage capacities, software/service availability, and network characteristics, ultimately delivering services through a unified, standardized interface.

Through years of development, scientific regional centers have become indispensable components of international astronomical mega-facilities, serving as hubs for data processing and storage, platforms for research collaboration, education outreach, and technology transfer. Their core functions include:

Data Storage and Management. Astronomy is experiencing a data revolution driven by advances in observational technology. ALMA generates 250 TB of data daily; SKA will produce several TB per second, accumulating approximately 740 PB annually; LSST' s large-scale survey generates 2 TB each night. These massive datasets challenge and transform astronomical research from traditional observation-driven to data-driven and computation-driven paradigms. This involves receiving data from telescopes, transferring it between regional centers, storing it in secure systems, and processing it with specialized software to extract valuable scientific information. Simultaneously, centers provide global researchers with data access interfaces, ensuring accessibility and transparency.

User Support. Regional centers offer scientists technical support and consulting services, helping them resolve technical issues, plan research projects, and access necessary software and hardware resources. They also regularly organize training workshops and exchange meetings to enhance users'research capabilities and data processing skills.

Education and Training. By partnering with educational institutions, regional centers develop curricula and materials, provide internships, and organize public lectures and observation activities. These initiatives cultivate the next generation of astronomers and engineers while stimulating public interest in astronomy.

Research Collaboration and Technology Transfer. Regional centers significantly promote cross-border research collaboration and technology transfer. By supporting international projects, they facilitate knowledge and resource sharing, strengthening global scientific cooperation. Overall, scientific regional centers in current mega-facility construction provide essential services in data management, user support, education, research collaboration, and technology transfer, laying a solid foundation for astronomy research and contributing to the scientific community' s sustainable development. They not only advance scientific discovery and cultivate talent but also promote economic development.

3.1 ALMA and Regional Center Construction

The Atacama Large Millimeter/submillimeter Array (ALMA) is an international observatory involving multiple countries and regions. The partnership among the European Southern Observatory (ESO), the U.S. National Science Foundation (NSF), and Japan's National Institutes of Natural Sciences (NINS) through the National Astronomical Observatory of Japan (NAOJ) operates through a multi-level, multi-dimensional model. Partners provide funding and technical support according to their capabilities and expertise. ESO represents its member states, NSF collaborates with Canada' s National Research Council (NRC) and Taiwan' s Ministry of Science and Technology (MOST), while NINS partners with Taiwan' s Academia Sinica (AS) and Korea' s Korea Astronomy and Space Science Institute (KASI) [3]. ESO contributes 37.5% of the total budget, including 25 12-meter antennas, transporters, water vapor radiometers, and key software. North America, represented by the National Radio Astronomy

Observatory (NRAO), contributes an equal share and antennas. East Asia, represented by NAOJ, contributes 25% of the budget and antennas including the Atacama Compact Array (ACA). Chile provides a world-class site offering ideal conditions for ALMA operations. Additionally, partners support their regional users through respective regional centers [10, 11]: the European ALMA Regional Center (ARC), the North American ALMA Regional Center, and the Asian ALMA Regional Center. This multinational cooperation ensures ALMA' s smooth operation and promotes global astronomical progress.

The ARC network is integral to ALMA, supporting and serving astronomers and researchers in each region to effectively participate in ALMA scientific activities. Each regional center has specific responsibilities:

1. **User Support:** Assisting scientists in preparing and submitting observation proposals and in post-observation data processing and analysis.
2. **Data Access and Archiving:** Storing and managing ALMA observation data to ensure convenient user access and download.
3. **Scientific Collaboration and Technical Training:** Organizing seminars, training courses, and workshops to enhance users' scientific and technical knowledge, while promoting collaboration and coordinating cross-regional projects.
4. **Outreach and Education:** Participating in public outreach and education to raise awareness and interest in ALMA and astronomy.
5. **Software and Tool Development:** Developing and maintaining software tools for data processing, analysis, and visualization.
6. **Research Funding Assistance:** Helping users apply for research grants to support their ALMA projects.
7. **Research Output Tracking:** Tracking and documenting scientific publications using ALMA data to assess scientific impact.
8. **Communication with ALMA Project:** Serving as a bridge between users and the ALMA central team, conveying user needs and feedback while disseminating project updates.

