NATIONAL STRATEGY FOR MULTI-WAVELENGTH ASTRONOMY

[2025-2035]

science, technology & innovation

Department:
Science, Technology and Innovation
REPUBLIC OF SOUTH AFRICA

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ABBREVIATION/ACRONYMS

Table 1: List of abbreviations

Acronym	Meaning	Acronym	Meaning
ADS	Astrophysics Data System	IDIA	Inter-University Institute for Data Intensive Astronomy (IDIA)
AERAP	Africa-Europe Science Collaboration and Innovation Platform	IGS	International GNSS Service
AfAS	African Astronomical Society	ILRS	International Laser Ranging Service
AMT	Africa Millemetre Telescope	IRSF	Infrared Survey Facility
APC	African Partner Countries	IVOA	International Virtual Observatory Alliance
APT	African Pulsar Timing	IVS	International VLBI Service for Geodesy and Astrometry
ARAP	African Radio Astronomy Programme	JIV-ERIC	Joint Institute for VLBI European Research Infrastructure Consortium
AT-LBA	Australia Telescope Long Baseline Array	LBA	Australian Long Baseline Array
BAWG	Brics Astronomy Working Group	LFC	Laser Frequency Comb
BHEX	Black Hole Explorer	mHEMT	metamorphic High Electron Mobility Transistor
CARTA	Cube Analysis and Rendering Tool for Astronomy	MACS	Multiwavelength Astronomy Coordination Structure
CTA	Cherenkov Telescope Array	mm-VLBI	Millimetre-wave VLBI
DARA	Development in Africa through Radio Astronomy	ngEHT	next generation Event Horizon Telescope
DEDAT	Northern Cape Department of Economic Development and Tourism	ngVLA	next generation Very Large Array
DHET	Department of Higher Education	NRF	National Research Foundation
DSAA	Data Science and Advanced Analytics	NSMWA	National Strategy for Multi-Wavelength Astronomy

DSTI	Department of Science, Technology and Innovation	PAPSSN	Pan-African Planetary and Space Science Network
EHT	Event Horizon Telescope	RATT	Radio Astronomy Techniques and Technologies
EVN	European VLBI Network	SAAO	South African Astronomical Observatory
GGOS	Global Geodetic Observing System	SA3	South African Astro-informatics Alliance
GNSS	Global Navigation Satellite Systems	SARAO	South African Radio Astronomy Observatory
HEASA	High Energy Astrophysics in Southern Africa	SANSA	South African National Space Agency
HERA	Hydrogen Epoch of Reionisation Array radio telescope	SDGs	Sustainable Development Goals
HIRAX	Hydrogen Intensity and Real-time Analysis eXperiment	SIS	Superconductor Insulator Superconductor
HRS	High-Resolution Spectrographs	SKA	Square Kilometre Array
EVN	European VLBI Network	SLR	Satellite Laser Ranging
GGOS	Global Geodetic Observing System	VGOS	VLBI Global Observing System
ICRF	International Celestial Reference Frame	VLBA	Very Long Baseline Array
IDIA	Inter-University Institute for Data Intensive Astronomy (IDIA)	VLBI	Very Long Baseline Interferometry
IFU	Integral Field Units	IGS	International GNSS Service

EXECUTIVE SUMMARY

The **2025–2035 National Multi-Wavelength Astronomy Strategy** sets out South Africa's vision to maintain and strengthen its role in global astronomy. The strategy builds on the country's geographical strengths, such as dark skies, and state-of-the-art Telescopes, and its success in multi-wavelength research. It addresses emerging challenges and opportunities while promoting a collaborative approach to advance research in radio, optical, infrared, and gamma-ray astronomy.

The strategy emphasises that multi-wavelength and multi-messenger astronomy thrives on collaboration rather than mastery of all methods by individual researchers. It values diverse expertise, encouraging closer cooperation across disciplines. This approach drives progress, supports the study of complex celestial phenomena, and ensures efficient use of resources and infrastructure.

Transformation and inclusivity are key pillars of the strategy. It prioritises scholarships, training, and mentoring, particularly for underrepresented groups, to grow a skilled workforce and foster socio-economic development. Governance is strengthened through the Multi-Wavelength Astronomy Coordination Structure (MACS), which ensures better use of national facilities like the South African Astronomical Observatory (SAAO) and South African Radio Astronomy Observatory (SARAO).

The socio-economic impact of astronomy is significant. Applications in data science and technology transfer support growth in related industries, while astro-tourism contributes to rural economies. The strategy aligns with global goals, advancing the United Nations Sustainable Development Goals, including education, infrastructure, and climate action.

International partnerships reinforce South Africa's leadership in astronomy. Initiatives like the African VLBI Network and Development in Africa with Radio Astronomy project (DARA) expand regional capabilities while linking local efforts with global projects. These collaborations position South Africa as a bridge between local priorities and international advancements.

This strategy provides a framework for expanding South Africa's contribution to global astronomy while delivering measurable benefits in the country. It balances scientific excellence with economic and social progress, ensuring lasting value for the next decade and beyond.

INTRODUCTION

Astronomy represents humanity's enduring quest to explore the unknown and uncover the secrets of the universe. It is a science rooted in curiosity, yet its impact extends far beyond the stars, shaping advances in technology, education, and economic development. South Africa, with its clear skies and cutting-edge facilities, has emerged as a critical hub for global astronomical research and innovation.

The **2025–2035 National Multi-Wavelength Astronomy Strategy** builds on decades of investment and achievement in the field. It addresses the need for greater coordination across radio, optical, and gamma-ray astronomy, bringing together diverse methods and perspectives to advance knowledge. This strategy champions a collaborative approach, where individual expertise combines to tackle some of the most profound questions about our universe.

As the world embraces new frontiers in multi-wavelength and multi-messenger astronomy, South Africa has an opportunity to cement its leadership role. This strategy not only seeks to push the boundaries of what we know but also to strengthen the foundations of how astronomy contributes to society. It invites us to reimagine the role of science in addressing both local and global challenges, from fostering skilled workforces to inspiring the next generation of thinkers.

This is a vision for the future of South African astronomy—a future that balances discovery with inclusivity, and scientific progress with societal impact.

ACKNOWLEDGEMENTS

This Strategy is the result of extensive collaboration and consultation with key stakeholders across South Africa's astronomy sector. Special acknowledgment goes to the Astronomy Community Task Team (ACTT), whose leadership and efforts have been instrumental in developing this strategy. Through their tireless work, they have brought together diverse perspectives, ensuring that the strategy not only reflects the current needs of the sector but also anticipates future challenges and opportunities.

We also extend our deepest gratitude to the nominated members of the astronomy community who represented the various pillars of this strategy. Their expertise, commitment, and collaborative spirit have been invaluable in crafting a strategy that is

comprehensive, inclusive, and sustainable. Their hard work ensures that the strategy addresses the key priorities of scientific advancement, human capital development, infrastructure optimization, and international collaboration, providing a solid roadmap for the next decade of South African astronomy. Their contributions have laid the groundwork for an exciting new chapter in the country's astronomical endeavors.

STRATEGIC VISION AND MISSION

Vision Statement

To position South Africa as one of the global leaders in multi-wavelength, multi-messenger, and multi-technique astronomy, driving scientific discovery, technological innovation, and socio-economic development, while developing a diverse, inclusive, and collaborative astronomical community that contributes to both national advancement and the shared understanding of the universe.

Mission Statement

Our mission is to grow and sustain astronomy through inclusivity, collaboration, high-impact research, human capital development, public engagement and outreach.

Strategic Objectives

1. Establish robust governance and coordination frameworks to integrate national and international astronomy efforts, optimise resources, and foster collaboration across institutions and disciplines.
2. Prioritise human capital development by expanding training, scholarships, and mentoring, with a focus on promoting inclusivity and addressing historical inequities in the astronomy sector.
3. Maximise the scientific and socio-economic benefits of South Africa's astronomy infrastructure by advancing multi-wavelength research, modernising facilities, and driving technological innovation and rural development.

GOVERNANCE OF THE STRATEGY

The governance of South Africa's National Multi-Wavelength Astronomy Strategy is underpinned by key national legislation and strategic frameworks, alongside global goals such as the United Nations Sustainable Development Goals (SDGs). These frameworks ensure that the growth of astronomy in South Africa aligns with national priorities, legislative requirements, and global development targets.

1. **Astronomy Geographic Advantage Act (2007)**

The Astronomy Geographic Advantage (AGA) Act is central to protecting areas critical for astronomical research, such as the Karoo, where the Square Kilometre Array (SKA) and MeerKAT telescopes are located. It grants the authority to protect radio-quiet zones, ensuring the long-term viability of astronomy in South Africa by preventing radio frequency interference. The Act helps South Africa maintain its competitive edge in global astronomy projects.

2. **National Development Plan (NDP) Vision 2030**

The National Development Plan emphasizes inclusive economic growth, particularly in rural areas. Astronomy projects such as those based in Sutherlands, at the South African Astronomical Observatory, contribute to this by nurturing economic opportunities in underdeveloped regions through job creation, skills develo[1]pment, and infrastructure investment. By leveraging these astronomical projects, the strategy supports national goals of poverty reduction and sustainable development.

3. **White Paper on Science, Technology, and Innovation (2019)**

The White Paper sets a vision for harnessing science, technology, and innovation (STI) to drive inclusive growth in South Africa. It prioritizes fields like astronomy, which offer opportunities for technological advancements and human capital development. The Multi-Wavelength Astronomy Strategy aligns with this vision by fostering scientific excellence, driving innovation, and creating socio-economic benefits through strategic investments.

[1] https://www.dsti.gov.za/index.php/legal-statutory/acts ;
https://www.dsti.gov.za/index.php/legal-statutory/white-papers

4. **The Decadal Plan (2022–2031)**

The Decadal Plan outlines South Africa's long-term goals in science and innovation, prioritizing international collaborations and strategic investments in areas like astronomy. The plan emphasizes the importance of astronomy for driving scientific progress and contributing to the socio-economic upliftment of South Africa, particularly through educational and infrastructure investments.

5. **Protection, Promotion, Development and Management of Indigenous Knowledge Act ([2]2019)**

This Act protects and promotes indigenous knowledge, including Indigenous Astronomy. Incorporating Indigenous celestial narratives and products into the strategy not only ensures that this knowledge is preserved but also brings socio-economic benefits to Indigenous communities through education and tourism. It aligns with the broader goal of fostering inclusivity in the scientific community.

6. **United Nations Sustainable Development Goals (SDGs)**

Astronomy aligns closely with the United Nations Sustainable Development Goals (SDGs), supporting the 2030 Agenda's vision for peace, prosperity, and environmental sustainability through key contributions to systemic transitions. The Multi-Wavelength Astronomy Strategy directly addresses SDG 4 (Quality Education) by promoting inclusive education and skills development in underserved communities, fostering a skilled workforce in astronomy and geodesy. Investments in astronomical infrastructure drive innovation and resilience, aligning with SDG 9 (Industry, Innovation, and Infrastructure). Geodetic science supports SDG 11 (Sustainable Cities and Communities) by enabling essential satellite-based services for sustainable urban planning. Additionally, the strategy contributes to SDG 13 (Climate Action) by protecting radio-quiet zones and providing critical data for monitoring climate change impacts. It also advances SDG 14 (Life Below Water) and SDG 15 (Life on Land) by supporting marine spatial planning, biodiversity conservation, and sustainable land use through precise geospatial data. Finally, SDG 17 (Partnerships for the Goals) is addressed through international collaboration and capacity building, demonstrating astronomy's integral role in achieving global sustainable development.[2]

[2] **https://sdgs.un.org/2030agenda**
https://unsdg.un.org/sites/default/files/2023-09/Six%20Transitions%20English.pdf

SWOT Analysis

Table 2: SWOT Analysis

1. Strengths
1.1 Geographic Strengths for Astronomy
● South Africa's dark skies, low Radio Frequency Interference (RFI), clear atmosphere, and dry climate provide ideal conditions for high-quality astronomical observations. ● Its geographic advantages offer critical access to southern sky features and unique coverage for global astronomical and geodetic Very Long Baseline Interferometry (VLBI) networks, making it a critical location for international collaborations.
1.2 World-Class Research Facilities
● South Africa hosts world-class multi-wavelength astronomy facilities and a fundamental geodetic station, making it a critical contributor to global astronomy and geodesy through nationally and internationally recognized research infrastructure.
1.3 Strong Government and Institutional Support
● South Africa's robust institutional framework and consistent government backing provide substantial funding and policy support for astronomy infrastructure and research. ● International partnerships further strengthen South Africa's capacity to achieve its astronomical goals, ensuring the development and maintenance of world-class facilities.
1.4 Leadership in Global Collaboration and Innovation

- South Africa's scientific infrastructure, supported by world-class astronomers, and engineers, attracts key international collaborations, strengthening its influence and credibility in global scientific circles.
- With established, long-term ties to major international projects and participation in world-class research collaborations, South Africa is a critical hub for innovative, multi-wavelength, and multi-messenger astronomy and geodesy.
- As a leader in African astronomy, South Africa fosters regional collaboration and capacity-building, advancing the continent's collective contributions to global science.

1.5 Strategic Governance and Coordination Frameworks

- South Africa's comprehensive strategic frameworks and legislation provide a strong foundation for the long-term development of astronomy.
- The Multiwavelength Astronomy Coordination Structure (MACS) and the expanded Astronomy Chief Directorate strengthen top-down coordination, ensuring organized collaboration and equitable growth across all astronomy fields.

1.6 Human Capital and Research Excellence

- South Africa's strong educational programs, scholarship programs, and partnerships foster growth in astronomy, preparing students for advanced fields like data science and machine learning.
- Established and effective outreach programs in national facilities, supported by dedicated outreach teams, leverage astronomy's appeal to inspire youth, create role models, and open diverse career paths
- South Africa's diverse expertise across radio, optical, infrared, and gamma-ray astronomy, as well as astroparticle physics and geodesy, enables multi-wavelength, multi-messenger, and multi-technique synergies and innovative collaborations.
- A strong mix of interdisciplinary, multi-skilled individuals with expertise in hardware, software, observational, operational, and scientific research, as well as data science, enriches South Africa's contribution to global astronomy and geodesy.

1.7 Technological and Research Leadership

- South Africa’s enduring legacy in astronomy and geodesy, combined with significant advancements in radio astronomy, solidifies its position as a global leader in astronomical and geodetic research.
- The country’s astronomy community has experienced remarkable growth, with research groups maturing into centres of excellence, consistently supported by national programs.
- South Africa has access to advanced engineering capabilities, high-quality infrastructure, and expertise in Artificial Intelligence (AI) and data science, driving innovation across astronomy projects and generating spin-off technologies with applications in other fields.
- Investments in big data infrastructure and computational resources enable the management of vast astronomical datasets, fostering national and international collaborations and supporting extensive research opportunities in data-intensive fields.

2. Weaknesses

2.1 Resource and Funding Challenges

- South Africa's funding opportunities are fragmented, with a strong focus on flagship facilities like MeerKAT and SKA. This allocation leaves other sub-disciplines, such as optical astronomy, VLBI, and geodesy, underfunded, with insufficient support for infrastructure upgrades and innovation.
- A lack of funded university and observatory positions for PhD graduates and postdoctoral fellows, combined with limited opportunities for scholarships in non-radio wavelengths, hampers the growth of a diverse research community.
- Insufficient funding for outreach and public engagement restricts broader societal impact and inclusivity in astronomy.

2.2 Infrastructure and Maintenance Challenges

- Aging infrastructure, deferred maintenance, unreliable electricity, and inadequate internet impact research capabilities, while other facilities remain underutilized, missing repurposing opportunities.
- Challenges in infrastructure optimization, data integration, and lack of joint observing programs between optical and radio facilities lead to underutilization and missed opportunities for synergistic research.

