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Towards a More Equitable Future for Global Astronomy Research and Partnerships

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Abstract

Space- and ground-based astronomical instruments, such as Hubble and the VLT, have been pivotal in advancing our understanding of the Universe. The methods and collaborations that shape astronomy research also inspire the next generation to pursue STEM careers. As emerging spacefaring nations, such as South Africa, expand their activities, it becomes essential to broaden perspectives in the field of astronomy. Ground-based observatories, in particular, often reflect significant collaborations between the Global North and South. This paper examines the role of these facilities, focusing on the contributions of local scientific communities by evaluating North-South cooperation through the metric of Local Scientific Return (LSR). Our findings reveal large disparities in LSR across regions and observatories. In Chile, LSR values show considerable variation around the mean, influenced by historical and policy-related factors, with the upcoming ELT and Vera C. Rubin Observatory exhibiting low values. South Africa's observatories, such as SALT and MeerKAT, exemplify high local involvement, bolstered by consistent government policies and strong international partnerships. Mexico, with its strategic investments and infrastructure development, also demonstrates high LSRs with robust local engagement. Emerging astronomy communities in Namibia, Morocco, and Egypt highlight the impact of targeted investments and collaborative initiatives in significantly enhancing local scientific contributions.

Acronyms/Abbreviations

AfAS	African Astronomical Society
AAAS	American Association for the Advancement of Science
ALMA	Atacama Large Millimeter/submillimeter Array
APEX	Atacama Pathfinder Experiment
AURA	Association of Universities for Research in Astronomy
C-BASS	C-Band All Sky Survey
ELT	Extremely Large Telescope
ESO	European Southern Observatory
FL	First Light
HartRAO	Hartebeesthoek Radio Astronomy Observatory
H.E.S.S.	High Energy Stereoscopic System
HAWC	High-Altitude Water Cherenkov Observatory
HERA	Hydrogen Epoch of Reionization Array
INAOE	Instituto Nacional de Astrofísica, Óptica y Electrónica
IAF	International Astronautical Federation
IAU	International Astronomical Union
ISAAC	International Society for Archaeoastronomy and Astronomy in Culture
IYA2009	International Year of Astronomy 2009
LMT	Large Millimeter Telescope
LSR	Local Scientific Return
M&E	Monitoring and Evaluation
MOSS	Morocco Oukaïmeden Sky Survey Program
NGTS	Next-Generation Transit Survey
OAN	Observatorio Astronómico Nacional
OAO	Office for Astronomy Outreach
OYA	Office for Young Astronomers
OAD	Office of Astronomy for Development
OAE	Office of Astronomy for Education
OWL-Net	Optical Wide-field patroL Network
PAERIP	Promoting Africa European Research Infrastructure Partnerships
SIAC	Sociedad Interamericana de Astronomía en la Cultura
SEAC	Société Européenne pour l'Astronomie Dans la Culture
SPIE	Society of Photo-Optical Instrumentation Engineers
SAAO	South African Astronomical Observatory
SARAO	South African Radio Astronomy Observatory
SALT	Southern African Large Telescope
SSO	SPECULOOS Southern Observatory
SKA	Square Kilometre Array

TRAPPIST	Transiting Planets and Planetesimals Small Telescope
UN SDG	United Nations Sustainable Development Goal
VLT	Very Large Telescope
VLTI	Very Large Telescope Interferometer
VST	VLT Survey Telescope
VISTA	Visible and Infrared Survey Telescope for Astronomy

1. Introduction

Astronomy, as a global scientific discipline, has long been shaped by Western scientific developments, often overlooking the rich contributions of diverse cultures and knowledge systems. This focus remains pervasive in many educational curricula, outreach programs, and research activities, influencing how astronomy is taught, communicated, and practiced worldwide [1, 2].

Over a decade ago, the Royal Society and the American Association for the Advancement of Science (AAAS) introduced the "New Frontiers in Science Diplomacy," a framework grounded in three key principles: science in diplomacy, diplomacy for science, and science for diplomacy [3]. Since then, the democratization of space technologies and the space sciences [4] has further underscored the need to engage local scientific communities and incorporate diverse knowledge systems into the practice of astronomy. This approach fosters more inclusive and effective international partnerships, aligning with the "3G" priorities (Geography, Generation, Gender) of the International Astronautical Federation (IAF), as well as the United Nations Sustainable Development Goals (UN SDGs) [5].

1.1 Astronomy Education

1.1.1 Heritages From Beyond the Global North

Education in astronomy typically involves the dissemination of knowledge through formal instructions, including school curricula, university courses, and educational resources. Historically, these educational materials have emphasized Ancient Greek and Roman constellations, star names, and mythologies. These references to Western Classics have significant influence also on debates and developments in astronautical activities. Consider, for example, the reference to the mythology of Artemis in recent major space initiatives, such as the Artemis Accords, which includes an international consortium of countries in pursuit of the next stage of moon-bound efforts [6].

Given this emphasis, the rich astronomical traditions of other non-Western cultures, including those from Arabic, African, Indian, Chinese, and Polynesian civilizations are at times not fully registered at the global stage [7, 8]. However, contributions from beyond the Global North, such as those from Ancient Arabic, Indian, Chinese, and Indigenous scholars, offer rich insights into the history of astronomy and beyond. Aryabhata composed a compendium of mathematics and astronomy in 499 CE [9], Bhramagupta described gravity as an attractive force in 628 CE [10, 11], al-Farghani revised Ptolemy's Almagest in 850 CE [12], while Shen Kuo discovered and developed the compass in the 11th century with significant implications for astronomical observations and celestial mapping [13].