Each center provides customized support tailored to its region and user community. The European ARC serves Europe, the Middle East, and Africa; the North American ARC serves North America and the Caribbean; and the Asian ARC serves East and Southeast Asia. Through these regional centers, ALMA better serves the global astronomy community.

3.2 LOFAR Regional Centers

LOFAR [12] consists of 38 stations in the Netherlands, 6 in Germany, and a total of 51 stations across other European countries. Figure 2 [Figure 2: see original paper] shows the LOFAR station distribution. Each station operates in the 10-80 MHz range with 96\$$\times 2 dipolesandinthe 110–240 MHzrangewith 48\times 16 or 96\times$\$16 antennas (each with 2 dipoles). Unlike other array antennas, signals from individual LOFAR dipoles are not directly combined to form a single large antenna. Instead, the two types of LOFAR dipole antennas can be partially combined and digitized in analog electronics, then combined again across the station. Data from all stations are transmitted via fiber to a central digital processor and combined in software to simulate a traditional radio telescope.

LOFAR began scientific observations in December 2012, generating tens to hundreds of terabytes daily. The LOFAR Long-Term Archive (LTA) [13–15] is a distributed data archiving system. LOFAR data are preprocessed at a computer cluster in Groningen, the Netherlands, then distributed to three LTA sites: the SURF cooperative university computing facility in the Netherlands, the Jülich Supercomputing Centre (JSC) in Germany, and the Poznan Supercomputing and Networking Center (PSNC) in Poland.

As shown in Figure 3 [Figure 3: see original paper], preprocessed data from the central processing system are read by data provider nodes, processed, and transferred to data transfer nodes, which transmit the data via GridFTP to LTA nodes for remote storage. Data integrity is maintained through checksums and file size comparisons at various stages (e.g., at data transfer nodes). After successful transfer to remote storage, metadata including observation attributes and data products are provided to the LTA catalog by the telescope manager normalization system. As of October 2023, JSC in Germany had 1.5 PB of disk storage and 21.6 PB of tape storage, growing at 2 PB annually [16].

The LOFAR LTA provides astronomers with a platform for storing and accessing vast radio astronomical data throughout the research process from collection to analysis and sharing:

1. **Data Storage and Management:** The LTA stores raw and preprocessed LOFAR data. After preprocessing, data are distributed to different archive sites, including the Jülich facility in Germany, providing reliable long-term preservation.
2. **Data Access and Retrieval:** Astronomers access LTA data through the LOFAR web service interface, selecting specific observations and retrieving data via a custom staging service. This process is transparent: users submit requests, wait for data to be "brought online" to a cache pool, then download it.
3. **Data Preprocessing and Analysis:** Before storage, LOFAR data are preprocessed at the Groningen cluster, including signal digitization and partial combination. Preprocessed data are more useful for subsequent analysis.
4. **Support for Large-Scale Computing:** The LTA integrates with high-performance computing (HPC) resources, enabling large-scale data processing and analysis near the storage location without remote data transfer.
5. **Long-Term Availability and Sustainability:** The LTA is designed for long-term data availability, ensuring access even years after acquisition, which is crucial for long-term research projects.
6. **FAIR Principles:** The LTA adheres to FAIR (Findable, Accessible, In-

teroperable, and Reusable) principles, organizing data so other researchers can easily find, access, and use them, promoting shared and reusable scientific discovery.

3.3 LSST and Research Center Overview

The Large Synoptic Survey Telescope (LSST) is led by the U.S. Stanford Linear Accelerator Center National Accelerator Laboratory and the Association of Universities for Research in Astronomy, with international partners from 22 countries including Argentina, Australia, Brazil, Canada, China, France, Germany, the UK, Italy, and South Korea, involving institutions such as Brazil' s National Astrophysics Laboratory, the University of Toronto, France' s National Institute for Nuclear and Particle Physics, Italy' s National Institute for Astrophysics, Korea' s KASI, the Max Planck Institute for Astrophysics, and the UK' s Science and Technology Facilities Council.