2.3 Policy and Regulatory Limitations

- Slow policy adaptation, governance-policy misalignments, and restrictive legislation limit innovation, hinder international collaborations, and reduce operational flexibility.
- Bureaucratic delays in visa, study permit, and special skills permit processes create significant obstacles for international students and researchers, impacting South Africa's global competitiveness.
- Human Resource function and regulatory challenges, including policies restricting scholarship top-ups, delays in the recruitment of skilled personnel and limited financial support for students, affects capacity and development in academia and research.

2.4 Coordination and Integration Issues

- A disconnected community, limited coordination across astronomy branches, inconsistent monitoring, and the absence of systematic top-down frameworks hinder collaboration, productivity, resource optimization, and multi-wavelength research efforts.
- The lack of centralized information hubs, coherent data-sharing platforms, and streamlined communication between Time Allocation Committees (TACs) across different facilities further restricts research synchrony and multi-wavelength potential.
- Insufficient training programs for multi-wavelength data handling amplify challenges in fostering collaborative and integrated research efforts.

2.5 Challenges in Talent Development and Retention

- Scattered and uncoordinated graduate statistics impede accurate reporting and hinder strategic workforce planning.
- Unclear employment pathways for PhDs, retention challenges for Master's graduates, and unfilled postgraduate and postdoctoral roles are often the result of bureaucratic funding limitations
- Insufficient training programs, workshops, and mentorship opportunities in the reduction and analysis of multi-wavelength astronomy, VLBI, and geodetic data hinder the development of skilled researchers in these areas.
- Limited opportunities for international internships, exchange programs, and graduate programs restrict professional growth and exposure to global research environments.
- A lack of clear and consistent career path strategies in national facilities leaves researchers uncertain about their long-term prospects.
- A lack of robust skill and talent retention strategies, uncompetitive salaries, and mismatches between niche roles and qualified graduates contribute to staffing shortages, particularly in VLBI and geodetic facilities.
- Negative perceptions of VLBI as a complex and demanding field discourage graduate participation, further intensifying staffing challenges in these critical areas.

2.6 Barriers to Education and Public Engagement

- Limited public awareness, inclusive outreach, and education programs, particularly in rural areas, coupled with socio-economic disparities, inadequate resources, and insufficient stakeholder partnerships, hinder access to science education and digital literacy.
- Educational inequalities in Mathematics and Science at the basic education level, along with language barriers and specialized jargon, restrict public engagement in astronomy and the development of future postgraduate candidates.
- Isolation among the astronomy community, facilities, agencies, and government limits effective collaboration, reducing public interest and awareness of astronomy's opportunities and socio-economic benefits.

2.7 Data Management and Technological Gaps

- The absence of standardized, accessible multi-wavelength data-sharing platforms and fragmented Data Science and Advanced Analytics (DSAA) research across universities hinder effective collaboration, integration, and streamlined research opportunities.

2.8 Geographic and Political Barriers to Collaboration

- Geographic isolation and long distances between institutions in South Africa limit internal and international collaborations, creating resource gaps, critical mass challenges outside major metropolitan areas, and difficulties competing for international funding and research programs due to a limited number of local researchers.
- Logistical barriers, including high travel costs, visa delays, and slow hiring processes, hinder timely recruitment of international researchers and staff.
- Fields like VLBI, and in particular geodetic VLBI and related initiatives, face challenges in securing sustainable funding and political backing because they are not perceived as immediate national priorities, despite being critically important to advancing global science.

3. Opportunities

3.1 Expanding Global and Regional Partnerships

- By leveraging South Africa's geographic advantage and established partnerships and expanding participation and collaboration in major international astronomical and geodetic initiatives, South Africa enhances knowledge exchange, skill-building, and observational research, bolstering its global standing and scientific impact.
- Hosting major events like the International Astronomical Union General Assembly (IAU GA) and involvement in global astronomy initiatives promotes knowledge exchange, strengthens international collaboration, and drives technological spin-offs, advancing both the national astronomy sector and broader socio-economic impact.
- South Africa's active role in regional African programs and associations strengthens opportunities for further collaboration across Africa, providing valuable returns on investments in partner programs in both astronomy and geodesy.

3.2 Infrastructure Development and Global Engagement

- South Africa’s geographic advantage and proximity to major international facilities supports hosting new global research projects and fostering participation in international collaborations.
- Continues upgrading of core astronomical instrumentation and investing in new and innovative observational techniques will enable South Africa to address emerging scientific needs and maintain competitiveness.
- Advancing expertise in cost-effective manufacturing and testing of advanced astronomical instrumentation positions South Africa as a global leader in these technologies, opening new opportunities for international partnerships.
- The ongoing work in multi-wavelength and multi-messenger astronomy and infrastructure development, including the growing integration of astronomy and geodesy efforts and technologies, presents a unique opportunity for synergistic advancements in all fields, driving further innovation and spin-offs.

3.3 Technological Innovation and Data Science Growth

- Increased investments in data science and infrastructure, including high-performance computing, advanced data storage, and high-speed networks, enable South Africa to handle vast astronomical datasets, complementing the growth in national and international research projects. Expanded data transport capacity also supports advanced interferometric correlation, strengthening South Africa’s capacity in large-scale radio astronomy data processing and analytics.
- South Africa's growing investments in Big Data infrastructure and AI offer significant opportunities for innovation, creating career pathways for students skilled in Data Science and Advanced Analytics (DSAA) while enhancing access to tools and applications that advance data-driven astronomy.
- Opportunities to promote open science and enhance data accessibility through initiatives like the Virtual Observatory strengthen multi-wavelength research collaboration and enable broader participation across the scientific community.

3.4 Human Capital Development and Educational Growth

- Expanding astronomy education to Historically Disadvantaged Institutions (HDIs) offers an opportunity to enhance diversity by leveraging existing Physics or Mathematics programs to introduce postgraduate options in astronomy and data science, even in institutions without undergraduate astronomy programs.
- Gradual introduction of undergraduate astronomy courses to HDIs will further broaden access and interest.
- Coherent and formalized training programs in multi-facility data reduction, data handling, and telescope usage can drive future multi-wavelength research and innovation across South Africa.
- The growing number of young astronomers trained in data-intensive astronomy fosters diverse career paths in both academia and industry. Coupled with exposure to international facilities, these efforts support technological dvancements, economic spin-offs, and South Africa's global competitiveness in astronomy and related fields.

3.5 Strategic Coordination and Cross-Sectoral Collaboration

- Enhanced coordination within the astronomy community, supported by both top-down and bottom-up approaches, presents an opportunity to improve resource distribution, implement joint funding programs, and integrate decision-making processes to drive strategic growth and collaboration across the sector
- Advancing multi-wavelength research collaboration and shared technological development will unite the astronomy community, driving innovation and new discoveries.
- Additionally, cross-science and cross-sector collaborations, along with strengthened public-private partnerships, will expand scientific impact and fuel further innovation and growth
- The development of unified data-sharing platforms, which make public data easily accessible in standardized formats, present an opportunity to enhance multi-wavelength research collaboration by enabling easier access to multi-wavelength astronomical data beyond the constraints of specific facilities or research teams focused on individual wavelengths.

3.6 Astro-Tourism, Public Engagement, and Inclusivity

- Implementing the Astro-tourism strategy and integrating indigenous astronomy knowledge with modern scientific practices offer opportunities to enrich cultural heritage, promote inclusion, and stimulate local economic growth. These initiatives also broaden public engagement and foster shared benefits across communities.

4. Threats

4.1 Funding and Economic Constraints

- Inconsistent and declining funding streams, coupled with a struggling economy and government budget cuts, jeopardize the maintenance of critical infrastructure, retention of skilled staff, and support for students and outreach, while limiting access to resources for critical projects and partnerships.
- Economic challenges and potential political shifts threaten recruitment of scarce skills, transformation efforts, and long-term career prospects for young South Africans, increasing the risk of brain drain.

4.2 Infrastructure and Technological Obsolescence

- Aging and undervalued infrastructure, particularly VLBI and geodetic infrastructure, is at imminent risk of operational failures and obsolescence without urgent and sustained repairs and upgrades. These vulnerabilities threaten South Africa's critical role in global astronomical and geodetic networks.
- Additionally, reliance on critical staff, coupled with a lack of redundancy, creates vulnerabilities that risk disrupting facility operations and maintenance in the event of retirements, illnesses, or career changes.

4.3 Talent and Resource Allocation Risks

- Internationally competitive funding and salaries, coupled with more lucrative industry opportunities, draw skilled researchers and data scientists both away from South Africa and out of the academic research sector, risking a loss of expertise critical to astronomy and data science.
- A strong emphasis on SKA-focused radio astronomy creates deficits and disinterest in other wavelengths and areas, reducing scholarships, postdoctoral positions, and research opportunities needed for a diverse multi-wavelength and multi-messenger astronomy and geodesy community.
- Reliance on international recruitment for research leadership persists as emerging local astrophysicists are predominantly junior.
- The loss of critical staff with multidisciplinary expertise in engineering, operations, and science, combined with a growing disconnect between these areas—particularly at South Africa's radio astronomy facilities—jeopardizes effective facility management and long-term sustainability. This disconnect also limits the integration of science goals and data reduction with engineering and operational processes, hindering fault detection and overall system improvement.

4.4 Risks of International Dependency

- South Africa's reliance on international partnerships poses risks to its autonomy in astronomy and geodesy, compounded by sensitivity to global geopolitics and limited funding for international travel, isolating local researchers from collaborations and knowledge exchange.
- International groups leveraging South Africa's geographic advantage more effectively pose a challenge to local initiatives.
- Furthermore, heightened competition for international funding and resources, combined with overextended research staff and limited domestic employment opportunities, hampers collaboration, knowledge exchange, and skill transfer.

4.5 Environmental and Regulatory Challenges

- Environmental challenges, including climate change, space pollution, light and dust pollution from mining and fracking, construction activities, along with increasing RFI and spectrum occupancy demands, significantly impact observational conditions, threatening data quality and the viability of radio quiet zones.

CORE STRATEGIC PILLARS

The 2021 South African Astronomy Scientometric Study and the recent Astronomy Institutional Landscape studies highlight the substantial investment and growth achieved in the field over recent years. These studies also identify key areas needing further attention and development to fully realize our mission. Building on insights from these studies, the inaugural 2015 South African Astronomy Strategy, and its implementation, this strategy is shaped around strategic pillars identified by the astronomy community. These pillars are designed not only to drive the growth of astronomy but also to transform the sector, fostering socio-economic benefits for all South Africans. They provide a focused approach to the continued work required in this field.

Pillar 1: Funding, Governance, and Strategy Optimization

The Department of Science, Technology and Innovation (DSTI) oversees the overall strategic direction and funding for astronomy, working closely with the National Research Foundation (NRF) which manages funding allocations and supports research and human capital development through its various grants and scholarship programs. The National Strategy for Multi-Wavelength Astronomy (NSMWA) and the decadal plans provide comprehensive guidance for the development of astronomy in South Africa. These strategies ensure that the country's efforts are aligned with international developments to ensure international competitiveness and address both current and future needs. Institutions such as the South African Astronomical Observatory (SAAO), South African Radio Astronomy Observatory (SARAO) and Universities are pivotal in the implementation of such strategies and in conducting cutting-edge research. This governance framework should not only support high-quality research and innovation but also strive to promote inclusivity and sustainability, positioning South Africa as a key player in global astronomy.

Funding remains a critical enabler for the continued growth and success of astronomy in South Africa. It supports the maintenance and advancement of research facilities, fosters innovation, develops human capital, promotes inclusivity, enhances international collaboration, and delivers economic and societal benefits. Leveraging funding nationally and internationally for research and astronomy-related HCD and outreach work while ensuring that funding strategies promote sustainability and equitability will ensure the long-term impact of this sector.
Strategy optimization should focus on enhancing the effectiveness, efficiency, and impact of the country's astronomical research and development efforts. This involves a

systematic approach to improving various aspects of the astronomy sector, ensuring that resources are used wisely, strategic goals are met, and the field remains competitive globally.

Objectives:

- Enhance effective governance and coordination by developing an integrated decision-making approach to ensure seamless collaboration between national and international facilities, universities, industry, and government agencies.

- Optimize resource allocation by implementing effective funding and resource management strategies and platforms to support the long-term sustainability and growth of Astronomy research and infrastructure.

- Ensure sustainability by promoting policies and practices that foster equitable and sustainable development of the astronomy sector (i.e. in education, research, innovation, facilities), balancing local needs with international collaboration and agreements.

Recommendations

Streamline Processes: There is a need for this within the NRF Facilities and within the Universities. It should involve streamlining funding applications, simplifying reporting requirements and reducing the layers of administrative approval required.

Enhancing Flexibility: It is important to increase the flexibility in the management of funds and resources, allowing astronomers to adapt to new discoveries and new opportunities without being hampered by bureaucratic constraints. This means reversing changes made by the NRF in recent years.

Community Involvement: Encourage the involvement of the astronomy community, including their engineering partners, in the redesign and implementation of bureaucratic processes, ensuring that they are more closely aligned with the needs and realities of research.

Policy and Funding Alignment: Ensuring research priorities are aligned with national and continental policy frameworks and securing sustainable funding to support long-term research initiatives.

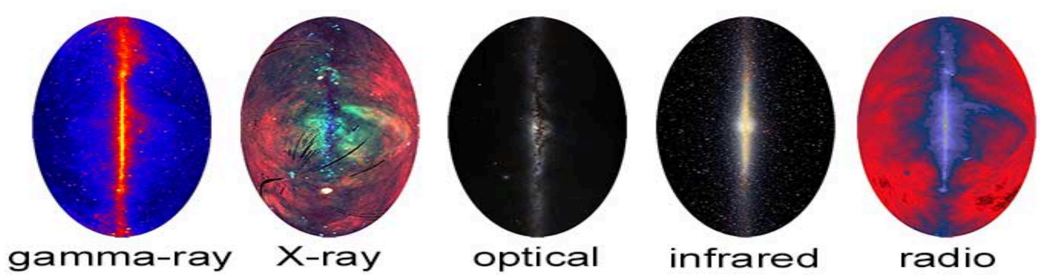
Pillar 2: Multi-Wavelength Astronomy Coordination

This pillar strengthens the coordination and oversight of South Africa's astronomy sector, aiming to optimize resource use, foster collaboration, and support sustainable growth within a unified framework. Through streamlined communication, resource-sharing, and strategic alignment across institutions, the Multi-Wavelength Astronomy Coordination Structure enables diverse research efforts, infrastructure optimization, and effective capacity building. This approach ensures a cohesive environment that integrates all stakeholders, enhances multi-wavelength synergies, and brings astronomy's socio-economic benefits to a wider audience.

Objectives

- To strengthen the coordination and oversight of the astronomy sector.
- Facilitate communication and outreach between researchers and students at different institutions and within different research areas (e.g. promote interdisciplinary research efforts)
- Coordinate efforts to optimise the use of existing infrastructure and avoid duplication of resources.
- To support and enable the growth and sustainability of the Multiwavelength Astronomy Coordination Structure (MACS).
- Establish a coherent coordination framework that includes all Astronomy Stakeholders.

Figure 1: Multiwavelength Astronomy[3]



[3] https://imagine.gsfc.nasa.gov/science/toolbox/multiwavelength1.html

Multi-Wavelength Astronomy Coordination Framework

Table 3: Coordination Framework

Institutions / Groups	Governance	Research	Enablers	Capacity Building
Stakeholders	National Treasury Department of Science & Innovation United Nations Sustainable Development Goals National Development Plan White Paper – Science, Technology & Innovation 2019, Science & Innovation Astronomy Geographic Advantage Act 2007, Science & Innovation The Decadal Plan 2022-2031, Science & Innovation	SARAO SAAO SKAO SALT SA-GAMMA HIRAX CRC HERA RATT ARAP	NRF RISA SARChI Chairs AfAS BAWG/BAC OAD CHPC ASSA IKS Centre	Universities SARAO HCD NASSP DARA IDIA
Roles & Responsibilities	Funding and Policy: Supporting efficient and sustainable public financial management; Ensure transparency, accountability and sound financial controls in the management of public finances; To ensure availability of and access to internationally comparable research and innovation infrastructure to	Production of Science, cutting edge Engineering, Human Capacity Development, Infrastructure Development & Maintenance, Instrumentation, World-class Innovation	Funding disbursement,, grant allocations, national, continental and international coordination, data storage, public engagement and education, sustainable development,fostering astronomical passion	HCD Transformation Training Equity Cultivating expertise in data-intensive research,

<table>
<tr><td></td><td>generate new knowledge and train new researchers;

Supports the development of astronomical sciences around a multi-wavelength strategy, and provides strategic guidance and support to relevant astronomy institutions.