In the South Pacific, Polynesian astronomy was important both in ocean voyaging and in the ritual-calendrical cycle that was carried from ancestral homelands in the central Pacific out to islands scattered over many thousands of kilometers [14]. Astronomy in Ancient Africa is evidenced not just in myths and calendars, but in ancient megalith observatories such as Nabta Playa in southern Egypt, which predates Stonehenge and other European megaliths [15], and Ng'amoritung'a in Kenya, which features a 2000 year old calendar system predating any European influence [16].

Mesoamerican astronomy established very precise measurements of the cycles of the Earth, Sun, Moon, and the visible planets, and was not only used for practical purposes such as constructing calendars but was deeply interwoven with the development of writing systems [17, 18]. Aboriginal Australians similarly recorded and measured cyclical phenomena, which informed both navigation across the Australian continent and the creation of calendars - many of which feature six seasons, marked by the appearance of specific stars. Their constellations often depict dark patches in the sky rather than illuminated stars; one notable example is the Emu constellation, composed of dark nebulae set against the backdrop of the Milky Way, which is widely referenced in Aboriginal cultures [19]. In South African /Xam starlore, celestial bodies possess anthropomorphic characteristics and are imbued with supernatural potency that can bring both misfortune and good fortune to people's everyday lives [20].

The influence of some of these contributions extends beyond education. Chinese records of comets, among the most extensive and accurate from the ancient and medieval periods, continue to be invaluable to modern astronomers [21]. The Crab Nebula has been identified with the supernova - called a "guest star" by the Chinese - observed in the year 1054 while the first pulsar (the Crab Pulsar) was discovered in 1967 in the center of the nebula [22, 23]. In the aftermath of the discovery, some astronomers made use of Chinese records in their attempts to discover other pulsars. Chinese records have also aided the study of sunspot cycles and the variation of the Earth's rotation period [24, 25].

Despite these detailed astronomical records, advanced mathematical methods, and sophisticated observational techniques, many educational resources, including textbooks, planetarium shows, stargazing apps, and academic courses worldwide, still fail to fully capture this valuable knowledge to enrich perspectives of the skies [26–28]. This narrow focus restricts students' exposure to a more comprehensive and inclusive view of the cosmos.

1.1.2 Cultural Astronomy

Cultural astronomy - a term first used by Ruggles and Saunders [29] - argues that all forms of astronomy, are shaped by the histories and societies from which they emerge. To cultivate a truly inclusive scientific education, it is crucial for scientists and students to critically engage with academic astronomy while also exploring its intersections with the astronomical knowledge systems of other cultures.

Archaeoastronomy, a sub-discipline of cultural astronomy, explores the significance of astronomy as an integral part of human culture and civilization, spanning from the Paleolithic era to the present. Over the past few decades, archaeoastronomy has evolved beyond its speculative origins, which once led to its rejection by the archaeological community [30]. Despite this progress, much of the material on astronomy used in education and outreach lacks diversity in terms of perspectives, often reducing these rich knowledge systems to anecdotal examples. Fortunately, organizations such as the Sociedad Interamericana de Astronomía en la Cultura (SIAC), the Société Européenne pour l'Astronomie Dans la Culture (SEAC), and the International Society for Archaeoastronomy and Astronomy in Culture (ISAAC) offer professional expertise to help deepen our understanding of diverse ways of knowing the sky [31].

1.2 Astronomy Outreach

1.2.1 Interplay Between Inclusive Astronomy and the Next Stage of Space Activities

The renaissance of space activities in recent years saw an increasing number of new and emerging space actors (e.g. South Africa). While space activities were mainly driven by a handful of spacefaring countries in the past, the next stage of both human and robotic space explorations (e.g. future space-based telescopes, moon-bound crewed and robotic missions) will see countries from both the Global North and South all strive to jointly assert and demonstrate their capabilities in Outer Space. Recent moon-bound missions launched by India and China introduced the space community to conceptions of the moon in Sanskrit and Chinese languages. Consider, for example, the references to Chinese folklore for Beijing's lunar missions (e.g. Chang'e, Yutu).

As emerging economies join the next stage of space activities, an understanding of the cultures encapsulated in the naming of these efforts become increasingly important. As space is increasingly perceived as a contested and competitive domain, being able to appraise and comprehend perspectives on space from diverse cultures could help the global community better interpret and evaluate the intentions and motivations of new emerging spacefarers. The field of astronomy marks one of humankind's earliest attempts to understand the Universe. A more inclusive approach in studying the field could help the space community better understand and navigate diverging space-bound activities pursued by countries beyond the Global North. In other words, inclusive astronomy could play a critical role in ensuring the continuous peaceful uses of Outer Space.

1.2.2 The IAU's Strategic Vision

The fascination with celestial bodies and astronomy at a young age often sparked many individuals to pursue a space career, e.g. John Grunsfeld, Ron Rosano [32, 33]. Given its accessibility and universal appeal, astronomy serves as an excellent gateway for introducing children and teachers to science and technology [34, 35].