LSST observes in six optical bands covering 320–1050 nm, surveying approximately 18,000 km^2 of sky [17]. Over its 10-year survey, LSST will uniformly image this area more than 800 times. These data will support multiple scientific objectives, including detecting dark energy and dark matter [18]—major puzzles in modern cosmology. Through weak gravitational lensing observations, LSST will help measure cosmic expansion rates more precisely to infer dark energy' s nature. Additionally, LSST will map the Milky Way' s detailed structure, crucial for understanding galaxy formation and evolution.

The LSST system includes a large-aperture, wide-field, ground-based telescope [19], a 3.2-gigapixel camera [20], and a data management system [21]. The primary facility is located on Cerro Pachón in northern Chile, with an 8.4-meter aperture and an extremely wide 9.6-square-degree field of view. LSST' s CCD camera, the world' s largest, captures an image every 20 seconds, enabling a complete sky survey every three days. This extensive coverage and rapid cadence give LSST advantages in detecting distant cosmic phenomena while capturing transient events in real time. LSST is expected to generate 15 TB of data nightly, with the final catalog database reaching approximately 15 PB.

To handle this massive data stream, LSST designed a comprehensive data management system to automatically process raw data into scientifically useful catalogs and images. The system comprises three layers [22]: an infrastructure layer [23] including computing, storage, network hardware, and system software; a middleware layer providing distributed processing, data access, user interfaces, and system operations; and an application layer [24, 25].

LSST data management includes four key facilities: a summit facility at Cerro Pachón (for detector crosstalk correction), a base facility in La Serena (as a forwarding node for data upload to North America and a data access center for the Chilean community), a central archive facility at the National Center for Supercomputing Applications (NCSA) in Champaign, Illinois, and a satellite data processing center at the Computing Center of the National Institute of

Nuclear and Particle Physics (CC-IN2P3) in Lyon, France. Figure 4 [Figure 4: see original paper] shows the topology of LSST' s international data access centers, with data transmitted between centers via existing and new high-speed fiber links, where processing centers possess powerful computational capabilities.

3.4 SKA Regional Center Development Progress

The Square Kilometre Array (SKA) is the world' s largest radio telescope under construction [26]. Phase 1 includes two telescopes: SKA1-MID in South Africa (observing at 350 MHz to 14 GHz) and SKA1-LOW in Western Australia (observing at 50–350 MHz). SKA' s broad scientific goals aim to explore unknown frontiers in astronomy, including detecting the epoch of reionization (EoR) signals, understanding cosmic magnetic field origins and evolution, and galaxy formation and evolution [27].

As shown in Figure 5 [Figure 5: see original paper], SKA data flows from the SKA1-LOW telescope in Australia' s Murchison interior to processing facilities in Perth at an average rate of 8 TB/s over hundreds of kilometers. South Africa' s SKA1-MID has a similar design but with higher data rates—approximately 20 TB/s from the Karoo desert telescope to Cape Town processing facilities. This is roughly 1,000 times ALMA' s equivalent data rate and 10^5 times faster than estimated 2022 global average household broadband speeds [29, 30]. During scientific operations, SKA is expected to generate about 700 PB annually, with high-priority science programs producing approximately 8.5 EB every 15 years [28]. The enormous volume of data requiring transmission, processing, storage, and distribution to global end-users leads many to consider SKA the ultimate big data challenge [29, 30].

Limited by on-site computing capacity, the SKA Observatory (SKAO) is collaborating internationally to create SKA Regional Centres (SRCs). Preliminary scientific products from the Scientific Data Processor (SDP) will be transmitted to SRCs, where subsequent deep processing continues using SDP software. In this model, SKAO will be supported by a global network of SRCs distributed across member countries, forming an end-to-end scientific data system with distributed storage and shared computing and network capabilities. SRCs' role in SKA data processing is shown in Figure 6 [Figure 6: see original paper]. The worldwide SKA Regional Centre Network (SRCNet) [31, 32] (see Figure 7 [Figure 7: see original paper]) will provide deep processing, scientific analysis, long-term storage, and user support for SKA data, enabling all scientists to conduct research following FAIR (Findable, Accessible, Interoperable, Reusable) principles. SRCNet will adapt its processing capacity to astronomers' needs, providing SKA community access to data products and collaboration platforms; offering transparent, location-independent interfaces for all SKA users; and providing a platform for developing software tools (analysis, modeling, visualization). Different SRCs may be heterogeneous, using existing national HPC infrastructure, new dedicated facilities, or even cloud components. Regardless of composition, each SRC will serve SKA users in a standardized manner. SRCNet is designed to effectively archive, distribute, and process SKA' s massive scientific data products, playing a key role in advancing astronomical research.