Facilitates national, continental, and international coordination of astronomy projects and initiatives.</td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Stakeholder Engagements</td><td>To ensure cohesive, coordinated and collaborative efforts in the astronomy sector.</td><td>To align research activities with strategic goals and secure the necessary support.</td><td>To understand their needs and priorities, ensure that funding, grants, and resources are allocated effectively to support impactful projects.</td><td rowspan="2">To oversee and coordinate capacity-building activities.
To enhance the skills of students and emerging researchers, facilitate joint research projects that involve students, faculty, and researchers from different institutions. This promotes cross-institutional learning and resource sharing.
To avoid duplication in certain areas.</td></tr>
<tr><td colspan="3">Engage with local communities and stakeholders to involve them in astronomy activities and events, cultivating a passion for astronomical sciences.

Engage with global partners to leverage astronomy for development, addressing societal challenges through innovative projects.</td></tr>
<tr><td>Current Coordination Problems?</td><td>The 2015 multiwavelength strategy has not been fully implemented due to limited coordination, changing priorities, limited capacity and funding constraints.</td><td>No real systematic “top-down” multiwavelength astronomy coordination system e.g. coordination is done in “closed” collaboration in research groups.</td><td>In the current South African climate, resources seem heavily skewed towards radio astronomy. This has slowly created a deficit and disinterest at other wavelengths.</td><td>Duplication of efforts, slower productivity and lack of resource optimization.</td></tr>
</table>

	Inequitable and imbalanced distribution of resources. The Astronomy community, facilities, agencies, and government work in isolation for a common goal, e.g. outreach.	No central hub such as a dedicated website or similar platforms to keep calls for proposals for multiwavelength facilities updated. This might prompt a better multiwavelength synchronisation for Calls for proposals (CfPs). Lack of communication between TACs hinders coordination and collaboration efforts. (e.g. if one wants SALT data but also needs MeerKAT data simultaneously to get maximum returns).		Lack of information or the provision of filtered/incomplete information creates uncertainty and instability.
		No real database platform with information about South African researchers and their expertise. Missed opportunities for collaboration, knowledge sharing, and skill transfer.		
Benefits	Consistent and progressive coordination efforts to include and grow the African astronomy community, i.e. African Astronomical Society Better strategic coordination, scientific collaboration and sharing of resources.	Better communication between facilities for improved coordination of calls for proposals and synchronisation of observing schedules. Coordinated communication between TACS from the multiwavelength facilities and unified multiwavelength proposal to coordinate between TACs.	The involvement of RISA and NRF in the MACS will yield quicker turnaround times for reported problems and issues. By hosting AfAS conferences and coordinating BRICS Astronomy Working Group meetings, African astronomers gain visibility on international stages. This exposure allows them to showcase their research and achievements to a global audience, elevating Africa's	Better coordination will result in Astronomy Development in Histroically Disadvantaged Institutions.

	The recent growth of the Astronomy Chief Directorate at DSTI equates to increased capacity and efforts to equitably and effectively coordinate, facilitate, include and grow all multiwavelength astronomy activities and stakeholders in South Africa. The establishment of the Multiwavelength Astronomy Coordination Structure (MACS), consisting of multiple stakeholders, is a positive step toward better coordination using the top-down approach.		reputation in the field.	
		The establishment of the Astronomy Community Task Team means better coordination efforts among the astronomy community from the bottom-up approach. A more balanced distribution of resources can be achieved. An example, an established joint multiwavelength funding programs (scholarships/fellowships).		
Strategic Activities/ Recommendations	Champion policy/strategy implementation efforts Determine responsibility for comprehensive monitoring and evaluation Advocate for equitable resource distribution aligning with national priorities and promoting balanced growth. Facilitate national and international coordination Establish feedback mechanisms to gather input from stakeholders on funding processes and outcomes	Promote and coordinate collaborative research across institutions and wavelengths. Coordinate to creating a unified Data-Sharing platform Coordinate the standardizing of Data formats and protocols	Ensure transparent and equitable Resource Allocation. Developing joint funding programs and grant opportunities	Engage and coordinate with Policymakers to align capacity-building efforts Promote and coordinate joint research projects to encourage collaboration
		Develop a centralized platform for communication Establish a Comprehensive Database of Researchers and Expertise Expanding the Astronomy Town Meeting. Work with various stakeholders to coordinate research efforts, avoid duplication, and leverage synergies across different projects and institutions.		

	allowing for continuous improvement and alignment with strategic goals.			
Resources	Endorsed Multiwavelegnth Strategy 2025 - 2030. Relevant ACTS e,g AGA Act. Strategic plans and funding.	Implementation Champions Time Administration Information Technology	Funding Grants Various Reports	Funding Mentees
Coordination Mechanism	MACS, Steering Committees, Working Groups, Clusters, Portfolio Committees, Cabinet, Parliament Submissions, Gazettes, Reports, Meetings and Memos, websites, emails	Astronomy Town Meetings, Astronomy Community Tast Team, Workshops, Conferences, Reference Groups, Science Talks (public and network) Meetings, Press releases, websites, reports, email lists		

Pillar 3: Instrumentation, Infrastructure and Observational Techniques

South Africa has firmly established itself as a global leader in multi-wavelength astronomy through strategic investments in sustainable infrastructure, advanced instrumentation, and innovative observational techniques and a long history of scientific excellence and an extensive track record of delivering world-class science. The country hosts leading optical and radio facilities, including the Southern African Large Telescope (SALT), the MeerKAT radio telescope, and VLBI telescopes used for both astronomy and geodesy. Projects such as the Hydrogen Intensity and Real-time Analysis eXperiment (HIRAX), currently under deployment, and the construction of the Square Kilometre Array Mid-Frequency Array (SKA-MID) telescope, set to become the largest and most sensitive radio telescope in the world, further solidify South Africa's reputation as a global hub for astronomical innovation and discovery.

In addition to flagship projects, South Africa hosts an array of instruments and facilities that further solidify its standing as a global hub for astronomy and geodesy. The mountain top at SAAO's Sutherland station has evolved into a major hub for numerous optical and infrared observatories hosted by international partners. Similarly, the Boyden Observatory near Bloemfontein houses a range of optical telescopes, supporting both research and educational activities. The SARAO Losberg site near Carnarvon in the is home to the MeerKAT telescope, a world-renowned precursor to the SKA. MeerKAT will be integrated into the mid-frequency component of the SKA telescope, currently under construction. This site also hosts the HIRAX telescope alongside various other smaller instruments.

At the SARAO Hartebeesthoek site, three radio telescopes support VLBI, complemented by an array of other complementary geodetic instruments. This site is one of only a few *fundamental geodetic stations* in the world, tying VLBI to geodetic techniques—a unique achievement on the African continent, following a ~30-year investment. South Africa's role as a key player in global geodesy is further emphasized by a new geodetic site currently under development near Matjiesfontein in the Great Karoo. In addition, SARAO operates geodetic infrastructure at multiple sites across South Africa and beyond, including the SAAO station in Sutherland, the SARAO site in Carnarvon, and locations across South Africa and Africa, as well as remote stations on Gough Island in the South Atlantic Ocean, Marion Island in the Indian Ocean, and at the SANAE IV Antarctic station. Beyond its national facilities, South Africa plays a significant role in advancing regional and continental astronomy initiatives, with involvement in various smaller observatories and training instruments deployed across South Africa and Africa.

In addition to its world-class facilities, South Africa's emphasis on a diverse set of observational techniques strengthens its global scientific contributions. These methods produce high-impact astronomical data and essential products for international objectives, such as refining celestial and terrestrial reference frames vital for global navigation, positioning, and timing. By aligning its infrastructure and instrumentation with key research priorities—multi-wavelength, multi-messenger, time-domain astronomy, transient events, and large-scale surveys—South Africa drives cutting-edge science while delivering broader technological and socio-economic benefits.

At SAAO advanced observational techniques include agile, multi-modal operations that provide flexible and continuous observations beyond traditional survey modes. This is complemented by wavelength coverage across optical and infrared ranges, enabling diverse research applications. Key operational techniques include spectroscopy, photometry, and polarimetry for detailed analysis, as well as high-speed photometry and spectroscopy to capture rapid and transient events. Specialized methods, including high-precision radial velocity measurements, support stellar and planetary motion studies, while wide-field imaging and spectropolarimetry contribute to large-scale surveys and polarization research. SAAO's infrastructure supports a variety of observing modes—including manual, queue-scheduled, service, and robotic operations—with autonomous systems facilitating efficient and consistent data acquisition.

At SARAO, the MeerKAT telescope demonstrates cutting-edge radio interferometric techniques. It operates in multiple modes, including imaging mode for high-fidelity sky mapping, spectroscopy mode for measuring spectral line emission and absorption, and time-domain mode for pulsar timing and detecting fast transients. Its continuum mode allows for wide-frequency imaging, while its VLBI mode will integrate MeerKAT into global VLBI networks. The SARAO Hartebeesthoek site, home to three radio telescopes, operates primarily in VLBI mode for geodetic applications, with the larger 26-m telescope additionally supporting astronomical and astrometric VLBI over multiple radio frequencies, as well as supporting single-dish observations in both continuum and spectroscopy mode for long-term, high-cadence maser line monitoring and continuum surveys.

This combination of capabilities, including optical, infrared, and radio facilities, positions South Africa as a leader in multi-wavelength and multi-technique astronomy, enabling groundbreaking scientific discoveries. Furthermore, the country's expertise in geodesy and geodetic infrastructure supports critical global initiatives, ensuring South Africa remains at the forefront of international scientific collaboration and technological innovation. Examples of South Africa's leadership include multi-wavelength initiatives such as the MeerLICHT project, which bridges optical and radio astronomy by operating in synergy with the MeerKAT telescope. This coordination enhances the scientific output of both facilities, showcasing the power of combined observations. Regionally, South Africa's contributions to the High Energy Stereoscopic System (H.E.S.S.) in Namibia add vital gamma-ray data, strengthening collaborative astronomy efforts in the southern hemisphere.

Multi-messenger capabilities are advanced through initiatives such as the Intelligent Observatory (IO) program, led by the SAAO. The IO program supports agile, multi-wavelength, and multi-messenger research by enabling rapid, coordinated responses to transient astronomical events. This centralized, automated control system fosters cross-disciplinary collaboration among experts in radio, optical, and astroparticle physics. Cross-disciplinary innovation is further demonstrated through projects that make astrometric and geodetic VLBI data usable for astronomy through improved scheduling and observing techniques while also achieving more optimal use of existing facilities.

South Africa not only hosts world-class astronomical facilities but also possesses advanced expertise in hardware, software, and engineering, supported by state-of-the-art laboratories and machining capabilities, particularly in fiber optics and receiver development. The country's interdisciplinary and multi-skilled workforce excels in observational, operational, and scientific research, underpinned by a rapidly growing radio astronomy and VLBI community. Strong engineering capacity at SAAO and SARAO, bolstered by partnerships with universities and industry, ensures sustained innovation and positions South Africa at the forefront of global astronomy and technological development.

South Africa's current instrumentation and observational capabilities are strategically aligned with high-impact research goals. World-class facilities provide agile, multi-modal opportunities across multiple wavelengths. However, challenges remain in maintaining and upgrading and modernizing aging infrastructure while the loss of expertise due to retirements, migration, and disconnects between engineering and astronomy further jeopardizes the sustainability and full utilization of these facilities. Significant opportunities for technological innovation exist and by leveraging its strengths, addressing infrastructure challenges, and capitalizing on technological opportunities—such as receiver upgrades, next-generation instrumentation, and multi-wavelength synergies—South Africa will sustain its leadership in global astronomy and geodesy. These advancements will ensure continued contributions to cutting-edge science while driving broader technological and socio-economic benefits.

Objectives:

- Ensure South Africa's astronomy infrastructure remains globally competitive by modernizing existing facilities, addressing maintenance challenges, and aligning with international standards.
- Maximize the scientific output of flagship facilities such as SALT, MeerKAT, SKA, and VLBI by optimizing operations and integrating them into the global multi-wavelength and multi-messenger landscape.
- Address funding gaps and deferred maintenance to secure operational continuity and enable medium-scale research projects alongside flagship initiatives.
- Drive technological innovation and next-generation development by advancing instrumentation, software, and hardware capabilities to address current and emerging research needs.
- Foster sustainable resource use in the development, maintenance, and operation of astronomy infrastructure.
- Develop and retain critical expertise by fostering a skilled and diverse workforce in astronomy, engineering, and advanced observational techniques.
- Enhance interdisciplinary research and innovation by promoting efficient observational strategies and integrating multi-wavelength and multi-technique data.
- Position South Africa as a global leader in astronomical instrumentation and technological innovation through strategic investments in research, development, and partnerships.

Recommendations and Strategic Priorities:

Enhance the scientific output of MeerKAT and prepare for SKA integration: Ensure that these facilities continue to deliver world-class research and are seamlessly integrated into the broader multi-wavelength landscape.

Regularly maintain and upgrade aging infrastructure: Undertake consistent maintenance and modernization of infrastructure, with a particular focus on the VLBI components at the Hartebeesthoek site, where urgent repairs to critical systems and upgrades to next-generation receivers are required. Prioritize the development and implementation of cutting-edge technologies, including upgrades to high-frequency, wide-band VLBI receivers to align with global trends. Additionally, advance optical and infrared capabilities through the deployment of Laser Frequency Combs (LFC) for High-Resolution Spectrographs (HRS), Integral Field Units (IFUs) on SALT, and enhancements such as the Infrared PRIME telescope and Infrared Survey Facility (IRSF) upgrades at SAAO.

Invest in Advanced Instrumentation: Develop funding proposals and strategies to secure financial resources for medium-scale projects beyond flagship programs like SKA and MeerKAT, while prioritizing targeted funding for infrastructure maintenance and operational needs.

Repurpose and optimize infrastructure: Transform underutilized infrastructure, such as KAT-7, into training platforms or smaller-scale observational projects, while developing cost-effective and sustainable strategies for infrastructure maintenance and upgrades, particularly in remote areas.

Strengthen Multi-Wavelength and Multi-Technique Synergies: Assess and integrate radio facilities with optical and infrared counterparts to enhance multi-wavelength research. Implement novel observational strategies, such as time-domain astronomy and transient event follow-ups, to maximize research output and scientific discoveries.

Leverage Emerging Technologies: Leverage emerging technologies such as machine learning and AI to advance observational strategies and data processing and analysis.

Conduct Training and Address Skills Transfer: Host workshops and training programs on advanced observational techniques while implementing mentorship and skills transfer initiatives to mitigate the loss of expertise due to retirements or migration. Provide ongoing professional development opportunities for researchers and technical staff, ensuring they remain updated on the latest observational techniques, technologies, and interdisciplinary research methods.

Bridge the Disconnect Between Engineering and Astronomy: Foster closer collaboration between engineering and astronomy teams to improve facility management, maximize infrastructure utilization, and ensure innovative research outcomes.

Establish a Technology Hub for Innovation: Create a technology hub that connects national facilities, universities, and industry partners to drive innovation in hardware, software, data processing, and instrumentation development.