The success of the International Year of Astronomy 2009 (IYA2009) inspired the International Astronomical Union (IAU) to develop an ambitious strategic plan for the period 2010-2020, which significantly expanded its educational and developmental activities, including the establishment of the IAU's global Office of Astronomy for Development (OAD) at the South African Astronomical Observatory (SAAO) in Cape Town [36, 37]. Building on this foundation, the IAU's 2020-2030 strategic plan provides for the establishment of the Office of Astronomy for Education (OAE), aimed at developing global standards for teaching astronomy at the elementary to high school level. This initiative works in conjunction with the IAU's other key branches: the Office for Astronomy Outreach (OAO), the Office for Young Astronomers (OYA) and the OAD [38].

1.2.3 Astronomy for Development

Under the mandates of the OAD and OAO, astronomy outreach spans a wide range of activities, from engaging the public through planetarium shows, lectures, and stargazing events, to educational initiatives at universities and research institutions aimed at developing the next generation of scientists. School programs also play a key role in sparking young students' interest in astronomy. Chapman et al. (2015) developed an operational, theory-based monitoring and evaluation (M&E) framework for the OAD, identifying key process and outcome indicators/measures for three major OAD programs [39]. This framework allows to assess both the implementation (process) and the short- and intermediate-term impacts (outcomes) of a program, which can aid in distinguishing between a theory and implementation failure. The OAD encourages the use of M&E templates for regular progress reporting [40].

Since its inception in 2011, the OAD has funded and coordinated a total of 215 projects across five continents, making a significant impact on global engagement with astronomy. Numerous case studies, reports, and external reviews attest to the OAD's success as a model for cost-effective STEM knowledge dissemination and development [41]. Many of these outreach efforts are also culturally inclusive, such as Brazil's "OruMbya" project, which unearths African and Indigenous roots within Brazilian culture through the lens of astronomy [42]. Several projects outside of OAD funding also successfully merge effective STEM knowledge dissemination with cultural sensitivity, such as McMaster University's "Reconciliation through Community and Curriculum-Building in Astronomy," which fosters deeper collaboration with Indigenous groups and incorporates Indigenous astronomy into the curriculum [43].

1.2.4 Local Specificity

Successful outreach initiatives, like those previously mentioned, consider the cultural and local contexts of diverse communities. A truly effective global outreach program is adaptable to local needs and sensitive to the cultural significance of celestial phenomena in different regions. Long-term North-South knowledge transfer requires more than just fulfilling quotas or allocating funds for travel and accommodation. It would warrant efforts that go beyond minimal outreach activities [7].

Building on the importance of inclusive outreach, emphasizing diverse knowledge systems could yield significant ripple effects, particularly in the realm of global conservation. Indigenous stewardship is increasingly recognized as pivotal to conservation efforts, not only because Indigenous peoples manage or hold tenure over roughly a quarter of the Earth's land surface, but also because two-thirds of that land is "essentially natural" [44]. Acknowledging the critical role of Indigenous lands and leadership in biodiversity conservation could pave the way for mutually beneficial partnerships that strengthen conservation efforts on Indigenous territories, with the potential to advance global conservation efforts dramatically [45]. However, nearly 60% of Indigenous Peoples' lands are currently under moderate to high threat from industrial development [46].

1.3 Astronomy Research

1.3.1 Translational Benefits of Astronomy Research

Astronomy research, which is the primary focus of this paper, involves the systematic investigation of celestial phenomena through observational and theoretical methodologies. This research not only enriches our understanding of the Universe and fosters a sense of shared humanity and drives human progress by sparking innovation and facilitating the cross-pollination of ideas through its discoveries and technological advancements.

The ability to predict the motions of the Sun and stars played a crucial role in the emergence of agriculture and navigation in early civilizations [30]. The OAD also cites a number of technologies and skills developed for astronomical research that have found applications across various fields, including industry and medicine [47]. Notable examples include CCDs used in digital cameras and cellular phones, Martin Ryle's aperture synthesis technique repurposed for medical imaging [48], adaptive optics technology utilized in high-precision laser applications and medicine, and the WLAN technology based on John O'Sullivan's method for improving radio telescope images [49].

1.3.2 Astronomy as a Catalyst for Scientific Innovation

Beyond its direct contributions to technological and societal advancements, professional astronomy can also have a profound influence on other scientific fields, serving as a catalyst for cross-disciplinary innovation and knowledge expansion. The Square Kilometre Array (SKA) radio telescope, for example, is poised to revolutionize not just astronomy but also fields such as astroparticle physics, cosmology, galactic and extragalactic astronomy, solar system science and astrobiology, by providing unprecedented data and insights [50].

Similarly, the Southern African Large Telescope (SALT) exemplifies how astronomical infrastructure can drive scientific progress on multiple fronts while also fostering broader socio-economic development. The SALT project, as documented by the Promoting Africa European Research Infrastructure Partnerships (PAERIP) project, has not only advanced our understanding of the cosmos but has also led to significant developments in related sciences, all while contributing to local capacity building, employment opportunities, and educational outreach [51]. These examples highlight how investments in astronomy can have far-reaching impacts, propelling advancements across various scientific domains and strengthening the global knowledge economy [52, 53].

1.3.3 Challenges for Inclusive Astronomy

While the overall scientific return from astronomy research is a crucial indicator of success, it is important to assess how these returns are distributed among participants, the relative benefits accrued by different stakeholders, as well as knowledge transfer between contributing stakeholders. In North-South collaborations, inclusive scientific practices aim to integrate local scientists from the Global South into the research process. This approach transcends temporary initiatives, such as one-off seminars or workshops, and focuses on establishing sustained, collaborative partnerships.