The computational model within SRCNet remains to be determined, with proposed approaches including cloud-based environments, distributed systems, or data grid solutions. Scientific users will submit diverse computational processes, from complex pipelines running on workload managers (e.g., Slurm) to isolated operations focusing on large datasets. Data from telescopes will be distributed globally across SRCNet nodes, requiring consideration of data and compute locality to move computation to data whenever possible [33]. End-users have conducted preliminary estimates of expected computational volumes and types in SRCNet through SKA Data Challenges [34, 35].

As SKA construction progresses, developing SRC-based scientific data processing and analysis systems has become a national priority, with some countries (e.g., the UK, Australia, South Africa) already developing scientific data processing pipelines. The Advanced European Network of E-infrastructures for Astronomy with the SKA (AENEAS) brings together all current European SKA member states, potential future EU SKA partners, the SKA Organization, and major international partners including the two host countries, Australia and South Africa. AENEAS has been developing design concepts for European SKA Regional Centres, while the ESCAPE project (The European Science Cluster of Astronomy & Particle Physics, 2019–2022) provided technical solutions for SRC prototypes and defined the European Open Science Cloud for astronomy and particle physics. The ERIDANUS project (Exascale Research Infrastructure for Data in Asia-Pacific astroNomy Using the SKA) focuses on deploying data-intensive research infrastructure prototypes and middleware at Australian and Chinese SRCs.

The Canadian Initiative for Radio Astronomy Data Analysis (CIRADA) will establish new hardware to enhance research databases and scientific data products, aiming to achieve groundbreaking science from next-generation radio astronomy facilities through to SKA. CIRADA' s work includes scientific data products (including user story examples), preprocessing pipeline systems, high-capacity data storage, cross-matching, and public accessibility. The Spanish prototype of an SRC (SPSRC) actively participates in open science practices to support future SKA projects, including scientific research using SKA pathfinders such as MeerKAT and LOFAR. SPSRC development includes hardware and cloud infrastructure construction, scientific archives, software and services, user support and training, and collaboration with other SRCs. SPSRC construction considers open science principles to promote data findability, accessibility, interoperability, and reusability, and to support storage and analysis of massive data from the SKA Scientific Data Processor (SDP). SPSRC is expected to complete most functions by 2025 and achieve full operational capability by 2030 [36].

India plans to build an SKA Regional Centre prototype (proto-SRC) to address SKA' s massive data volumes [37, 38]. This proto-SRC will analyze data from Indian participation in SKA pathfinders and major telescope projects (uGMRT, MeerKAT, and MWA) and provide a platform for technical testing and talent training for future full-scale SRCs. Currently planned storage capacity is approximately 10 PB, with corresponding computing resources and software development for SKA data processing and analysis, including algorithm implementation, data processing pipelines, and visualization software. The Indian proto-SRC will collaborate with global regional centers, sharing knowledge and experience in new hardware and software technologies to lay the foundation for a comprehensive SKA Regional Centre.

China has completed construction of the world' s first SKA Regional Centre prototype (CSRC-P) [39, 40], marking a significant step toward large-scale SKA data deployment. CSRC-P includes a fully functional high-performance computing system designed with scientific requirements in mind, considering SKA data complexity, varying resource demands across scientific projects, and highly concurrent data streams. The system employs general-purpose and heterogeneous computing architectures, with completed performance testing showing ARM processors—used for the first time in SKA—demonstrating performance comparable to Intel processors. CSRC-P also shows significant performance improvements in storage and networking, with its software environment successfully deployed and high-speed data transmission connections established with Australia' s Pawsey Supercomputing Centre, providing global scientists with necessary computing resources, high-quality data products, and technical support to advance early SKA scientific exploration.