Pillar 4: International Collaboration and African Leadership

South Africa's exceptional geographic advantages—including its southern hemisphere location, dark skies, low Radio Frequency Interference (RFI), clear atmosphere, and dry climate—combined with state-of-the-art infrastructure and expertise in astronomy, engineering, and geodesy, position the country as a premier site for astronomical and geodetic observations. Over the past few decades, South Africa has established itself as a global leader by hosting world-class facilities such as SALT, MeerKAT, and the SKA-Mid, currently under construction. In addition to these flagship projects, the country hosts numerous other telescopes, such as HIRAX and telescopes for VLBI and critical geodetic infrastructure, most of which operate under international partnerships and networks. These collaborations reinforce South Africa's status as a hub for transformative scientific infrastructure and global research excellence.

Beyond its borders, South Africa also actively participates in collaborations with world-leading astronomical facilities. South Africa's active participation in international collaborations underpins its significant role in advancing global astronomy and related sciences. These partnerships span a wide range of disciplines, wavelengths, and cutting-edge projects, showcasing the country's contributions to frontier science and its integration into global research networks. Fig. 1 illustrates the diversity of these regional and international collaborations, highlighting instruments and initiatives across radio, millimeter, optical, X-ray, gamma-ray, and neutrino astronomy. Details are provided in Pillar 6.

South Africa's role as a convener of global partnerships is also equally prominent. As the secretariat of the BRICS Astronomy Working Group (BAWG), South Africa fosters collaboration among Brazil, Russia, India, China, and South Africa, leveraging combined expertise to address global challenges. Similarly, through the Africa-Europe Science Collaboration and Innovation Platform (AERAP), South Africa strengthens ties between African and European institutions, advancing research, innovation, and capacity building in astronomy. The country also champions data accessibility and reusability, participating in the International Virtual Observatory Alliance (IVOA) and developing linked data archives at SALT and SAAO to ensure inclusivity and equity in science.

On the regional front, South Africa leads transformative initiatives positioning Africa as a growing leader in astronomy. Through its African Radio Astronomy Programme (ARAP), South Africa drives infrastructure and capacity development across the SKA African Partner Countries (APCs); Botswana, Ghana, Kenya, Madagascar, Mauritius, Mozambique, Namibia,

Figure 2: Overview of South Africa's astronomy ecosystem, highlighting local facilities, infrastructure and instruments, regional collaborations, and international partnerships (black-bordered boxes).

and Zambia. Notable examples include the operational radio telescope at Kuntunse in Ghana, which is advancing its science case and fostering international collaborations, the planned installation of a MeerKAT extension dish in Botswana by 2025, and South Africa's involvement in site testing for the planned African Millimeter Telescope (AMT), which is set to be constructed in Namibia. Additional training instrumentation is set to be deployed through SARAO's ARAP programme across the APCs over the next two years, further strengthening technical capacity and scientific infrastructure across the continent.

South Africa's leadership in capacity-building programs across Africa is equally significant. Initiatives like the Development in Africa through Radio Astronomy (DARA), a collaborative effort launched in 2015 between South Africa and the United Kingdom, aim to equip African scientists and engineers with high-tech skills essential for participation in global science projects. Similarly, the Pan-African Planetary and Space Science Network (PAPSSN), funded by the European Union, fosters postgraduate mobility among African universities, enhancing knowledge sharing in planetary and space science. Building on these achievements, the EU-funded Fast4Future program is developing a continent-wide postgraduate curriculum in space science and a Centre for Excellence, strengthening Africa's academic infrastructure and addressing the growing demand for skilled professionals in the space science sector.

South Africa also hosts and supports the African Astronomical Society (AfAS) Secretariat through the DSTI, which plays a critical role in coordinating collaborations among African astronomers, promoting research initiatives, and supporting public engagement and education in astronomy. In September 2024, the SKAO also signed a memoranda of understanding with SARAO and AfAS to enhance human capital development in Africa. The agreements, establish a five-year collaboration focused on providing training and educational opportunities for African students in astronomy and related fields. In addition, South Africa also dedicates 10% of its SALT observation time to African astronomers, fostering inclusivity and expanding access to world-class facilities, while broader collaborations across the continent, particularly in the SKA era, may be facilitated by the envisioned formation of the Southern African Physics Network (SAPhysNet).

This pillar highlights the importance of fostering collaboration across disciplines, sectors, and nations to maximize socio-economic benefits, achieve groundbreaking science, and position Africa as a significant contributor to global astronomy. By building on existing partnerships and investing in new opportunities, South Africa can further amplify its role as a leader in international astronomy and geodesy. However, despite South Africa's achievements in international collaboration, challenges persist. Limited permanent research positions, restrictive visa policies, and misaligned governance frameworks pose obstacles to attracting and retaining top talent. Addressing these barriers through targeted interventions, such as streamlined visa processes, expanded funding programs, and new collaborative platforms, is essential to sustaining South Africa's leadership in global astronomy.

Objectives:

- Utilize South Africa's unique geographic location, world-class facilities, and expertise in astronomy and geodesy to maintain and foster strategic collaborations with international and continental partners, strengthening the country's global positioning.
- Pursue partnerships with leading global institutions and observatories to drive advancements in multi-wavelength, multi-messenger, and multi-technique astronomy, data-driven research, infrastructure development, and human capital. Leverage these collaborations to enhance the global impact of South African astronomy and provide opportunities for knowledge exchange and skill transfer.
- Maintain alignment between South Africa's multi-wavelength astronomy initiatives and global scientific and technological trends, ensuring the nation remains globally competitive with high-impact research outputs.
- Identify and invest in niche scientific areas where South Africa can achieve and sustain global leadership, such as high-frequency VLBI, transient astrophysics, multi-messenger astronomy, dark energy, galaxy evolution, and advanced geodetic applications, while fostering interdisciplinary research to address complex challenges, enhance competitiveness, and broaden the socio-economic impact.
- Beyond international partnerships, prioritize fostering collaborations within Africa by leveraging existing networks and resources to improve coordination, efficiency, and resource allocation. Build South Africa's scientific capacity and leadership while advancing Africa's broader role in global astronomy.

Recommendations and Strategic Priorities:

Strengthen Infrastructure Development: Develop, maintain, and fully utilize cutting-edge observational facilities to sustain South Africa's leadership in global astronomy and maximize the impact of research outputs on the global stage. Develop and maintain data management infrastructure and *strengthen efforts to link South African data archives to the IVOA to enhance data accessibility and re-usability.*

Support and Enhance International Collaborations: Actively recognize and strengthen regional and international partnerships to ensure long-term sustainability, scientific impact, and workforce development, in particular:

- SKA Leadership: Strengthen partnerships with international SKA member countries and institutions to ensure active participation and leadership in the project. Foster collaboration on scientific research, infrastructure development, and capacity building to maximize South Africa's contribution to and benefits from the SKA initiative.
- Global VLBI Networks: Enhance collaboration with the global VLBI community and strengthen partnerships with VLBI networks to advance geodesy and astronomy research.
- International Facilities at SAAO: Maximize the scientific opportunities provided by international telescopes hosted at SAAO through targeted research initiatives and partnerships.

Strengthen Multi-Wavelength and Multi-Messenger Collaborations: Sustain and build new international collaborations across multi-wavelength (radio, optical, infrared, gamma-ray) and multi-messenger (neutrinos, cosmic rays, and gravitational waves) observational facilities. This will also foster the flow of data, theoretical ideas, and access to international high-performance computational resources, ensuring South Africa remains a critical player in global astronomical research.

Expand Pan-African Collaboration: Strengthen pan-African initiatives, such as the African VLBI Network (AVN) and DARA program, to position South Africa as a central hub for astronomical research on the continent. Prioritize mutual capacity building and skills development to foster sustainable growth in regional expertise and scientific leadership. Establish strategic agreements with emerging observatories in African countries to ensure South Africa realizes a return on its significant investment in African astronomy through initiatives like DARA and the African Radio Astronomy Platform (ARAP), while promoting the establishment and expansion of the AVN.

Facilitate International Collaboration Through Policy Alignment: Align national and continental policies with international frameworks to support long-term global partnerships. Advocate for streamlined visa processes and harmonized governance policies to enable seamless researcher mobility and strengthen South Africa's role as a key partner in international astronomy initiatives.

Promote Global Visibility and Collaboration Programs: Enhance South Africa's global presence and strengthen international partnerships through targeted initiatives. Establish an ambassador program to showcase South Africa's world-class astronomical infrastructure, secure new collaborations, and attract scientific investments at major astronomy conferences and research institutions. Expand bilateral agreements, funding programs, and studentships to create new opportunities for international research.

Additionally, develop structured exchange programs, including internships and research visits, to facilitate global collaboration, capacity building, and knowledge exchange.

Enhance Mobility and Inclusivity: Foster inclusivity and diversity within South Africa's astronomy community by promoting international mobility and collaboration. Facilitate the inclusion of international experts through hybrid and remote work options, enabling broader participation and skills diversification. Establish a structured visitor program to support extended research visits, ranging from short-term stays to year-long sabbaticals, and develop cross-border internship and student holiday programs to encourage learning, research collaboration, and capacity building.

Advance Research and Development: Prioritize impactful research fostering international collaborations to drive cutting-edge discoveries, including:

- **High-Energy Astrophysics:** Study black holes, neutron stars, and supernovae through collaborations with facilities like H.E.S.S. and CTA.
- **Early Universe and Fundamental Physics:** Investigate cosmic origins and physics with observatories like the Simons Observatory and CMB-S4.
- **Dark Matter and Dark Energy:** Contribute to global efforts by leveraging data from facilities such as the Rubin Observatory and SKA.
- **Transient Astronomy:** Explore variable and transient phenomena, including X-ray transients and tidal disruption events, through collaborations with missions like the Variable Objects Monitor (SVOM) satellite and the Einstein Probe, a Chinese Academy of Sciences (CAS)-led mission with international partners.
- **Galaxy Formation and Evolution:** Study galaxy clusters, jet formation, and star formation feedback mechanisms, and investigate how galaxies convert gas into stars and evolve within large-scale structures.
- **Exoplanets and Planetary Science:** Research planetary formation, habitability, and life beyond Earth through studies of exoplanets, Solar System bodies, and meteorites. Utilize facilities like PLAnetary Transits and Oscillations of stars (PLATO), a European Space Agency (ESA) mission, to study habitable-zone planets and collaborate with institutions such as Heriot-Watt University on high-precision radial velocity research for exoplanet detection.

Pillar 5: VLBI for Astronomy, Astrometry and Geodesy[4], and Other Geodetic Techniques

South Africa has a distinguished legacy in Astronomical, Astrometric, and Geodetic VLBI, spanning over half a century. This expertise played a pivotal role in securing the SKA mid-frequency array, leveraging decades of innovation and international collaboration. VLBI has delivered exceptional scientific, commercial, and societal value while training generations of researchers for the MeerKAT and SKA era.

Astronomical VLBI provides the highest angular resolution in astronomy and is a cornerstone of multi-wavelength and multi-messenger astronomy, offering unparalleled insights into contemporary astrophysics and fundamental physics questions. These include high-energy and neutrino astrophysics, pinpointing gravitational wave sources, testing General Relativity through black hole imaging, exploring the nature of dark matter, and understanding relativistic jet formation. South Africa's Hartebeesthoek site, a facility of the SARAO, holds strategic significance as the only radio astronomy facility on the African continent participating in routine VLBI observations and one of only a few VLBI sites in the Southern Hemisphere.

HartRAO's geographic location offers unique Fourier coverage, providing long north-south and east-west baselines that are critical for high-resolution astronomical observations. The 26-meter telescope participates in astronomical VLBI (see network map in Fig. 2) as part of the European VLBI Network (EVN), the Australia Telescope Long Baseline Array (AT-LBA), the East Asia VLBI Network (EAVN), and global networks, including the Very Long Baselines Array (VLBA) and Global mm-VLBI Array (GMVA). It has also contributed to space VLBI programs like RadioAstron. South Africa is also actively engaged in scientific partnerships with other global VLBI initiatives, contributing to efforts such as the Event Horizon Telescope (EHT) and supporting the integration of VLBI capabilities within the future SKA Observatory. Furthermore, recent advances in mm-VLBI technologies enhance South Africa's geographic advantage by extending phase coherence at higher frequencies (>30 GHz) to lower elevation sites.

Geodesy, on the other hand, underpins all positioning, navigation, and timing systems vital to modern life. Astrometric VLBI defines the celestial reference frame, while

[4] In South Africa, geodesy is integrated into the astronomy strategy as it falls under the broader domain of astronomy and extensively utilizes radio telescopes for its measurements. Often referred to as "Fundamental Astronomy," geodesy plays a critical role in defining global reference frames essential for pointing telescopes, tracking celestial sources, and providing calibrator sources for astronomy. This synergy underscores the importance of geodesy in supporting both scientific discovery and practical astronomical applications.

geodetic VLBI, along with techniques such as Satellite Laser Ranging (SLR), Global Navigation Satellite Systems (GNSS), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), establishes terrestrial reference frames and essential geospatial data. The precision of astrometric and geodetic VLBI observations is interdependent, ensuring robust and reliable frameworks. In this context, 'geodesy' encompasses the entire supply chain and data products derived from both astrometric and geodetic VLBI as well as other geodetic instrumentation (SLR, GNSS, DORIS).

Geodesy is indispensable for deep space navigation and the rapidly growing commercial space sector. It ensures the precise operation of satellites that provide navigation, telecommunications, and Earth observation services essential for disaster response, environmental monitoring, urban planning, and sustainable resource management. Mapping and surveying are foundational geodetic outputs, supporting transportation networks, resilient buildings, land use management, and urban planning. Geodesy also plays a critical role in weather forecasting, climate change adaptation, precision agriculture, and many other applications. Furthermore, geodesy underpins global timekeeping, vital for financial transactions, power grid synchronization, telecommunications, real-time navigation, and numerous industrial and defence applications. It is also integral to astronomy, providing essential data for telescope alignment and calibration, tracking celestial objects.

Recognized by the United Nations for advancing Sustainable Development Goals (SDGs), geodesy contributes uniquely to both astrophysics and trillion-dollar global industries, significantly impacting society. South Africa's Hartebeesthoek site is central to the continent's geodetic infrastructure, serving as the only fundamental geodetic station in Africa, following more than three decades of investment, and one of the few worldwide to integrate VLBI with other geodetic techniques. The 15- and 26-meter telescopes, alongside the new VLBI Global Observing System (VGOS) telescope, participate in routine astrometric and geodetic VLBI observations coordinated through the International VLBI Service for Geodesy and Astrometry (IVS) and the United States Naval Observatory (USNO), with high-frequency work coordinated by SARAO (see map of station in Fig. 2). Imaging of astrometric and geodetic VLBI data within South Africa adds significant value, catalyzing collaboration between astronomical and geodetic communities.

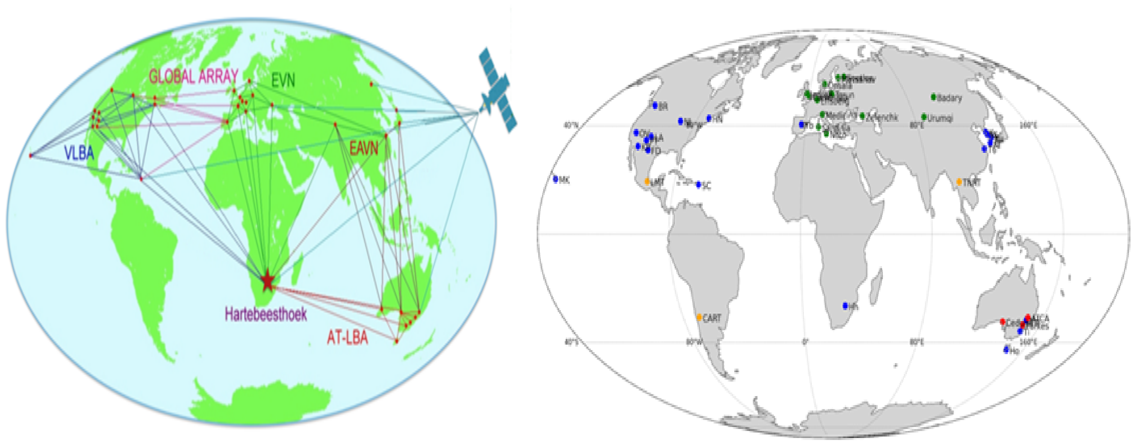


Figure 3: A global map of VLBI networks for astronomical VLBI (on the left), and VLBI stations participating in high-frequency astrometric and geodetic VLBI, with upcoming stations highlighted in orange (on the right), showcasing direct links to South Africa.