Inclusive astronomy has the potential to equip the scientific community with a stronger understanding of local needs, demonstrating a strong commitment to strengthen the UN SDGs by avoiding practices like "parachute science" that does not allow for a more contextualized approach to engagement. Employing a science policy officer with expertise in local contexts, who can negotiate international collaborative efforts and drive more local dialogues, could be a significant step forward, as seen in parts of Europe and the Unites States [7].

Efforts toward more inclusive scientific practices are generally more visible in other disciplines like marine biology or geology [54–57]. Within the astronomical community, several Working Groups of the IAU seek to provide support to individuals in regions where IAU membership statistics are poor, such as the Working Group on Space Sciences in Africa, which also publishes the journal African Skies [58]. In general, ambitious goals have been established, such as the IAU's commitment to allocate at least 0.7% of budgets from astronomical institutes and projects in high-income countries to support astronomy education and research in low-income nations, consistent with the UN development aid target [37]. However, there is significant room to strengthen the implementation of the 0.7% allocation and other IAU initiatives, including but not limited to the institute twinning scheme between well-established and emerging astronomy institutions. This underscores the importance of continued efforts to enhance inclusivity within the field of astronomy.

Modern astronomical research often relies on facilities that are prohibitively expensive for even individual high-income nations to develop and maintain. One of the most prominent historic cases is the servicing of the Hubble telescope, which saw the instrument serviced by astronauts through multiple servicing missions with the Space Shuttle program. Given the significant cost and expertise that astronomical research often requires, its realization typically requires extensive international collaboration.

This paper focuses on large-scale partnerships surrounding ground-based observatories which often require significant collaboration and coordination between economies in both the Global North and South. Specifically, this paper seeks to assess the Local Scientific Return (LSR), defined here as the proportion of research outputs, namely scientific publications, that include contributions from host institutions. Through an analysis of relative research outputs, the study aims to identify the contributions and benefits that flow back to local scientific communities. By subsequently comparing these findings with literature on historical factors and science-related policies, this study then seeks to illuminate trends that tentative link high LSRs to factors such as access to telescope time or supportive policies.

While LSR is a coarse measure of local involvement, we argue that it might offer valuable insights into promoting more inclusive research and building local scientific capacity. This approach has the potential not only to strengthen the rigour of scientific inquiry but also to help ensure a more equitable distribution of benefits across the global astronomical community [37, 59].

2. Methods

2.1 Local Scientific Return

This study first examines the LSR from various ground-based astronomical observatories and telescopes across selected nations. Collectively referred to as astronomical *facilities*, these sites are evaluated to assess the scientific contributions and benefits returned to their host countries.

The nations selected for this study - Chile, South Africa, Mexico, Namibia, Morocco, and Egypt - represent both established and emerging players in modern astronomical research, extending the focus beyond the traditional centers of the Global North. Chile and South Africa are renowned hubs of astronomical research, each hosting some of the world's most productive facilities. Chile's ascent as an astronomical powerhouse began in the 1960s with the establishment of the European Southern Observatory (ESO). Today, the country accounts for roughly 50% of the world's light-gathering capacity from ground-based telescopes [60]. South Africa has become a critical player in both optical and radio astronomy, with the completion of SALT in 2005 and the development of the MeerKAT array, following the KAT-7 test bed completed in 2011 [61]. Together, these facilities have cemented South Africa's role in the global astronomy landscape.

Mexico has a longstanding tradition in modern astronomy, dating back to the establishment of the Observatorio Astronómico Nacional (OAN) in 1878, which was relocated multiple times before settling atop the Sierra San Pedro Mártir mountain range in 1967 [62]. The field has seen considerable growth since the 1990s, and today, astronomy is one of Mexico's most productive scientific disciplines [63]. Namibia, home to the High Energy Stereoscopic System (H.E.S.S.), has risen as a key site for gamma-ray astronomy since the early 2000s. Morocco and Egypt, while possessing smaller, developing infrastructures, are also included as they reflect the expansion of astronomical research in the Arab world and provide important case studies for estimating the LSR in emerging astronomy hubs.

Many facilities in these nations maintain close research and financial collaborations with Western institutions, making them ideal for our analysis. Our study evaluates local scientific contributions to these international astronomical facilities through the following key data points:

1. *Facilities*: Each facility is categorized by its host country, with a focus on capturing the most scientifically productive astronomical observatories within the selected nations. This approach aims to include key research-driven facilities that significantly contribute to the advancement of astronomical science.

2. *First Light (FL)*: Facilities in each country are listed by the year of their first light, which marks the initial use of a telescope to capture an astronomical image (or “fringes” in the case of interferometric arrays like the Atacama Large Millimeter/submillimeter Array - ALMA - or MeerKAT) after construction.

3. *Total Research Output*: This metric captures the total number of published research papers associated with each facility, providing an overview of the research output generated.

4. *Host Researcher Contributions*: To assess local scientific engagement, the number of published papers authored or co-authored by researchers affiliated with institutions in the host country is reported.

5. *Citation Count*: This metric tallies the total number of citations received by the published papers, offering insight into the impact and reach of the research.

6. *Citations from Host Researcher Papers*: This subset of the previous metric focuses on the impact of local contributions, counting citations from papers authored or co-authored by researchers from the host country.