4.1 Funding Challenges

Funding constraints represent a critical challenge in constructing and operating scientific regional centers for international astronomical mega-facilities. Funding is not only the foundation for building these centers but also essential for their continuous operation and maintenance. As scientific research deepens, particularly in astronomy, required investments often grow exponentially, making resource allocation difficult for many nations.

The high cost of astronomical projects makes fundraising complex. Scientific regional center construction typically requires massive upfront investment in infrastructure, equipment procurement, and technology development. For example, ALMA' s initial investment exceeded \$1.4 billion, covering not only hardware procurement but also software development, personnel training, and operational support. For many countries, such investment exceeds research budget capacity, limiting project advancement.

Funding uncertainty negatively impacts long-term planning and stability. In many nations, research funding depends on government budgets and annual appropriations, creating volatility. Economic downturns, policy changes, or shifting priorities can lead to budget cuts affecting operations. During economic crises, many countries have reduced research budgets, delaying or canceling planned projects, which not only hinders scientific progress but also damages trust in international cooperation. Funding constraints also directly affect talent cultivation and recruitment. Scientific regional centers require high-level researchers and technical support teams, but inadequate funding makes it difficult to offer competitive salaries and development opportunities, leading to brain drain and inability to attract top talent, further limiting research capacity and innovation potential. Another aspect of funding uncertainty is exchange rate impact, as fluctuations can significantly alter actual contributions and affect national support capacity.

International cooperation offers an effective solution to funding challenges. Indeed, all international astronomical mega-facilities discussed here address funding through international collaboration. Multi-national joint investment shares construction and operational costs, reducing individual country burdens. Additionally, public-private partnership (PPP) models attracting corporate and private investors provide new avenues for sustainable development. For example, some astronomical projects have secured funding through partnerships with technology companies while promoting technology transfer.

Overall, insufficient funding is a major problem in constructing and operating scientific regional centers. Addressing this requires nations to innovate in fundraising, resource allocation, and international cooperation to ensure these centers can sustainably advance astronomy.

4.2 Complexity and Challenges of International Cooperation

As globalization deepens, cross-border research collaboration has become the norm. While international cooperation solves funding problems, its inherent complexity has become an important challenge in building scientific regional centers.

Differences in national laws and regulations create complexity. Scientific regional center construction and operation must comply with host country laws covering taxation, labor, and intellectual property protection. For example, data sharing and privacy protection laws vary by country, requiring centers to establish unified data management standards ensuring compliance across all participating nations. Notably, China encourages international exchange and cooperation in data security governance and data development and utilization, and participates in formulating international rules and standards for data security. In international cooperation, cross-border data flow issues can be handled according to international treaties and agreements China has concluded or acceded to, or based on the principle of equality and mutual benefit.

Cultural differences are also significant factors. Researchers from different cultural backgrounds may have varying work habits, communication styles, and decision-making processes, potentially causing misunderstandings and conflicts that affect team efficiency. To address this, centers must establish effective cross-cultural communication mechanisms, including cultural sensitivity training, multilingual platforms, and inclusive management strategies. Language barriers also require attention. While English is the scientific lingua franca, some researchers have limited proficiency, restricting their participation and communication efficiency.

International political changes also threaten cooperation stability. Political factors can cause project interruptions or renegotiations, affecting continuity and progress. Tense international relations may impact funding flows, personnel mobility, and data sharing. Therefore, centers need flexible cooperation mechanisms to address political uncertainties.

Fair resource allocation is another consideration. Scientific regional center construction and operation require rational distribution of funding, equipment, and talent. Different countries' contributions and needs vary, and balancing interests to ensure fairness and sustainability presents an ongoing challenge.

4.3 Sustainability Issues

Sustainable maintenance and development of scientific regional centers is a key challenge, particularly as astronomical data volumes continue growing. Data centers, as core components, require stability, security, and scalability to ensure research continuity and long-term data value.

From ALMA' s current regional center experience, energy consumption poses a sustainability challenge. As data centers scale up and computing power increases, energy demands grow continuously, creating both economic costs and environmental impacts. Hardware and software maintenance requires continuous investment. With rapid technological development, equipment and systems need regular upgrades to maintain performance and security, requiring not only funding but also specialized technical teams for management and operation.