Hartebeesthoek's strategic location and advanced capabilities make it indispensable for fostering regional collaborations and capacity building across Africa, positioning the continent as a key contributor to global geodesy and VLBI. This pillar leverages South Africa's heritage in VLBI and geodesy, capitalizing on emerging global opportunities to expand VLBI's role within multi-wavelength and multi-messenger astronomy. By strengthening African and international collaborations, fostering innovation, and driving co-investment from universities and national facilities, this pillar aims to deliver impacts far beyond astronomy. These include contributions to climate change adaptation, urban development, disaster response, and the commercial space sector. Sustained growth in this area will ensure continued contributions to groundbreaking science, societal advancements, and economic resilience, aligning with the overarching goals of South Africa's Multi-Wavelength Astronomy Strategy.

Objectives:

- Build a well-connected South African community encompassing VLBI and geodesy practitioners, including scientists, engineers, and space geodesists, to foster collaboration and knowledge exchange on national and global projects.
- Conduct a comprehensive study of South Africa's VLBI and geodetic activities to identify bottlenecks, address gaps, and explore new infrastructure opportunities.
- Sustain and enhance VLBI and geodetic capacity in South Africa, ensuring alignment with global trends and long-term operational resilience.

- Expand education, training, and public awareness programs in VLBI and geodesy, focusing on building expertise, strengthening institutional ties, and showcasing societal and economic benefits.
- Align VLBI and geodesy initiatives with broader astronomy and space science priorities, including SKA Key Science Goals, to maximize impact and collaboration.
- Advocate for a high angular resolution focus in MeerKAT and SKA Science (i.e. MeerKAT/SKA-VLBI capability) to fully leverage Africa's geographic advantage and ensure alignment with the continent's long-term vision for VLBI and radio astronomy.
- Highlight South Africa's regional leadership in geodesy and VLBI, supporting African collaborations and capacity-building initiatives and leveraging partnerships with emerging VLBI and geodetic stations in neighbouring countries.
- Bridge the gap between astronomical and geodetic VLBI communities by fostering commensality and promoting joint research opportunities.

Recommendations and Strategic Priorities:

Strengthen and Expand Infrastructure: Prioritize the repair and replacement of aging yet critical VLBI and geodetic infrastructure to ensure operational resilience and continued participation in global networks. Upgrade, expand, and establish new VLBI stations and geodetic infrastructure to align with emerging global trends and enhance South Africa's capabilities within international networks.

Secure Sustainable Funding: Develop alternative funding mechanisms to replace legacy streams and ensure consistent support for VLBI and other geodetic infrastructure (GNSS, DORIS, SLR) and meteorological systems. Prioritize targeted funding for long-term maintenance, operational needs, and research, particularly for innovative instrumentation and high-frequency applications.

Leverage Emerging Opportunities: Capitalize on the global shift toward high-frequency VLBI by harnessing South Africa's geographic and technical strengths. This will not only enhance participation in global VLBI networks such as EVN, KVN, GMVA, and EHT but also leverage existing expertise in radio telescope instrument development. These efforts will position the country as a regional leader in high-frequency VLBI signal chain technologies and a key international partner and service provider.

Enhance Multi-Wavelength Synergies: Strengthen integration between VLBI and multi-wavelength or multi-messenger astronomy efforts, ensuring alignment with SKA Key Science Goals and other global research priorities.

Foster Collaboration and Regional Capacity: Strengthen collaboration across astronomy, geodesy, and engineering communities by integrating operational, technical, and scientific expertise. Deepen regional partnerships with African countries and global networks to advance VLBI and geodetic cooperation. Support initiatives like the AMT in Namibia to expand continental capacity and observational capabilities. Leverage South Africa's VLBI expertise to drive capacity-building across Africa, positioning the region as a key contributor to global geodetic and astronomical research.

Support GGOS Africa Establishment: Facilitate the establishment of GGOS Africa, an African affiliate of the Global Geodetic Observing System (GGOS) under the International Association of Geodesy (IAG), to coordinate geodetic activities, promote knowledge sharing, and amplify Africa's global contributions to geodetic research and innovation.

Facilitate Resource and Data Sharing: Promote resource and data sharing among SARAO, the South African National Space Agency (SANSA), and the National Geospatial Information division of Department of Agriculture, Land Reform and Rural Development (DALRRD) to enhance geodetic research capabilities in South Africa and deliver broader societal benefits.

Promote Education, Training, and Retention: Expand geodetic and VLBI science programs to address workforce gaps and build a robust pipeline of qualified professionals. Establish mentorship initiatives, cross-training programs, and long-term retention strategies to address staffing challenges at VLBI and geodetic facilities. Simplify access to training resources to attract students and researchers, while developing redundancy in critical skill areas and implementing succession plans for operational resilience.

Raise Awareness and Demonstrate Societal Impact: Highlight the societal, technological, and commercial impacts of VLBI and geodetic science, emphasizing their roles in navigation, positioning, climate monitoring, disaster management, urban planning, and environmental sustainability. Promote awareness of their contributions to mitigating climate change, supporting disaster response, and advancing the commercial space sector.

Advance Research and Development: Prioritize research in areas with significant scientific and societal impact, including:

- Active Galactic Nuclei (AGN): Leverage observations from geodetic and astrometric VLBI to support astronomical research, fostering synergies with high-energy astrophysics and multi-messenger astronomy. These dual-purpose observations enable advancements in both geodesy and cutting-edge astronomical studies.
- Transient Astrophysics: Utilize multi-wavelength facilities to study Galactic and extragalactic transient phenomena.
- Fundamental Physics: Conduct investigations, including tests of general relativity, binary supermassive black hole systems, and dark matter studies using strong gravitational lensing.
- High Angular Resolution Science: Enhance capabilities with MeerKAT and SKA, particularly focusing on SKA-VLBI science goals.
- International Celestial Reference Frame (ICRF): Contribute to the maintenance and refinement of the ICRF through advancements in instrumentation, operations, data reduction, analysis methods, and calibration techniques.
- Next-Generation VLBI Technologies: Develop wide-band, multi-band, and millimeter-wave receiver systems, along with frequency-phase transfer algorithms, to advance high-frequency VLBI observational capabilities and ensure global competitiveness.
- Geodetic Networks and Climate Applications: Enhance VLBI, GNSS, DORIS, and SLR networks, along with meteorological systems, by improving data collection, analysis, and data integration to support positioning services, space science, disaster risk mitigation, and climate change adaptation.

Pillar 6: Observational Research and Theoretical Modelling

South Africa is committed to pursuing excellent, fundamental observational and theoretical research in astrophysics, astronomy, and space science, aligning with the country's strategic priorities of inclusivity and sustained development. By leveraging its geographic advantage and hosting world-leading facilities, South Africa plays a pivotal role in advancing global astronomy while fostering world-class Human Capital Development (HCD) and contributing to the country's knowledge economy.

South Africa's geographic location has been instrumental in the development of its world-class astronomical facilities. It is one of the few places where the Galactic Centre, the Magellanic Clouds, the southern Milky Way, and other southern celestial targets can be observed throughout the night with advanced instrumentation. These advantages have established South Africa as a hub for global astronomy. The local astronomy community has grown significantly, organizing into broader networks like NITheCS and

SA-GAMMA, with initiatives such as the HEASA annual conference series. Smaller research groups have evolved into centers of excellence, often supported by SARChI chairs. Preparing for the vast data influx from projects like the SKA, South Africa has invested heavily in big data and computational infrastructure, fostering opportunities for research and postgraduate projects. SALT, supported by the South African government and operated by the SAAO for its international partners, allocates over 50% of observing time to South African PIs. Calls for MeerKAT Open Time or Director's Discretionary Time afford radio astronomers the opportunity to access MeerKAT radio data. Being very over-subscribed, this is an extremely competitive venture. South African contributions are welcomed and significantly strengthen such proposals. The African Pulsar Timing (APT) consortium further coordinates local radio pulsar research, paving the way for South Africa's entry into the International Pulsar Timing Array Consortium.

Beyond its borders, South Africa actively engages in research collaborations with world-leading astronomical facilities. These include major high-energy astrophysics projects, such as the Fermi Gamma-ray Space Telescope and partnerships with facilities like H.E.S.S. in Namibia and the Cherenkov Telescope Array (CTA), which is currently under construction. Local astronomers play key roles in H.E.S.S., Fermi LAT, and the future CTA, with coordination efforts supported by the SA-GAMMA consortium. Discussions are underway to extend the operation of H.E.S.S., with South African and Namibian astronomers taking on more prominent roles as the CTA progresses through development and commissioning.

South Africa is at the forefront of global efforts to understand dark matter and dark energy, utilizing data from the Vera C. Rubin Observatory in Chile and participating in its Legacy Survey of Space and Time (LSST). Through the LSST In-Kind Contribution Program, South Africa ensures access to proprietary data while promoting inclusivity and empowering Historically Disadvantaged South Africans.

South African researchers are also collaborating on frontier science projects that explore the early universe and fundamental physics, including initiatives like the Simons Observatory and the next-generation cosmic microwave background experiment (CMB-S4). Additionally, the country contributes to groundbreaking multi-messenger astronomy through its involvement in the KM3NeT neutrino telescope and its essential role in the Event Horizon Telescope (EHT) collaboration, which famously captured the first images of black holes. South African universities play an active part in the EHT, showcasing the nation's growing expertise in astrophysical research. Future initiatives include the proposed African Millimetre Telescope (AMT) on the Gamsberg in Namibia, which would further integrate the region into the EHT network, and the proposed underground laboratory (PAUL) in the Du Toitskloof Tunnel, offering transformative opportunities for astroparticle physics and cosmology.

Despite this growth and these strengths, significant challenges remain. There has been an erosion of the reliability of infrastructure on which instrumental performance and the scientific work environment depend. Erratic electricity supply and, in some locations, insufficient internet speed and access impact both instrumental and computational infrastructure, limiting capabilities for simulations and data analysis. The local astronomical community is comparatively isolated from international peers, with long flights and high travel costs hindering in-person interactions. This limits the frequency and depth of international collaborations, while substantial internal isolation, caused by large distances between institutions, exacerbates the challenge.

This pillar seeks to address these challenges by enhancing infrastructure, fostering collaboration, and expanding opportunities for observational and theoretical research. By leveraging these strengths, South Africa aims to advance observational and theoretical astronomy, foster innovation, and position itself as a key contributor to global astrophysics and space science.

Objectives:

- Create new knowledge in the fields of astronomy, astrophysics, and space science through fundamental, innovative observational and theoretical research, supported by sustained and adequate funding.
- Grow international and cross-disciplinary collaboration in a multi-messenger astronomy context, expanding South Africa's role in global research networks.
- Expand regional infrastructure, including computational resources for high-performance computing, as well as advanced hardware and instrumentation, to support cutting-edge research. Enhance data-driven astronomy through investments in big data infrastructure and advanced analytics to enable cutting-edge research and global collaborations.
- Foster the development of pockets of excellence in observational and theoretical research, supported by sustained capacity building and mentorship initiatives.

Recommendations and Strategic Priorities:

Invest in Computational and Hardware Infrastructure: Develop and upgrade computational facilities, high-performance computing resources, and state-of-the-art instrumentation to support data-intensive research in observational astronomy and theoretical modeling. Mitigate infrastructure challenges by ensuring reliable electricity supply, improving internet access, and fostering stronger institutional connections to overcome geographic isolation.

Foster International and Regional Collaborations: Strengthen partnerships with international multi-wavelength and multi-messenger facilities and projects to enable cutting-edge research and knowledge sharing. Advance regional collaborations through initiatives such as the African VLBI Network (AVN) and other pan-African platforms.

Enhance Multi-Wavelength and Multi-Messenger Partnerships: Promote collaborations that leverage South Africa's geographic advantage to gain comprehensive insights into celestial phenomena uniquely observable from its vantage point, such as the Galactic Center and the Magellanic Clouds.

Ensure Equitable Growth Across Astronomy Disciplines: Establish balanced funding streams to support diverse sub-disciplines, ensuring that fields such as optical and theoretical astrophysics receive adequate support alongside radio astronomy, fostering holistic development across all areas of astronomy.

Advance Research and Development: Many of the research priorities identified in the 2015 National Strategy for Multi-Wavelength Astronomy remain relevant and continue to guide South Africa's efforts in astronomy. Emerging opportunities over the past decade have expanded the scope of these priorities, introducing new frontiers that promise to shape the field in the next decade. These include:

- Cosmology: Continue exploring the origins and evolution of the universe, addressing key questions about dark matter, dark energy, the Cosmic Dawn, and the Epoch of Reionisation. Focus on improving measurements through international collaborations, such as the Simons Observatory, CMB-S4, LSST, and HI intensity mapping surveys with MeerKAT, SKA, and HIRAX.
- Galaxy Evolution and Supermassive Black Holes: Investigate galaxy formation and evolution at various redshifts, leveraging SALT, MeerKAT, and Integral Field Units (IFUs) for spectroscopic studies. Enhance understanding of AGNs through multi-wavelength follow-ups with MeerKAT, CTA, H.E.S.S., and gamma-ray telescopes.
- Stellar and Compact Objects / Gravitational Waves: Expand studies of compact objects such as white dwarfs, neutron stars, pulsars, and binaries. Prioritize searches for transient phenomena and their electromagnetic counterparts, leveraging facilities like SALT, MeerKAT, and global collaborations in gravitational wave astronomy, including pulsar timing arrays and LIGO/VIRGO.
- MeerKAT / SKA / EHT: Maintain MeerKAT's leadership as a top-class radio telescope, contributing to the SKA and expanding capabilities in pulsar timing and transient detection. Support efforts to include a Southern African telescope in the Event Horizon Telescope (EHT) to enhance imaging of black holes.

- Gravitational Waves (e.g., pulsar timing with MPTA): Maximize MeerKAT's contributions to the International Pulsar Timing Array (IPTA) and gravitational wave background studies. Foster theoretical modeling of sources for LISA's anticipated launch, including GRMHD simulations of black holes and neutron stars.
- SAAO / SALT / LSST (Dark Energy): Strengthen South Africa's role in Rubin Observatory's LSST through in-kind contributions and broaden access to its transformative survey data. Advance SAAO's Intelligent Observatory program to enable fully autonomous telescope operations, facilitating rapid response to alerts from LSST and other facilities.
- H.E.S.S. / CTA / Fermi LAT: Continue studies of Galactic and extragalactic sources, including pulsars, supernova remnants, and AGNs, with follow-ups across the electromagnetic spectrum. Support extended H.E.S.S. operations and CTA development for high-energy astrophysics.
- Time-Domain Astronomy: Enhance multi-wavelength follow-up capabilities for transient phenomena like GRBs, FRBs, and masers. Advance time-domain astronomy through coordinated triggers and alerts across facilities, probing fundamental physics through transient events.