7. *Host Country Financing*: We record whether the facility is primarily funded by the host country, providing context for the financial investment and its potential influence on the LSR.

8. *LSR*: The LSR is determined as the percentage of published research papers (co-)authored by researchers affiliated with local institutions compared to the total number of published papers.

2.2 Scopus Database

All publication-related data is sourced from the Scopus database. To gather this data, we consult the Scopus Master Journal List (as of August 31, 2024). Queries are constructed for each facility to retrieve the total number of publications within a specific timeframe. Our analysis includes research papers published between 1970 and August 31, 2024, in any language, that mention the facility in the paper title, abstract, or keywords, and fall within the fields of “Physics and Astronomy” or “Earth and Planetary Sciences.” This approach captures not only direct scientific output but also preparatory and ancillary work in related fields such as engineering, materials science, high-performance computing, and optics. As a result, our holistic methodology provides a broader assessment of scientific impact, including papers published outside of traditional astronomy journals.

Our approach complements that of commonly used databases, such as the ESO Telescope Bibliography (telbib), which tracks refereed papers that rely partly or exclusively on data from ESO facilities [64]. While our method may miss papers that use facility data without explicitly mentioning the facility in the title, abstract, or keywords, it includes many that reference the facility without directly using its data. For instance, for the combined Very Large Telescope (VLT) & Very Large Telescope Interferometer (VLTI) system, both Scopus and telbib report over 10,000 scientific papers in total [65].

The relative uncertainties in the raw counts (local and total papers) might vary significantly according to the exact methodology, but when expressed as a ratio, these fluctuations are mitigated because the LSR focuses on relative contributions, which may show more consistency. If uncertainties in both the numerator (host papers) and the denominator (total papers) are positively correlated (i.e., host papers and total papers move in the same direction upon changing the methodology), the relative uncertainty of the ratio is smaller than the individual uncertainties, according to error propagation rules.

We do not differentiate between document types, such as articles, conference papers, reviews, letters, book chapters, errata, short surveys, books, notes, or editorials. For the purposes of this study, the terms “scientific publication” or “paper” refer to any of these document types. Scopus allows for easy refinement of results by “country/territory,” enabling us to filter publications based on local authorship. When reporting citation counts, we include book citations and self-citations.

3. Results and Discussion

3.1 Scientific Return

Our comprehensive approach from Sec. 2.1 enables a detailed analysis of the scientific return from ground-based observatories to host countries. In Table 1, we present the scientific return across Chile, South Africa, Mexico, Namibia, Morocco, and Egypt.

3.1.1 Chile

The scientific output varies considerably across the facilities, as evidenced by the aggregated number of scientific publications and associated citations. The most productive individual ground-based astronomical facility to date is the VLT & VLTI system of telescopes [119], with more than 10,200 scientific publications (including engineering, material science, high-performance computing, and optics research). Among these, around 2,500 were (co-)authored by researchers affiliated with Chilean institutions, yielding an LSR of 25%. Several facilities in Chile have higher LSR values, with Cerro Murphy and the Next-Generation Transit Survey (NGTS) & SPECULOOS Southern Observatory (SSO) exhibiting the highest values around 55%. By far the lowest LSR is found for the Extremely Large Telescope (ELT), a future optical/near-IR telescope currently under construction on Cerro Armazones.

The relatively low mean LSR of approximately 29% for Chilean facilities, along with the considerable standard deviation of around 15%, could be attributed to a variety of factors. Barandiaran (2015) argues that there may have been inconsistent support for science in the second half of the 20th century, which may have affected the development of scientific infrastructure [120]. Instead of using astronomy as a direct injection of capital into the high-tech industries, the state remained committed to a development model based on exports rather than entrepreneurship [121, 122].

Another potentially compounding factor is that the observatories appeared largely inaccessible to Chilean astronomers until the late 1990s, when the Chilean government came under mounting pressure to negotiate improved conditions with the international organizations running the observatories. Specifically, under the renegotiated 1997 Convention [123], ESO grants 10% of the telescope's viewing time to projects proposed by astronomers at Chilean institutions.[1] Chile's allotted 10% viewing time as host contrasts with 15% for Hawaiian institutions and 20% for Spanish institutions seeking access to observatories in the Canary Islands [124].

Nonetheless, Chile's astronomy community has grown dramatically in recent years, in part thanks to the role of the Association of Universities for Research in Astronomy (AURA). As an organization of universities, AURA from the very beginning in the 1960s worked in partnership with the University of Chile, fostering cooperation among universities, rather than among states. AURA and other North American organizations also created a special fund for astronomy administered by the National Agency for Research and Development (ANID, formerly CONICYT) [125]. Throughout the 2010s, the number of universities offering graduate programs in astronomy expanded significantly. In addition to the longstanding programs at Universidad de Chile and Pontificia Universidad Católica de Chile, new programs were established at Universidad de Atacama, Universidad de Valparaíso, Universidad Andrés Bello, Universidad Diego Portales, and Universidad de La Serena. Currently, Universidad de Concepción is working to launch its own graduate program [126].