From a sustainability perspective, data management represents the greatest challenge. Data management strategies are crucial for sustainable development. As data volumes increase, effective storage, backup, and archiving, along with ensuring security and privacy, become critical issues. To meet growing data management demands, scalability is a key sustainability factor. As research advances, data volumes and user needs may grow rapidly, requiring flexible capacity and performance expansion. This necessitates modular, scalable architecture in center design. Disaster recovery and business continuity planning are essential for long-term stable operation. Natural disasters, human error, or unforeseen events can cause failures or data loss. Therefore, centers must develop disaster recovery plans including data backup, system redundancy, and emergency response mechanisms to protect data security and research continuity under any circumstances.

Overall, future sustainability requires comprehensive planning across energy efficiency, technical maintenance, data management, scalability, and disaster recovery. Through effective strategies, scientific regional centers can ensure long-term stable operation, supporting continuous astronomical research.

4.4 Implications for Future Scientific Regional Center Construction

China has achieved remarkable success in mega-science projects such as the Five-hundred-meter Aperture Spherical Telescope (FAST) and the China Space Station. The successful experience of international astronomical mega-facility scientific regional centers offers important lessons for China' s future leadership or participation in international mega-science projects. Based on the preceding discussion and analysis, we propose:

1. **International Cooperation is Essential.** The construction and successful operation of international scientific regional centers demonstrate the importance of global collaboration. In an increasingly globalized world, international cooperation is indispensable for mega-science projects. China should expand international cooperation in future mega-projects, establishing closer partnerships with global research institutions. Such cooperation enables resource, technology, and data sharing while promoting researcher exchange and training, enhancing Chinese scientists' expertise and international perspective.
2. **Sustainable Development Requires Long-Term, Stable Funding.** Diversified funding mechanisms are needed, including government investment, corporate funding, and international cooperation funds. Additionally, strengthened supervision and auditing of operational funds ensure effective use. Efficient management and operational mechanisms are crucial. China should learn from international advanced management experience to establish scientific, efficient management systems, including clear positioning and objectives, optimized organizational structures, improved decision-making mechanisms, and enhanced risk management. Furthermore, talent cultivation and recruitment must be strengthened to build high-level research and management teams.
3. **Science Popularization and Education Should be Prioritized.** Scientific regional centers are not only research bases but also platforms for science outreach and education. China should strengthen cooperation with educational departments in future center construction, conducting various science popularization activities to improve public scientific literacy and cultivate youth interest in science. Centers should also drive local socioeconomic development, promoting industrial structure optimization and upgrading.
4. **Emerging Technologies Will Transform Construction and Operation Models.** Contemporary scientific regional center construction depends on rapid IT development, with internet technology and high-performance computing as fundamental technical supports. High-speed

networks and PB/EB-level supercomputing have enabled these centers. Looking forward, artificial intelligence, next-generation internet, and emerging computing centers may bring new models. We should monitor these developments and, according to different facility requirements, fully utilize cutting-edge technologies in forward-looking planning and construction.

In summary, international scientific regional center construction provides multifaceted implications for China' s future center development, including strengthening international cooperation, ensuring funding, establishing efficient management mechanisms, enhancing science popularization and education, and considering environmental and social benefits. By learning from these experiences, China can better advance mega-science project construction and development, enhancing its influence and competitiveness in international science.

5 Conclusion

This paper' s in-depth exploration of scientific regional center construction and operation for international astronomical mega-facilities reveals their indispensable role in astronomical research. Analysis of ALMA, LOFAR, LSST, and SKA shows these centers serve not only as data processing and storage hubs but also as vital platforms for research collaboration, education outreach, and technology transfer, playing significant roles in advancing scientific discovery, cultivating talent, promoting science popularization, and driving economic development.

Facing challenges in resource allocation, data sharing, and cooperation mechanisms, scientific regional centers require continuous innovation and improvement. Future development should emphasize deeper international cooperation, diversified funding mechanisms, efficient management systems, and strengthened science popularization and education. Through these measures, centers can better adapt to growing data volumes and rapid technological development, making greater contributions to sustainable development in astronomy and other disciplines. We believe that with scientific and technological advances and enhanced international cooperation, scientific regional centers will play increasingly important roles in global research, pushing human understanding and exploration of the universe to new heights.

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