Pillar 7: Data Science and Advanced Analytics (DSAA)

Astronomical instrument development has advanced rapidly due to exponential growth in computing power, storage capacity, bandwidth, and data volumes. MeerKAT has already demonstrated both the advantages and challenges brought by this data explosion, and upcoming facilities like the SKA, HERA, and LSST will generate even greater data rates. To address these challenges, the South African Astro-informatics Alliance (SA3), a joint initiative of SAAO, SKA, HartRAO, and the NRF, has begun facilitating access to international Big Data by establishing mirror sites of key astronomy databases at the CHPC. Additionally, SA3 provides training through NASSP and the IAU OAD on tools for accessing, manipulating, and visualizing Big Data.

Within South Africa, two groups stand out in the Data Science and Advanced Analytics (DSAA) space: the Inter-University Institute for Data Intensive Astronomy (IDIA) and the Rhodes Centre for Radio Astronomy Techniques and Technologies (RATT). A survey of South African astronomers revealed that 92% of respondents were at institutions where Data Science and Advanced Analytics (DSAA)-related research is being conducted, with 80% directly involved in this work. However, 70% of respondents identified current computational facilities as insufficient to meet the challenges posed by data from

MeerKAT, SKA, LSST, and SALT. These findings highlight DSAA as a growing area that is currently under-resourced in terms of computational infrastructure.

Another challenge is the lack of collaboration among researchers and research centers beyond IDIA and RATT. Survey respondents represented nine South African universities and NRF facilities, indicating widespread interest but limited integration across institutions.

The Inter-University Institute for Data Intensive Astronomy (IDIA) Consortium:

IDIA is a partnership between the University of Cape Town (UCT), the University of the Western Cape (UWC), and the University of Pretoria (UP), in close collaboration with the SARAO. IDIA's primary objective is to build capacity and expertise in data-intensive research within South African universities, enabling global leadership in MeerKAT science and other SKA precursor projects, in preparation for the SKA.

IDIA established and manages ilifu, a federated cloud computing facility supporting data-intensive research in radio astronomy and bioinformatics. This facility serves hundreds of students and researchers in South Africa and globally, empowering them to analyze complex datasets with unprecedented efficiency. Recognized for its innovation, IDIA received the 2024 NSTF-South32 Special Theme Award for the 4th Industrial Revolution in South Africa. The award highlighted its cutting-edge infrastructure and global collaboration, facilitating advanced research in astronomy. Through international partnerships, IDIA also plays a leading role in developing new cloud-based visualization tools, such as CARTA (Cube Analysis and Rendering Tool for Astronomy) and iDaVie (immersive Data Visualization Environment), which are integral to SKA science.

The Rhodes Centre for Radio Astronomy Techniques and Technologies (RATT):

RATT, led by Distinguished Professor Oleg Smirnov, an NRF A-rated researcher since 2022, is a beacon of excellence in radio astronomy. RATT collaborates with world-renowned institutions, including the University of Bologna, Oxford University, and the Paris Observatory, and hosts visiting professors who co-supervise its cohort of over 20 postgraduate students. Additionally, RATT works with the Breakthrough Foundation (US) on projects involving the search for astrophysical transients and technosignatures in radio interferometry data.

RATT specializes in developing novel calibration, imaging, and data analysis algorithms and software for next-generation radio telescopes. Over the years, its scope has expanded into fundamental astronomy, cosmology, and astrophysics, driven by the integration of advanced data processing techniques. These techniques enhance the analysis of vast datasets generated by modern radio telescopes, improving the accuracy and efficiency of calibration and imaging pipelines. This synergy between data analysis and scientific discovery accelerates breakthroughs and pushes the boundaries of our understanding of the universe.

In recognition of its pioneering work, RATT received the prestigious NRF Science Team Award in 2023. This award celebrated the team's exceptional contributions, creativity, and accomplishments in advancing research in Africa. It also underscored RATT's role in elevating South Africa's reputation as a leading destination for world-class scientific research.

The DSAA research space holds significant potential for growth in the coming decade. While South Africa has already demonstrated notable success stories through initiatives like IDIA and RATT, there is a clear opportunity to replicate these achievements across the country through enhanced collaboration and resource sharing. A focused effort to improve computational infrastructure, alongside strategic investments in Human Capital Development (HCD), will position South Africa to play a leading role in major upcoming global collaborations, including LSST, SKA-Mid, HERA, and MeerKAT. Strengthening partnerships with industry stakeholders and other research institutions will not only drive innovation but also ensure the sustainable development of DSAA, reinforcing South Africa's place as a key contributor to global data-intensive astronomy.

Objectives:

- Develop a coherent strategy for South African astronomy in the data science domain to address the growing computational and infrastructure demands.
- Promote greater collaboration between universities, research groups, and industries to enhance the development of DSAA-related capabilities.
- Expand human capacity development in DSAA through scholarships, targeted training programs, and reskilling pathways for graduates in physical, mathematical, and computational sciences.
- Enhance access to national research facilities, cloud computing, and data infrastructure to improve usability and support broader collaboration in astronomy-driven data science.

Recommendations and Strategic Priorities:

Assess and Enhance Data Intensive Astronomy Infrastructure: Undertake a comprehensive assessment of the current state of Data Intensive Astronomy in South Africa to identify existing strengths, weaknesses, and opportunities. Use the findings to address computational infrastructure gaps and implement targeted improvements that will support world-class astronomy research and enhance South Africa’s position in global data-intensive science.

Strengthen Science Communication and Early Skills Development: Introduce DSAA-related concepts early through targeted science communication and skills awareness programs in primary and high schools. Expand the reach of hackathons to all universities and engage the Basic Education sector to introduce relevant concepts effectively.

Develop Ethical and Standardized Practices: Create a code of good practices to ensure quality research, fostering collaboration based on ethical standards and standardized data reduction pipelines. This framework would also promote the proper and ethical use of Large Language Models in DSAA-related research.

Enhance Human Capacity Development: Foster human capacity development by encouraging interdisciplinary research that integrates fields such as Physics, Economics, and Social Sciences with Astronomy projects. This approach will broaden research perspectives and drive innovative solutions to complex challenges.

Expand Access to Data and Computational Resources: Improve access to data and research facilities, such as SA3 and the computational cluster at SAAO, by ensuring they are better serviced, modernized, and user-friendly for researchers and stakeholders.

Forge Partnerships with Technology Companies: Explore partnerships with major technology companies like Microsoft, Google, and Amazon to facilitate broader access to advanced tools, infrastructure, and technological resources, fostering collaboration and innovation.

Leverage Global Platforms for Resource Accessibility: Join global platforms like Globus to enable streamlined and efficient access to research data and computational resources, enhancing collaboration and resource-sharing capabilities for South African researchers.

Expand DSAA Scholarships and Training Programs: Establish dedicated scholarships for DSAA-related research at the master’s level and implement training programs to help students with degrees in Physical and Mathematical Sciences skill up and actively participate in DSAA research fields.

Pillar 8: Human Capital, Transformation, and Outreach

This pillar focuses on attracting, training and retaining a transformed workforce for astronomy in South Africa.

Attracting students into astronomy (studies) should include outreach, education and awareness campaigns, directed mostly at school learners, but also to some extent to the broader public. These campaigns should inform, educate, and excite young people about astronomy and the opportunities afforded to students who pursue relevant studies. The campaigns must be structured in such a way that young students, particularly black and women students, feel empowered and motivated to study mathematics, physics and other relevant SET subjects/qualifications. As a priority, it is essential to challenge and change the perception that these subjects are difficult and primarily suited for a particular demographic.

Training the workforce (developing the relevant capacity) for astronomy takes place at universities, universities of technology, and TVET colleges, and must be supported with competitive scholarships for students studying relevant undergraduate and postgraduate degrees, or technical/artisanal qualifications.

To produce the relevant multiwavelength astronomy research and engineering capacity, funding should be directed to undergraduate students studying science and engineering degrees, and to postgraduate students whose research is aligned with the areas identified as key and relevant to astronomy in the coming decade. The ultimate goal being the creation of significant, and internationally recognised, university-based research centers, addressing key areas of astronomy and engineering, that become the foundation for ongoing capacity development. Transformation within astronomy research must be deliberately addressed, and this must include recognition that many equity candidates are financially disadvantaged, and in addition to full cost scholarships may require supplementary grants to retain them in postgraduate research. The reality is that many South Africans (mostly black South Africans) from financially disadvantaged circumstances leave university after their undergraduate degree because of pressure from their families to earn a salary and contribute to their family's needs, and while a few may be granted the opportunity to continue to a Master's level, family obligations will again direct the graduate to seek employment to earn a salary, instead of moving into a PhD degree.

Up until the implementation of the NRF Postgraduate Funding Policy, SARAO's postgraduate transformation policy allowed for top-ups to students who were financially disadvantaged, up to a maximum of 40% of the value of a scholarship. This intervention allowed students who would otherwise have needed to find employment in industry, to remain in postgraduate research. However, the NRF Postgraduate Funding Policy does not allow top-ups that exceed the level of a full cost of study (FCS) scholarship. As an example, very recently, a black South African student resigned from his PhD degree, citing *“My reason for leaving is purely financial. There's not much anyone can do about it, really. I have growing responsibilities, I'm the oldest, I have sisters to look out for. One is going to university next year (which I know is going to be really tough financially, and I don't want her to go through that) …..The PhD stipend is hardly sufficient to get by on your own and you can't help out at home (makes me feel useless). So, the best decision for me really is to start working and the industry doesn't really need a PhD and the money looks great.”*

In addition, to ensure that the skills required for the maintenance of astronomy facilities are available, funding should also be directed to students studying engineering technology at universities of technology, and to students training to be artisans. These skills are needed for the general maintenance of astronomy facilities to ensure operational efficiency. Currently these types of skills are significantly scarce in South Africa, and funding and training facilities (such as SARAO’s Training Centre in Carnarvon) must be available to produce the required person-power. Training initiatives focused on developing artisanal and other technical skills should be directed at the youth in the areas where telescope facilities are located, so as to provide the young people with skills and employment opportunities.

Employment opportunities for astronomy researchers and engineers, as well as for the technical maintenance workforce, requires funding and initiatives dedicated to creating positions. In the absence of such focused initiatives, South Africa’s investment into training and funding astronomy capacity will be wasted. To retain qualified PhD and postdoctoral astronomers, a significant number of permanent, funded positions in relevant university departments is required. Sustainability of such a recruitment campaign will require an agreement between the Department of Science and Innovation and the Department of Higher Education, at the highest level. The agreement should, inter alia, require the DHET to fund the positions in the universities. In parallel, astronomy observatories should be required to employ a quota of the trained capacity (astronomy researchers and engineers, as well as technicians and artisans). To ensure this is possible, high-level approval for deviations in the recruitment process should be in place.

1. Background to Astronomy HCD and Outreach in South Africa

1.1. Background of Astronomy Human Capacity Development in South Africa

There has been a significant increase in astronomy-related capacity in the past 20 years, most notably due to the efforts of NASSP, and SARAO's HCD programme.

1.1.1. Snapshot of capacity development funded by NASSP

NASSP is a multi-institutional initiative, funded by DSTI-NRF to train South African students in Astrophysics and Space Science at Honours and Master's levels, and to provide a pipeline to PhD studies in these and related research areas. NASSP's vision is to develop human capacity in astronomy and space science, particularly in under-represented communities, and to build a cohort of scientists at the core of an international network of African astronomers, space scientists and citizens, who are bonded by the common experience of schooling, interlinked both professionally and personally and able to make a major contribution to the transformation of society. The programme has been running since 2003 and is hosted at 3 'nodes': the University of Cape Town, the University of KwaZulu-Natal and North West University. Since the start of the programme more than 460 students have graduated with Honours degrees, and more than 220 have graduated with Master's degrees.

1.1.2. Snapshot of capacity development funded by SARAO (2005 to 2024)

The core functions of the SARAO HCD programme are to provide a platform that facilitates the training of the human capital required to design, build, commission and operate world-class radio telescopes that are located in South Africa and the wider African continent, and catalyze the growth and sustainability of a cohort of scientists in African institutions that are equipped to derive significant scientific knowledge from these telescopes. The scope of disciplines encompassed by the programme is necessarily broad to match the requirements of radio telescopes and the scientific programmes associated with them. The programme extends across a wide range of academic levels to provide a pipeline that facilitates progress of individuals from school, through higher education, to world-class scientists and engineers, and to provide an appropriately skilled workforce (technicians and artisans) for the functioning of radio astronomy facilities.

To date SARAO HCD has awarded 1647 grants, of which 34 have been to university faculty positions (including five research chairs), 155 to postdoctoral fellows, 215 to

Doctoral students, 341 to Master's students, 235 to Honours students, and 337 to undergraduate science and engineering students. In addition, 200 grants have been awarded to students studying technician qualifications, and 130 to students studying artisanal qualifications.

A recent study established that South Africa is producing PhDs at a rate comparable to countries with much longer histories in radio astronomy. In addition, the graduation rates of students funded by SARAO is significantly higher than the national average, and the rate of progression of students from one academic level to the next indicates a successful pipeline. Finally, a recent alumni tracing exercise, illustrated that more than two thirds of HCD's alumni are employed in South African, and other African research, and in South African industry.

1.2. Background to Astronomy Outreach in South Africa

Astronomy outreach refers to the efforts and activities aimed at engaging and educating the public about astronomy and related sciences. The goal of astronomy outreach is to inspire interest and curiosity in the subject, disseminate knowledge, and promote the importance and relevance of astronomy in our understanding of the universe. These activities can target various audiences, including school children, educators, and the general public, and can take many forms, such as public lectures and talks, educational workshops, hands-on activities, planetarium shows, open nights, science festivals, social media, school programs, community engagement and citizen science projects. The overarching aim of astronomy outreach is to make the science of astronomy accessible and exciting, fostering a deeper appreciation for the universe and encouraging future generations to pursue studies and careers in science, technology, engineering, and mathematics (STEM).

SARAO, since its early days as SKA Africa, has demonstrated dedication to promoting public awareness, understanding, and appreciation of radio astronomy and its contributions to science and technology. SARAO's outreach and education activities are multifaceted, aiming to engage various audiences, from school learners to the broader public. These initiatives include developing educational resources, training science communicators, and organising public events that encourage dialogue and curiosity about astronomy. Notably, SARAO provides free resources to support learning about astronomy, including the Mission MeerKAT cartoon series and the Shared Sky international indigenous art/astronomy exhibition. By promoting partnerships and utilising innovative approaches, SARAO ensures that its outreach efforts are inclusive and impactful, contributing significantly to science communication and education in South Africa.

SAAO through its SALT Collateral Benefits Programme (SCBP), engages in extensive outreach and education activities to promote astronomy and science. The SCBP aims to utilise the knowledge and resources from SALT to benefit society by enhancing education in mathematics, science, engineering, and technology, promoting science communication, and supporting socio-economic development. SAAO's efforts include organising school tours, public stargazing events, and participating in science exhibitions and festivals. By creating a culture of continuous learning and development, SAAO's outreach initiatives inspire and educate diverse audiences, fostering a scientifically literate and engaged public.

The AfAS, through its Outreach and Education committee, conducts numerous outreach and public engagement activities across South Africa and the African continent to increase exposure to astronomy and its opportunities. Notable projects include the cascade outreach model, which places young astronomy graduates in schools throughout Africa to conduct role modelling and career guidance sessions with learners and communities, promoting inclusion, representation, and public engagement. The AfAS outreach committee collaborates with various stakeholders, including the SAAO and SARAO, to ensure outreach even in the most remote communities. These collaborations enable the committee to implement more projects with greater reach, as they work with a community of astronomers who serve as outreach professionals and science communicators. Among its diverse partners, AfAS collaborates with science centres across the country, helping to run capacity-building workshops and training sessions. These initiatives equip the centres with the knowledge and skills needed to continue astronomy outreach and public engagement in their communities.