The case of ELT highlights ongoing disparities in global scientific collaborations, with only 5% of its preparatory and ancillary research work involving researchers affiliated with Chilean institutions. The ELT is currently under construction, which may partially explain the low figure of host engagement. Nevertheless, the figure does not seem to contradict the hypothesis that local communities may not be fully integrated into the design and engineering phases of the project. Additionally, a significant portion ($\approx 60\%$) of ELT-related publications thus far have appeared in the Proceedings of the Society of Photo-Optical Instrumentation Engineers (SPIE), reflecting the focus on early technical development. While this highlights a gap in local involvement at the initial stages, Chile's growing educational and institutional capacity suggests that this imbalance may potentially shift over time. With a robust and expanding network of universities offering graduate programs in astronomy and related fields - such as engineering - Chile is cultivating a new generation of astronomers and technical experts.

Similarly, the case of the Vera C. Rubin Observatory illustrates comparable disparities in global scientific collaborations, albeit with a slightly higher LSR of 10%. The Rubin Observatory, designed to conduct wide-field imaging surveys, is expected to have a profound impact on various fields of astronomy, yet much of the design and development work has been dominated by Global North partnerships, reflecting a lack of engagement with the local Chilean scientific community.

In contrast, the NGTS & SSO serve as a more promising model for equitable science and inclusive collaborations. While the total research output from the two facilities amounts to around 120 scientific publications, Chilean

[1] While ESO also accepted to apply aspects of Chilean labor law - such as the right to bargain collectively - to locally hired staff, it retained diplomatic immunity, significant tax exemptions and exemption from submitting environmental impact assessments.

Table 1. Scientific return from various ground-based observatories across Chile, South Africa, Mexico, Namibia, Morocco, and Egypt. The data include: (1) the name of the facility; (2) the ISO 3166-1 alpha-2 code for the corresponding country; (3) the first light (FL) of the facility; (4) the total number of published papers; (5) the number of these papers that were (co-)authored by the host; (6) the number of papers that utilized data from the facility; (7) the number of these data papers that were (co-)authored by the host; (8) whether the facility is majority-financed by the host; (9) the LSR. Data were sourced from the Scopus database.

Facility	Country	FL	Papers	Host Papers	Citations	Host Citations	Financed by Host	LSR [%]
Cerro Tololo	CL	1965 [66]	1077	398	43947	12918	✗ [67]	37
La Silla	CL	1969 [68]	2179	514	68326	14028	✗ [69]	24
Las Campanas	CL	1969 [70]	1434	286	42310	16399	✗ [70]	20
VLT & VLTI	CL	1998 [71]	10292	2547	296415	79195	✗ [72]	25
Gemini South	CL	2000 [73]	631	255	13487	5654	✗ [74]	40
APEX	CL	2005 [75]	1151	235	23882	6739	✗ [76]	20
Cerro Murphy	CL	2005 [77]	67	39	897	615	✗ [77]	58
Cerro Toco	CL	2007 [78]	707	177	21406	9499	✗ [79, 80]	25
NGTS & SSO	CL	2015/2008 [81, 82]	119	63	2240	1253	✗ [82, 83]	53
VISTA & VST	CL	2009/2011 [84, 85]	775	295	19563	8633	✗ [85, 86]	38
ALMA	CL	2011 [87]	2882	709	74565	22771	✗ [88]	25
Vera C. Rubin	CL	2025 [89]	1241	126	32144	4864	✗ [90]	10
ELT	CL	2028 [91]	755	41	8071	797	✗ [92]	5
Boyden	ZA	1927 [93]	19	11	47	26	✗ [94]	58
SAAO (excl. SALT)	ZA	1972 [95]	378	207	8970	3174	✓ [95]	55
HartRAO	ZA	1975 [96]	61	55	730	666	✗ [97]	90
SALT	ZA	2005 [98]	326	246	4619	3332	✗ [99]	75
C-BASS South	ZA	2014 [100]	24	12	246	149	✗ [100]	50
MeerKAT	ZA	2016 [101]	539	398	6040	4527	✓ [102]	74
HERA	ZA	2016 [103]	175	51	4647	1795	✗ [104]	29
SKA-Mid	ZA	2028 [105]	146	42	1453	403	✗ [106]	29
Guillermo Haro	MX	1987 [107]	39	35	363	347	✓ [108]	90
OAN	MX	1967 [62]	209	193	2509	2313	✓ [108]	92
LMT	MX	2011 [109]	205	137	1910	1034	✓ [110]	67
HAWC	MX	2012 [111]	420	128	5935	2586	✗ [112]	30
H.E.S.S.	NA	2002 [113]	1141	204	23462	10047	✗ [114]	18
Oukaïmeden	MA	2007 [115]	46	30	383	280	✗ [116]	65
Kottamia	EG	1964 [117]	46	39	187	158	✓ [118]	85

astronomers contributed to more than half of the research papers. Despite Chilean institutions not being part of the consortia operating NGTS or SSO [82, 83], their involvement in research conducted at these facilities underscores the importance of fostering local talent and expertise. Among all the Chilean observatories studied, Cerro Murphy stands out with an LSR of 58%, highlighting a significant local contribution to its scientific output.

3.1.2 South Africa

South Africa hosts a number of observatories that have excelled in integrating local scientists into the international astronomical research community. Facilities such as SALT, the Hartebeesthoek Radio Astronomy Observatory (HartRAO), and two majority South Africa-financed institutions - MeerKAT and SAAO - all attain high levels of LSR. More than half of the research papers from these observatories are co-authored by South African researchers, with HartRAO reaching LSR values as high as

90%. This highlights significant involvement of the local scientific community in cutting-edge research.

The success of these observatories in fostering local participation can be attributed to a variety of factors. First and foremost, there has been a strategic focus on building local talent and infrastructure. The South African Radio Astronomy Observatory (SARAO), for example, launched a Human Capital Development Program in 2005, aimed at developing a community of scientists, engineers, technicians, and artisans. The goal is equip local professionals with the necessary skills to design, build, and operate the MeerKAT and the SKA radio telescopes, and to secure South Africa's return on its strategic investments in radio astronomy. To date, SARAO has awarded over 1,500 grants as part of this initiative [127].

In parallel, international collaborations have been structured in a way that encourages local participation. The SKA-Mid facility, currently under construction in the Meerkat National Park, is a prime example of this. While the SKA is an international project, South African radio astronomers and engineers are deeply involved, with the facility achieving an LSR of 29%. This integration of local experts into a global mega-science project reflects a successful model of scientific collaboration.

Moreover, partnerships with organizations such as the African Astronomical Society (AfAS) and the SKA Organization have been pivotal. These collaborations have supported human capacity development across Africa, ensuring that South African astronomers and engineers are well-positioned to take on leading roles in international research [128].

Finally, South Africa's decade-long strategy for human capacity development in astronomy, outlined by the Department for Science and Innovation (formerly the Department of Science and Technology), has further strengthened this effort. It advocates for cross-disciplinary collaboration and a systematic, capacity-driven program that aligns with the country's ambitions in science and technology [129]. Together, these initiatives have enabled South Africa to leverage international collaborations while maintaining a strong local scientific presence, serving as a model for how astronomy hubs can promote equitable science and play a significant role on the global stage.

3.1.3 Mexico

Mexico offers yet another unique perspective on scientific equity. Facilities such as the Large Millimeter Telescope (LMT), the Guillermo Haro Observatory, and the OAN exhibit high LSR values. For instance, at the Guillermo Haro Observatory and OAN, LSR values exceed 90%, and the LMT's LSR is 67%, reflecting the deep involvement of local astronomers in the utilization of these facilities. This is potentially due to Mexico's long-standing commitment to financing its observatories, with many of them, including OAN and LMT, being majority-financed by the Mexican government [108, 110]. This financial backing ensures that local institutions have priority access to telescope time, fostering the development of a vibrant local astronomy community.

One of the primary drivers of this success is the role played by institutions like the Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE), which manages several major observatories and promotes research collaboration between Mexican and international scientists. The Mexican government has also prioritized the development of scientific infrastructure, resulting in initiatives like the establishment of the LMT, one of the largest and most advanced millimeter-wave telescopes in the world. This focus on infrastructure, combined with Mexico's strategic geographic location, has allowed Mexican researchers to remain at the forefront of astronomical discoveries, including in collaboration with international partners. Mexico's model illustrates how countries can enhance scientific returns by pairing substantial financial investment with efforts to build local capacity in astronomy.

3.1.4 Namibia, Morocco, and Egypt

Namibia, Morocco, and Egypt provide insightful examples of how smaller or emerging astronomy communities can achieve notable scientific returns, despite limited resources. In Namibia, the world-leading gamma-ray H.E.S.S. attains an LSR of 18%. Although this value is lower compared to many facilities in other countries, the ratio of host citations to total citations is in fact much higher at 43%. The participation of Namibian scientists is significant given that H.E.S.S. is part of a large international collaboration.

Namibia's growing role in astronomical research is bolstered by its strategic geographic location (clear skies and dry desert environment) and its investment in developing local capacity [130]. H.E.S.S. plays a pivotal role in global gamma-ray astronomy, and with increasing governmental support, Namibia's astronomy community is poised to further integrate into international scientific efforts. The Africa Millimetre Telescope (AMT) project has recently been given the green light - the first step towards having a radio telescope in Africa that is sensitive to millimetre wavelength radiation [131].

In Morocco and Egypt, the observatories of Oukaïmeden and Kottamia show very high LSR values of 65% and 85%, respectively. This reflects the dominant role that local researchers play in producing scientific output from these facilities. In Morocco, the Oukaïmeden Observatory, despite its small size, has emerged as a hub for astronomical research, driven by the dedication of local scientists and collaborations with international institutions. Several domes and instruments have been installed, enabling research in various fields, including planetary science, exoplanet detection, and variable stars. Instruments such as the Morocco Oukaïmeden Sky Survey (MOSS), the Northern Twin of the Transiting Planets and Planetesimals Small Telescope (TRAPPIST), and one telescope among the Optical Wide-field patroL Network (OWL-Net), have been instrumental in discoveries, including the detection of the TRAPPIST-1 exoplanet system [132].

Its contributions to planetary science, small solar system bodies, and exoplanet research have been substantial. Additionally, efforts are underway to establish a "Dark Sky Reserve" around the site, ensuring the preservation of sky quality for future astronomical observations [132]. The LSR is even higher when excluding OWL-Net, which is a South Korean initiative primarily focused on acquiring and maintaining orbital information of LEO satellites through optical means. When excluded, 30 out of 31 publications indexed by Scopus are found to be co-authored by local researchers, corresponding to an LSR of 97%. This underscores the vital role that the local scientific community plays in advancing astronomical research at the observatory.