Objectives

Table 4: HCD objectives

Enhance public engagement and outreach	● Increase awareness and excitement about astronomy among young people and the general public through targeted outreach programs, science festivals, public events, and citizen science initiatives. ● Develop educational resources and leverage diverse media platforms to communicate the importance of astronomy to broader audiences, with a special focus on inclusivity for

	marginalized and underserved communities.
Promote diversity and inclusion in Astronomy education	● Empower young South Africans, particularly black and women students, to pursue mathematics, physics, and STEM-related fields by addressing and reshaping perceptions around these subjects. ● Integrate outreach campaigns that highlight the opportunities in astronomy, ensuring young students from underrepresented demographics are motivated and supported in entering the field.
Expand Astronomy education in higher education Institutions	● Increase the presence of astronomy programs at historically disadvantaged institutions (HDIs) and other universities not currently offering astronomy, through partnerships and tailored capacity-building initiatives. ● Collaborate with DHET and other educational bodies to establish funded and permanent astronomy-related positions in universities, ensuring long-term sustainability in astronomy education.
Develop a transformed, internationally recognized Astronomy workforce	● Prioritize funding for scholarships, fellowships, and training programs aimed at transforming the astronomy workforce, focusing on retaining black South African and financially disadvantaged postgraduate students through additional financial support where needed. ● Establish mechanisms to address the attrition of postgraduate students due to financial pressures to ensure continued growth of a diverse research community.
Strengthen Human Capacity Development (HCD) and career	● Formalize and expand coherent training programs across national

pathways in Astronomy	facilities to enhance practical skills in multiwavelength astronomy, data handling, and observational techniques, ensuring accessibility for all students and researchers. ● Provide structured mentorship and career development pathways to support emerging researchers, encouraging retention and career growth in astronomy.
Foster cross-institutional collaboration and resource sharing	● Develop and implement collaborative research and training projects across institutions, encouraging interdisciplinary and multiwavelength approaches to expand the scientific reach and impact of South African astronomy. ● Create shared platforms, such as a central knowledge hub and comprehensive database, to facilitate communication, collaboration, and access to expertise, data, and resources.
Increase support for technical and artisanal skills development	● Support the training of technicians and artisans through targeted programs at universities of technology and TVET colleges, particularly in regions near astronomy facilities, to ensure a skilled maintenance and operations workforce. ● Expand SARAO's Training Centre in Carnarvon and other initiatives to address the scarcity of technical skills needed for astronomy infrastructure upkeep, providing employment opportunities for local youth.
Secure international and government partnerships for sustained funding and growth	● Establish high-level agreements between the DST, DHET, and other government entities to secure permanent astronomy positions at universities and observatories. ● Actively seek funding opportunities to support international collaborations,

	particularly for emerging researchers, enabling them to participate in conferences and collaborative research projects.
Integrate indigenous knowledge and cultural diversity in Astronomy outreach	● Incorporate South African cultural diversity and indigenous knowledge in outreach activities, enhancing public appreciation and pride in astronomy. ● Develop inclusive educational content that reflects local cultural perspectives, connecting modern astronomy with traditional knowledge systems.

Recommendations:

1. **Focus outreach on underrepresented and underserved communities:** Direct outreach activities toward young South Africans, particularly in remote and underserved communities, with a specific emphasis on engaging black and female students. Partner with science centers, museums, and local organizations to deliver educational programs, provide training to local educators and communicators, and empower these communities with resources that encourage interest in mathematics, physics, and STEM fields. This approach aims to promote inclusivity, inspire future generations, and broaden participation in astronomy across diverse demographics.
2. **Influence funding policies for financial support:** Advocate for policy changes that allow scholarships to exceed full-cost (FCS) scholarships, providing additional support to financially disadvantaged students and reducing postgraduate attrition.
3. **Link telescope access to student supervision:** Allocate telescope time on South African facilities contingent upon supervision or co-supervision of South African students, promoting direct mentorship and involvement of students in active research.
4. **Collaborate with government departments to create funded positions:** Partner with departments like DHET and DSTI to fund and establish permanent astronomy-related positions at universities, ensuring sustained career opportunities for PhD graduates and postdoctoral fellows.

5. **Create employment opportunities at observatories:** Establish mechanisms to employ trained astronomers, technicians, and artisans at national observatories (e.g., SAAO, SARAO) to retain skilled talent within South Africa.
6. **Extend astronomy education to historically disadvantaged institutions (HDIs):** Develop and implement partnership models (e.g., NASSP, PAUSSI) to bring astronomy education and research opportunities to HDIs not currently participating in astronomy programs.
7. **Collaborate among stakeholders for resource optimization:** Encourage collaboration among all relevant stakeholders to pool resources effectively, facilitating expansion of current initiatives and the development of future astronomy programs.
8. **Establish graduate statistical data protocols with dhet:** Engage with universities, the Scientometric Reference Group, and DHET to standardize and verify graduate data reporting in the HEMIS database for accurate tracking of progress.
9. **Train science communicators and educators:** Provide training programs for science communicators and educators, enhancing their skills to effectively convey astronomy's significance and inspire public interest.
10. **Incorporate indigenous knowledge and cultural diversity in outreach:** Include South African cultural diversity and indigenous astronomy in outreach programs, building public awareness and pride in local astronomical heritage.
11. **Establish structured and hands-on training programs at National Facilities:** Develop and formalize national training programs that provide structured and consistent skills development across key facilities, such as SALT and MeerKAT. These programs should offer hands-on training opportunities for students and researchers, allowing them to gain practical experience with diverse observational instruments and techniques. This approach will ensure that emerging astronomers and technicians are well-prepared to contribute effectively to multiwavelength research and facility operations.
12. **Integrate data-intensive research and data-reduction skills into Astronomy curricula:** Incorporate data-reduction and data-handling programs into astronomy curricula, such as NASSP, to build expertise in data-intensive research. This approach will equip students and emerging researchers with essential skills for analyzing and interpreting multiwavelength data, meeting the growing demand for proficiency in complex data management and analysis within the field of astronomy.
13. **Support international collaboration and mobility for emerging researchers:** Establish funding and travel grants to enable emerging researchers to participate in international collaborative projects, conferences, and research exchanges. This support will facilitate knowledge sharing, enhance skill development, and

expand expertise across multiple wavelengths, reinforcing South Africa's presence and impact in the global astronomy community.

14. **Expand mentorship programs for emerging scientists:** Establish mentorship programs linking experienced researchers with emerging scientists to promote skill development and career progression.
15. **Engage science communicators and journalists:** Collaborate with science communicators and journalists to increase astronomy's visibility in mainstream media, bridging the gap between science and the general public.
16. **Implement a cascade outreach model:** Develop a cascade outreach model, training young astronomers to teach their peers and creating a network of youth role models who inspire interest in astronomy.
17. **Partner with national education and science engagement bodies:** Collaborate with the Department of Education and organizations like SAASTA to coordinate national astronomy outreach efforts and leverage existing educational networks.
18. **Enhance public engagement through events and accessible educational content:** Organize public lectures, stargazing events, science festivals, and exhibitions to engage diverse audiences in the wonders of astronomy. Develop and distribute accessible educational content, such as documentaries, podcasts, and publications, to reach a wider audience and inspire interest in the field. This approach will promote public awareness, foster excitement about astronomy, and make scientific discoveries accessible to all.
19. **Establish citizen science programs:** Encourage public participation in astronomy through citizen science projects, providing tools and training to involve the public in data collection and analysis.
20. **Address career pathway gaps in national facilities:** Develop clear career pathways within national facilities to support the long-term retention and progression of researchers and technicians.
21. **Develop change management strategies:** Implement change management strategies in national facilities to minimize uncertainty and anxiety among employees during major transitions.
22. **Enhance multiwavelength data training programs:** Develop targeted training programs for emerging researchers focused on multiwavelength data reduction and analysis to meet the demands of diverse research methodologies.
23. **Increase funding for wavelength-specific research:** Provide additional scholarships and funding opportunities for postgraduate and doctoral research across underfunded wavelengths, ensuring balanced scientific growth.
24. **Include VLBI and space geodesy in NASSP curriculum:** Ensure that VLBI and Space Geodesy are integral components of the revised NASSP curriculum, with a focus on their connections to space science and technology.

25. **Leverage the presidential phd programme for VLBI and geodesy:** Utilize the Presidential PhD Programme to support growth in VLBI and Geodetic applications, linking these areas to broader national priorities in science and technology.
26. **Promote high-profile dissemination of VLBI research:** Capitalize on the public's interest in VLBI, as seen with the success of the EHT images, by promoting high-profile VLBI images and showcasing South Africa's role in creating them to boost public engagement.
27. **Prioritize VLBI and geodesy through education, knowledge sharing, and public awareness:** Expand support for VLBI-related developments in SARAO's bursary program and ensure VLBI and Geodesy are included in relevant curricula, such as NASSP, with an emphasis on their connections to space science and technology. Establish a Knowledge Hub for VLBI and Geodesy to consolidate data products, applications, and resources, facilitating collaboration across astronomical and geodetic sciences. Leverage this hub to create public awareness programs that showcase the societal benefits of VLBI, Space Geodesy, and Astronomy, engaging the public and highlighting South Africa's contributions to these fields.

Conclusion

The culmination of HCD efforts in just 20 years has been the creation of significant, and internationally recognised, university-based research centres addressing key areas of astronomy and related engineering, and which have become the foundation for ongoing capacity development. During this time, the astronomy community has established best-practice capacity development models, had the opportunity to harness the strengths of these models, and to identify the gaps in astronomy capacity development. Looking to the next ten years, while the focus should remain on funding all levels of the academic pipeline, priority should also be given to (i) reducing the attrition of black students from postgraduate research, due to personal financial obligations, (ii) maximizing South Africa's investment in astronomy capacity development by facilitating the creation of sufficient funded and permanent positions at universities, through a partnership with other government departments such as the DHET, and (iii) introducing astronomy into HDIs where it is currently not available.

Pillar 9: Indigenous Astronomy[5] & Astronomy Conservation

Indigenous people for thousands of years, valued and nurtured their relationships with the stars through observations, cultural ceremonies, navigation, and celestial landscapes. The distinction between Indigenous Astronomy and Western Astronomy lies in its holistic integration of mind, body, heart, and spirit. One significant aspect of Indigenous astronomy is the encoding of celestial knowledge in songs, stories, art, and poetry. Storytelling, identified as a crucial element, not only preserves these narratives but also serves as a cultural bridge, enabling the interpretation of the cosmos through relational and ecological perspectives.

Indigenous Astronomy is recognised within South Africa's Indigenous Knowledge System (IKS) and must be safeguarded under the Indigenous Knowledge Act (Act No. 6 of 2019). This legislation offers protection against exploitation, biopiracy, and neglect, ensuring Indigenous knowledge holders benefit intellectually and socio-economically. Recognised as one of 16 disciplines by the DSTI, Indigenous Astronomy falls under the Recognition of Prior Learning (RPL) framework. This supports Indigenous practitioners in gaining professional certification, contributing to community upliftment.

Despite existing initiatives such as collaborations with SARAO, SAAO and North-West University's IKS Centre, some communities report exclusion from astronomical projects and concerns regarding intellectual property rights. Responses from Indigenous representatives highlight the need for more robust frameworks to ensure active inclusion and fair representation in knowledge-sharing practices.

In April 2022, the DSTI established the Indigenous Steering Committee to guide the development of policies and initiatives supporting Indigenous Astronomy. The committee aims to promote inclusivity, cultural respect, and integration of Indigenous perspectives into the national science and innovation landscape. Further, it addresses ethical practices by advocating prior informed consent, respecting sacred knowledge, and ensuring Indigenous participation in decision-making processes. This committee seeks to empower Indigenous communities as co-creators in the preservation and application of their astronomical knowledge.

Objectives:

- To preserve Indigenous Celestial knowledge.
- To promote Indigenous participation in Astronomy.
- To strengthen Educational Integration.

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5 https://cdn.ymaws.com/www.ips-planetarium.org/resource/resmgr/vcon2020/posters/Indigenous_Astronomy_%E2%80%93_Best_.pdf

- Safeguard Intellectual and Cultural Rights to comply with IKS Act.
- Enhance Public Awareness on the significance and use of Indigenous Astronomy.

Recommendations

Indigenous Astronomy is integral to South Africa's Astro-Tourism Strategy, contributing to education, cultural preservation, and socio-economic growth. The following steps are recommended:

1. **Recognise Indigenous Knowledge as Equal:** Create platforms where Indigenous astronomical practices are represented on par with Western astronomy. Incorporate Indigenous narratives into mainstream conferences, workshops, and publications.
2. **Collaborative Research and Outreach:** Facilitate joint initiatives where astronomers and Indigenous communities collaborate on documenting star maps, celestial navigation techniques, and stories, ensuring proper attribution and ethical usage of knowledge.
3. **Promote Storytelling and Education:** Leverage storytelling traditions to enrich astronomy education through school curricula, public outreach, and interactive exhibitions. Engage Indigenous educators and elders to present culturally authentic programs.
4. **Safeguard Intellectual Property:** Implement legal frameworks aligned with the IK Act to prevent exploitation of Indigenous narratives in publications and commercial ventures.
5. **Public Engagement:** Support star-gazing events, cultural festivals, and workshops highlighting Indigenous celestial narratives to raise public awareness and foster cultural appreciation.
6. **Revive Steering Committees:** Reactivate the Indigenous Astronomy Steering Committee with an inclusive framework that reflects community aspirations and guides long-term policy alignment.
7. **Cultural and Environmental Linkages:** Highlight the ecological dimensions of Indigenous astronomy, such as its application to agricultural cycles and climate awareness. Responses emphasised the environmental stewardship embedded in Indigenous cosmologies, offering sustainable perspectives for contemporary challenges.
8. **Integration in Education:** Advocate the inclusion of Indigenous Astronomy in primary, secondary, and tertiary curricula with resources co-created by educators, knowledge holders, and astronomers.

9. **Encourage Ethical Practices:** Establish ethical guidelines ensuring research and outreach respect cultural sensitivities, prioritise informed consent, and involve Indigenous communities in all stages of project planning.

Conclusion

Indigenous Astronomy reflects a profound legacy of cultural and scientific knowledge. By embedding this heritage within South Africa's science strategies, the nation honours its diversity and builds bridges between traditional and contemporary understandings of the cosmos. Recognising Indigenous contributions is not just about preservation but about building and strengthening collaboration and mutual respect.

The proposed measures aim to amplify Indigenous voices, enhance knowledge-sharing platforms, and expand public appreciation of Indigenous narratives. These efforts will enable South Africa to lead in creating an inclusive astronomical landscape that values the contributions of all its communities.

Astronomy Conservation

Astronomy conservation in South Africa plays a critical role in safeguarding the nation's unique geographic advantages for astronomical research. The Astronomy Geographic Advantage (AGA) Act No. 21 of 2007 underpins these efforts by protecting key sites from light pollution, radio frequency interference, and other threats. The Karoo Central and Sutherland Central Astronomy Advantage Areas are pivotal in hosting world-class facilities like the SALT and the SKA. These observatories contribute not only to scientific discovery but also to South Africa's global reputation in astronomy.

Conservation encompasses the protection of naturally dark skies, the reduction of radio frequency interference, and the maintenance of telescope infrastructure. Light pollution from urban expansion and rapid electrification remains a pressing concern. Similarly, unregulated radio transmissions near observatories threaten the sensitivity of astronomical instruments. Maintenance of telescope sites ensures their long-term operational sustainability, while also preserving the heritage of these scientific assets.

South Africa is committed to balancing development with the preservation of its unique astronomical resources through regulatory frameworks, interdepartmental collaboration, and public education. The planned strategy includes the integration of responsible lighting practices and community engagement to enhance efforts in preserving the natural night sky and supporting scientific excellence. To address the challenges posed by urbanisation, pollution, and inadequate site maintenance, the conservation of astronomy necessitates a comprehensive approach that integrates policy enforcement, stakeholder collaboration, and sustainable practices. South Africa's strategic astronomical sites, which offer unparalleled research opportunities, require diligent protection to ensure compliance with the As AGA Act and promote sustainable resource use. The strategy aims to secure the long-term viability of astronomy in the region while strengthening partnerships and enhancing public awareness of its significance.

Objectives

- Protect Astronomical observation sites by ensuring the enforcement of the AGA Act to mitigate light pollution, radio frequency interference, and other environmental threats to Astronomy Advantage Areas.
- Preserve dark skies and promote sustainable practices by implementing responsible lighting practices enhancing environmental sustainability and astro-tourism potential.
- Maintain and upgrade infrastructure by allocating resources for the periodic maintenance and improvement of observatory facilities to ensure their long-term operational viability and preserve their scientific value.
- Hold Public and Stakeholder Engagements to promote awareness and education on astronomy conservation through workshops, community programmes, and partnerships with local and international organisations.

Recommendations

1. **Strengthen Legal Protections and Compliance:**
    - Ensure consistent enforcement of the AGA Act to mitigate light pollution and radio frequency interference in Astronomy Advantage Areas.
    - The Astronomy Management Authority from the DSTI should continue collaborating with the Independent Communications Authority of South Africa (ICASA) to regulate radio transmissions near observatory sites.
2. **Promote Dark-Sky Protection:**
    - Support International Dark Sky Place certifications for key sites like Sutherland and Carnarvon to enhance global recognition and boost astro-tourism.
    - Introduce responsible lighting practices in local municipalities, prioritising areas adjacent to observatories.
    - Implement community education programs to raise awareness about the benefits of dark skies for environmental, health, and economic sustainability.

3. **Enhance Infrastructure Maintenance:**
    - Allocate funding for the routine maintenance and upgrade of observatory sites to ensure their long-term sustainability.
    - Develop site-specific management plans that include preventive measures to address environmental challenges, such as weathering and vandalism.
    - Establish partnerships with local communities and businesses to support the upkeep of these sites.
4. **Advance Public and Stakeholder Engagement:**
    - Host workshops and campaigns to educate the public and local leaders about astronomy conservation.
    - Partner with international organisations, such as DarkSky International, to share best practices and technical expertise.
    - Involve local communities in conservation activities to foster ownership and stewardship of astronomical resources.
5. **Integrate Conservation into National Development Plans:**
    - Align conservation initiatives with national strategies, such as the National Astro-tourism Strategy, to maximise socio-economic benefits.
    - Include astronomy conservation goals in municipal Integrated Development Plans (IDPs) to ensure coordinated action across all government levels.

Conclusion

Astronomy conservation is a cornerstone of South Africa's efforts to maintain its global leadership in astronomical research and innovation. Protecting dark skies, reducing interference, and maintaining infrastructure are essential to preserving the scientific, cultural, and economic value of the country's astronomical sites. The recommendations provided offer a pathway to balance development with sustainability, ensuring that future generations can benefit from South Africa's unique astronomical heritage. By acting collectively, this country can safeguard its skies and support advancements in science, engineering and education that resonate globally.

Pillar 10: Innovation, Technology, Commercialization and Astro-Tourism

Advancing astronomy in South Africa depends on encouraging new technologies and innovation, promoting collaboration, and creating opportunities for commercialization. Astronomy has always driven scientific and technological progress, often resulting in tools and solutions that extend beyond research. This pillar focuses on building links between astronomy, industry, and emerging technologies to ensure South Africa remains competitive globally.

Strengthening infrastructure, supporting partnerships with industry, and fostering skills will enable the country to bridge the gap between research and practical applications. These efforts will also open opportunities for socio-economic development while supporting the national science and technology agenda.

Objectives

- Promote innovation by removing barriers within the management and administrative structures of astronomy institutions and agencies by encouraging cutting-edge technologies and methodologies that support astronomical research.
- Build stronger collaborations between research institutions, universities, and industry partners.
- Create opportunities to commercialize astronomy-driven technologies across different sectors.
- Develop infrastructure and platforms for advanced data processing, storage, and analysis.
- Promote skills development and capacity building to support technological growth in astronomy.

Recommendations

1. **Establish Innovation Platforms and Infrastructure:**

- Set up a Technology Hub to connect universities, national facilities, and industry. The hub will focus on developing hardware, software, and tools such as data visualisation systems, AI, and instrumentation.
- Support high-performance computing and cloud-based systems to handle large datasets and complex simulations.

2. **Strengthen Collaboration and Technology Transfer:**

- Encourage partnerships between astronomy, engineering, and computer science to solve shared technical challenges.
- Transfer astronomy-based technologies to sectors like telecommunications, environmental monitoring, and navigation.
- Identify opportunities to collaborate with international research facilities on projects such as Laser Frequency Comb (LFC) development and AI applications for instrumentation.

3. **Invest in Emerging Technologies:**

- Develop advanced radio receivers, multi-band receivers, and cryogenic systems to improve telescope capabilities.
- Support the development of Very Long Baseline Interferometry (VLBI) techniques to strengthen South Africa's global contribution to geodetic and astrometric research.
- Explore the use of rapid prototyping methods, such as 3D printing, to create essential astronomy infrastructure components.

4. Build Capacity and Develop Skills:

- Introduce training programmes and workshops to develop expertise in data analysis, instrumentation, and computational resources.
- Strengthen partnerships between industry and academia to create a pipeline of skilled professionals.

5. Promote Commercialization and Partnerships:

- Develop a technology roadmap to identify opportunities for commercializing astronomy innovations.
- Partner with private sector companies, start-ups, and investors to fund and scale astronomy-related technologies.
- Offer incentives such as grants, awards, and competitions to encourage research and recognise contributions to astronomy technologies.

Conclusion

Innovation, technology, and commercialization are key to ensuring South Africa remains at the forefront of astronomy. By strengthening infrastructure, promoting collaboration, and commercializing technology, this pillar supports both scientific progress and economic development. The recommendations aim to create lasting partnerships, build technical capacity, and transfer the benefits of astronomy to society at large.

Astro-Tourism

Astro-tourism is the practice of traveling to different locations with dark skies or radio quietness to observe astronomical phenomena such as meteorites, eclipses, and visible celestial objects in the night sky[6]. Astro-tourism is built around the traditions inherited

[6] https://www.tourism.gov.za/CurrentProjects/National_Astro_Tourism_Strategy/Documents/National%20Astro%20Tourism%20Strategy%20August%202023.pdf

from our ancestors by different ethnic cultures in observing the skies from time immemorial and through the development of professional astronomy of studying the universe over the last 200 hundred years in South Africa. Astro-tourism encompasses all offerings such as observatories, telescopes, museums, planetariums, meteorite sites, visitor centres, amateur astronomy clubs, stargazing, tour-guides, astro-routes and accommodation establishments, etc.

South Africa is an ideal region for astro-tourism to thrive with its competitive advantages such as favourable weather, dark skies, southern hemisphere sky advantage, unique multi-science offerings and Indigenous starlore.

The Department of Science,Technology and Innovation has partnered with the Department of Tourism to unlock opportunities in astro-tourism. The two Departments formed a Steering Committee led by the respective Director-Generals and a Working Group led by the respective Chief Directors. These two structures are constituted by representatives from the two Departments, the Northern Cape Department of Economic Development and Tourism (DEDAT), NRF, SARAO and SAAO. One of the projects being co-funded under this partnership is the planned construction of the SKA Science Tourism Visitor Centre in Carnarvon which is currently going through the detailed design phase.

The Astro-tourism Strategy (2024) seeks to enhance the performance of South Africa's astronomy tourism sector through infrastructure developments and improvements, optimal functioning of various streams of astronomy with tourism offerings and boosting transformation by enhancing the livelihoods of local communities.

The aim of the strategy is to position South Africa to become a world-class astrotourism destination that will yield sustainable benefit-sharing opportunities by maximising appropriate investments, improving marketing efforts, and enhancing visitor experience in South Africa. The strategy will also be used to educate the public about the importance of preserving our dark skies and radio silence as this is a geographic advantage that needs to be protected for astrotourism to thrive.

The Implementqtion Framework is premised on three pillars, where efforts are focused to grow and develop Astro-Tourism in South Africa:

- Indigenous Celestial Narratives and Human Capacity Development – to foster appropriate skills in the entire value chain and to drive and enhance transformation.

- Infrastructure Development – to enhance destination competitiveness through optimal use of new and existing infrastructure, equipment, and resources.
- Inclusive Tourism Growth and Partnerships – to strengthen competitiveness through strategic collaboration efforts and destination development whilst promoting inclusivity in the sector.

The framework further explores these pillars according to opportunities, challenges, key interventions and action projects.

The Implementation Plan is the practical approach to achieve the Strategic Objective of the Astro-Tourism Strategy (2024). The plan addresses each Strategic Pillar according to its specific objectives and interventions. The implementation plan further explores the implementation process, milestones and the established Astro-tourism Governance Body that will ensure coordination and actioning of the strategy. This structure is a multi-stakeholder platform to get relevant wider representation from the value chain of the sector. The terms of reference for this body have been drafted and approved.

The strategy indicated the need for tourist guide training, SMME development, indigenous astronomy product development, built infrastructure, bulk basic services, inclusive tourism value chain, effective marketing, tourism route development and public-private partnerships among other interventions. The cultivation of these interventions with the required funding will be among the responsibilities of the Governance Body.

The multiple benefits for South Africa once astro-tourism is fully established include amongst others the following:

- Increased foreign visitors to South Africa due to expanded tourism offerings
- Creation of jobs and growing SMMEs in the astrotourism value chain in cities and rural areas and thereby contributing to economic growth and transformation in the tourism industry.
- Infrastructure development along the astrotourism routes.
- Increased interest, awareness and opportunities in science and tourism for the public, especially the young people.

Recommendation

The recommendations and implementation plan can be found in the Astro-Tourism Strategy (2024), however, it is critical at a strategic level, for the DSTI to support and advocate for the development of astro-tourism initiatives, linking astronomy with socio-economic benefits.

MONITORING AND EVALUATION STRATEGIES

The Monitoring and Evaluation (M&E) strategies for the overall National Multi-Wavelength Astronomy Strategy provide a clear framework to measure progress and outcomes across its key pillars. Each pillar has specific activities and objectives that will be tracked using tailored indicators and regular reviews. These strategies focus on monitoring results, assessing effectiveness, and identifying areas for improvement. This approach ensures accountability and helps South Africa's astronomy sector remain aligned with its scientific and developmental goals while maintaining its competitive position globally. The expanded M&E framework, with timelines and responsibilities will be provided in the implementation plan.

Table 5: M & E Strategies

Pillar	Monitoring Strategies	Evaluation Strategies
Human Capital, Transformation, and Education Outreach	Track recruitment, retention, and participation of underrepresented groups. Monitor graduation rates, outreach attendance, and public awareness surveys.	Conduct surveys and public engagement analysis. Compare outreach impact and skill development progression over time.
VLBI, Space Geodesy, and Astrometry	Monitor user demographics, consortia participation, and publication metrics. Track geodetic projects and downstream societal impacts.	Benchmark VLBI usage globally. Convene panels to evaluate the societal and scientific outcomes of geodetic and space-related programmes.
Observational Research and Theoretical Modelling	Track publications, PhD completions, and observatory usage. Monitor postdoctoral fellowships and facility demand.	Evaluate research quality using high-impact publications and citations. Conduct critical 5-year reviews by external evaluators.
Instrumentation, Infrastructure, and Observational Techniques	Track uptime of telescopes, ongoing projects, and facility partnerships. Monitor maintenance activities and instrumentation project milestones.	Measure successful instrumentation commissioning and associated scientific contributions using publications and impact metrics.

International Collaboration and African Positioning	Evaluate continental and international partnerships. Track joint projects, benchmarking against global collaboration standards.	Conduct qualitative and quantitative reviews of partnerships through stakeholder interviews and collaborative outputs.
Innovation, Commercialisation, and Astro-Tourism	Monitor technology transfer, commercialisation outcomes, and astro-tourism statistics (visitor numbers, job creation, SMME participation).	Evaluate astro-tourism economic impact, infrastructure improvements, and technology hub contributions through KPIs and stakeholder input.
Funding, Governance, and Strategy Optimisation	Conduct annual funding assessments and governance audits. Track inclusivity and administrative performance through KPIs.	Perform biennial resource utilisation and governance reviews. Evaluate strategic alignment with institutional goals and global competitiveness.
Multi-Wavelength Astronomy Coordination	Monitor inter-institutional collaboration outcomes and strategy alignment with international astronomy trends.	Measure progress via biannual ACTT reporting and Town Hall Meetings. Assess multi-institutional knowledge-sharing initiatives.
Data Science and Advanced Analytics	Track development of data platforms, HPC usage, and machine learning adoption. Monitor big data analysis outcomes.	Evaluate success using adoption rates, infrastructure accessibility, and scientific advancements enabled through data platforms.
Astronomy Conservation	Measure telescope site maintenance, dark sky preservation, and radio frequency interference mitigation. Track regulatory enforcement progress.	Analyse outcomes of pollution mitigation programmes, infrastructure integrity, and compliance with conservation frameworks.
Indigenous Astronomy	Monitor preservation of Indigenous knowledge through storytelling and education programmes. Track participation in cultural initiatives.	Assess outreach impact using surveys and participation statistics. Evaluate socio-economic benefits from cultural astronomy initiatives.

STAKEHOLDER ENGAGEMENT

The successful delivery of the Multi-Wavelength Astronomy Strategy relies on active collaboration and engagement with a range of stakeholders. These include government agencies, research institutions, universities, industry partners, international collaborators, and local communities. Each stakeholder plays a specific role, from providing policy support and funding to driving innovation, capacity building, and public awareness. The table below outlines the key stakeholders and their roles in ensuring the effective implementation of this strategy.

Table 6: Stakeholder & Roles

Stakeholders	Role/Responsibility
Department of Science,Techonology and Innovation	Provides policy support, funding, and ensures alignment with national priorities.
National Research Foundation	Secures funding for research initiatives and supports astronomy development.
South African Radio Astronomy Observatory	Manages radio astronomy facilities, including MeerKAT and some SKA-Mid activities.
South African Astronomical Observatory	Develops and manages optical and infrared astronomy facilities.
Square Kilometre Array Observatory	Leads the SKA project and supports international collaborations.

South African National Space Agency	Supports VLBI and geodesy activities and space-related research.
Universities (Physics/Maths/Astronomy, Engineering)	Conducts research, develops human capital, and fosters innovation.
Centres of Excellence (NiTheCS, AIMS)	Drives interdisciplinary research, training, and capacity development.
African SKA Partner Countries	Enhances continental collaboration for shared resources and skills development.
Amateur Astronomers (ASSA)	Promotes public engagement and interest in astronomy.
JIVE-ERIC	Collaborates on VLBI infrastructure and data exchange.
International VLBI Service (IVS)	Supports geodesy and astrometry research through VLBI networks.
International GNSS Service	Provides global navigation satellite data for geodesy applications.

International Laser Ranging Service (ILRS)	Contributes to geodetic measurements and satellite tracking.
National Geo-spatial Information (NGI), a component of the Department of Agriculture, Land Reform and Rural Development (DALRRD)	Supports geospatial applications and geodetic data usage.
Department of Home Affairs and Department of International Relations and Cooperation	To fast track ‘study’ and other astronomy research-related visas
Industry Partners	Drives innovation, technology transfer, co-funding initiatives and infrastructure development.
Local Communities and Public	Support astro-tourism, education, and public awareness efforts.
Advisory/Steering Committees	Provide oversight and input for monitoring, evaluation, and strategic implementation.
International Research Institutions	Leverage global expertise, collaborations, and resource sharing.

Northern Cape DEDAT	Supports astro-tourism initiatives and regional economic development.
African Astronomical Society (AfAS)	Fosters continental collaboration and development of astronomy in Africa.
Local Astronomers and Researchers	Contribute research, expertise, and knowledge-sharing to advance strategy goals.
Students, Postdocs, and Staff	Engage in research, capacity development, and long-term skills growth.