Similarly, Egypt's Kottamia Observatory, which dates back to 1964, benefits from substantial local involvement in research. Both countries demonstrate how national scientific priorities and strategic partnerships can create opportunities for local scientists to take leading roles in astronomy, even when resources are constrained. These examples underscore the potential for high local scientific returns in countries where dedicated policies and collaborative networks are established to maximize the scientific output from local facilities.

However, due to a shortage of technical staff, the Kottamia Observatory has recently fallen into disrepair [133]. In addition, light pollution from urban sprawl is affecting visibility from the observatory, which is 80 km away from Cairo. Egypt has thus announced plans to construct in Sinai the largest astronomical observatory in the Middle East and the Mediterranean [134].

3.2 Limitations & Discussions

While this paper provides an initial evaluation of North-South scientific cooperation in astronomy through the lens of LSR, several limitations highlight areas for future research. First, the use of Scopus has inherent constraints, as it only retrieves papers that explicitly mention a facility in the title, abstract, or keywords. While this approach facilitates a broader assessment of scientific impact across various disciplines, it may overlook many works that reference the facility solely in the main text. Secondly, the citation count provided by Scopus reflects only the number of times a publication is cited by articles from journals included in its database. It does not account for citations from every journal published worldwide, nor does it include citations from books, conference proceedings, dissertations, patents, technical reports, or other types of publications.

We characterize the scientific contributions of local communities to international observatories using the LSR metric and emphasize the potential for more inclusive collaboration. As global partnerships evolve, the time-integrated LSR we report may offer valuable insights for current and future initiatives, ensuring that local contributions are recognized and integrated into the global scientific dialogue. However, the LSR is merely one of many metrics that can be employed to estimate local contributions to science and technology. Importantly, it does not account for the essential roles played by local workers, engineers, and technicians in constructing and maintaining international astronomical facilities. Furthermore, the LSR does not illuminate how the international scale of collaboration impacts local contributions. A low LSR may still exist despite significant participation by local scientists if an observatory is operated, funded, and developed within a large international consortium spanning multiple countries and institutions. Many forthcoming facilities, such as the ELT and the Vera C. Rubin Observatory, are indeed large consortia.

Additionally, the LSR metric does not account for the impact of knowledge transfer and outreach programs, such as training and capacity-building initiatives for local scientists and engineers, nor does it consider the broader benefits to local communities. While a detailed analysis of the factors influencing LSR at each facility lies beyond the scope of this study, future research focusing on a time-decomposed LSR could offer valuable insights into evolving global trends in inclusivity and collaborative practices in astronomy.

4. Conclusions & Outlook

This review of observatories across different regions highlights both the advancements and ongoing challenges in integrating local scientific communities. The findings emphasize the role of policies, international collaborations, and cultural considerations in shaping the landscape of astronomy.

Chile presents a mixed picture in terms of scientific output and local involvement. The VLT & VLTI stand out with over 10,200 scientific publications and a 25% LSR. Facilities like Cerro Murphy and NGTS & SSO achieve the highest LSR values, reflecting greater local involvement. The ELT project, currently under construction, shows the lowest LSR of 5%, pointing to ongoing challenges in integrating local researchers into major international projects. Historical factors, such as inconsistent support for science and delayed access to observatories, contribute to the variability in LSR values. Despite these challenges, the growth of Chile's astronomy community, supported by organizations like AURA, demonstrates the potential for significant local contributions when conditions are favourable.

In Mexico, facilities such as the LMT, the Guillermo Haro Observatory, and the OAN show high LSR values, reflecting deep local involvement. The Guillermo Haro Observatory and OAN exceed 90% in LSR, while the LMT stands at 67%. This success could be attributed to Mexico's commitment to financing its observatories and prioritizing local access. Institutions like the INAOE play a crucial role in fostering research collaboration and developing infrastructure, such as the LMT. Mexico's approach highlights how strong financial support and strategic investments in scientific infrastructure can maximize local scientific returns and maintain a prominent role in international collaborations.

In South Africa, the success of observatories such as HartRAO, MeerKAT, and SAAO reflects the effectiveness of government policies aimed at fostering local scientific talent and infrastructure. Investments in human capital development, alongside international collaborations, have resulted in strong LSR outcomes. Efforts to engage local communities in the planning and development phases, particularly with the SKA-Mid project, underscore South Africa's commitment to aligning scientific progress with local socio-economic benefits.

Namibia, Morocco, and Egypt showcase how emerging or smaller astronomy communities can achieve notable scientific returns through strategic investments and international partnerships. Namibia's involvement in gamma-ray astronomy with H.E.S.S. and its efforts to develop local capacity signal its growing prominence in the field. Morocco's Oukaïmeden Observatory and Egypt's Kottamia Observatory highlight how dedicated local researchers and strategic partnerships can drive significant scientific contributions even with limited resources. Both countries demonstrate high LSRs through well-established policies and collaborative networks.

Overall, the reviewed cases illustrate that fostering meaningful collaboration with local scientific communities and achieving significant scientific outcomes - both on a global and local scale - are possible through thoughtful policies, respectful partnerships, and cultural sensitivity. Our findings underscore the importance of adopting tailored approaches, informed by local contexts and challenges, to ensure inclusive and equitable scientific practices. While progress is being made, the shift from consultation to deeper empowerment of local scientific communities remains an ongoing process. This transition is essential for building sustainable, long-term partnerships that truly benefit both the global astronomical community and the local regions hosting the observatories.

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