

Heritage-Informed Instrumentation: A Comparative Assessment of Astronomical Methods and Infrastructure in the Islamic World

Belay Sitotaw Goshu¹, Muhammad Ridwan²

¹Department of Physics, Dire Dawa University, Dire Dawa, Ethiopia

²Universitas Islam Negeri Sumatera Utara, Indonesia

Email belayisitotaw@gmail.com, bukharyahmedal@gmail.com

Abstract

The astronomical tradition of the Islamic world represents a continuous enterprise of instrumental innovation spanning twelve centuries, yet the relationship between its classical achievements and contemporary infrastructure remains underexamined. This expert review synthesises historical, archaeological, and contemporary sources to assess astronomical methods and instrumentation across three phases: the classical period (8th–15th centuries), the present revival (21st century), and prospective future directions. The review examines the functional taxonomy of classical instruments; astrolabes, quadrants, armillary spheres, and mural quadrants and evaluates their observational precision, including the 40-metre mural quadrant at Marāgha and the 36–40 metre sextant at Samarkand, which achieved tropical year measurement within 58 seconds of modern values. Contemporary infrastructure is assessed through facilities including the Kottamia Observatory in Egypt, the Sharjah Academy for Astronomy, Space Sciences and Technology, and the AlUla Manara project in Saudi Arabia, which will house a four-metre telescope with median nighttime seeing of 1.5 arcsec and clear-sky fraction exceeding 79%. A comparative analytical framework identifies institutional continuities between Marāgha and AlUla Manara, including state patronage, integrated research and education, international collaboration, and sustainable funding. The review proposes a five-domain research agenda: regional observatory networks, computational reconstruction of historical instruments, heritage-science protocols, integrated education, and space-based astronomy. It argues that Islamic astronomy's heritage constitutes an active epistemological resource capable of informing contemporary practice, positioning the Islamic world as a bridge between scientific traditions and a contributor to global astronomical knowledge.

Keywords

Islamic astronomy;
astronomical
instrumentation; astrolabe;
observatory studies; AlUla
Manara; heritage science;
knowledge transmission;
observatory networks



I. Introduction

The history of astronomy in the Islamic world presents a paradox for contemporary scholarship. On the one hand, the achievements of the classical period, from al-Battānī's precision planetary observations to Ibn al-Shāṭir's non-Ptolemaic lunar models are extensively documented and widely recognized as foundational to the global history of science (Saliba, 2011; Ragep, 2007). Muslim astronomers not only preserved and transmitted Greek astronomical knowledge but critically engaged with and transformed it, producing innovations that directly influenced Copernicus and the European Renaissance (Saliba, 2007; Dallal, 2010). On the other hand, the relationship between this historical

legacy and the contemporary astronomical infrastructure emerging across the Islamic world remains remarkably underexamined. Saudi Arabia's recent approval of AlUla Manara, featuring a four-metre telescope that will place it among the world's largest observatories, exemplifies this contemporary revival (Royal Commission for AlUla, 2026). Yet the conceptual and institutional connections between such mega-projects and the observatory traditions of Marāgha and Samarkand have received little systematic scholarly attention (Mozaffari, 2013; Mozaffari & Zotti, 2013).

This disjuncture in the literature is compounded by a temporal specialisation within the field. As noted in the Oxford Bibliographies survey of Islamic astronomy, most historians have specialised either in the medieval or the modern period, and "a comprehensive account of all of Muslim astronomy, from the 7th to the 21st centuries, is still missing" (Oxford Bibliographies, 2019, para. 2). Saliba (2011) has argued forcefully that the Islamic scientific tradition must be understood not as a mere conduit for Greek learning but as an original enterprise with an "organic relationship" to the science that emerged in Renaissance Europe (p. 4). Extending this argument into the contemporary period, however, requires a framework that treats instrumental and methodological principles as historically persistent features of Islamic astronomical practice, rather than as discrete artifacts of a bygone era (King, 2004; Charette, 2006).

This review addresses that gap by posing three interrelated questions: What instrumental and methodological principles characterised Islamic astronomy during its Golden Age? How do contemporary observatory projects in the Islamic world relate to this heritage? And what research directions emerge from a comparative, heritage-informed assessment? The central argument is that contemporary projects such as AlUla Manara represent not a rupture from the classical past but a re-emergence of principles established during the Golden Age, state patronage, integrated research and education, precision instrumentation, and problem-driven observation, adapted to modern governance and technological capabilities (Lombardi et al., 2024; Mokhtarzadeh, 2025).

The review is structured in five principal sections. Section 2 examines the historical instruments and observational methods of the classical period, focusing on the Marāgha and Samarkand observatories as paradigmatic institutions (Mozaffari, 2013). Section 3 assesses contemporary infrastructure, with particular attention to AlUla Manara and comparative site characterisation (Lombardi et al., 2025). Section 4 develops a comparative analytical framework relating historical institutional models to contemporary practice (Saliba, 2011; Mamat & Yusuff, 2025). Section 5 proposes a research agenda for heritage-informed instrumentation, regional observatory networks, and computational reconstruction of historical instruments (Charette, 2006; King, 2004).

II. Review of Literature

2.1 Historical Phase: Instruments and Methods of the Classical Period (8th–15th Centuries)

a. Instrumental Taxonomy

Islamic astronomers developed a diverse instrumental toolkit that can be classified into four functional categories (Table 1). The astrolabe was the most sophisticated and versatile of these instruments, serving as both a scientific device and a spiritual compass for determining prayer times and qibla direction (King, 2004). Muslim scientists substantially reworked and improved the astrolabe between the 8th and 14th centuries, turning it into a symbol of Islamic innovation (Mamat & Yusuff, 2025). Well over a thousand astrolabes and hundreds of globes survive in museum collections worldwide, testifying to the scale of production and the instrument's centrality to Islamic astronomical practice (Charette, 2006). A characteristic feature of Arab-Islamic astronomy during the Middle Ages was the promotion and tremendous growth of practical astronomy, manifested primarily by the establishment of scores of observatories and by the production of copious literature on astronomical instruments (*ālāt al-raṣād*). The enormity of this literature can be gauged by the list of extant works given by Matvievskaia and Rosenfeld, which includes 349 treatises on astrolabes, 138 on sine-instruments, 81 on quadrants, 4 on sextants and octants, 41 on armillary spheres and celestial globes, 77 on sundials, and 77 on "other instruments", in all, 767 treatises (Şen, 2016).

Table 1. Functional taxonomy of Islamic astronomical instruments

Functional Category	Principal Instruments	Primary Applications	Key Innovations
Time-measuring	Sundials, shadow horary quadrants	Prayer times, timekeeping	Calibration for latitude
Angle-measuring	Armillary spheres, dioptries, parallactic rulers	Planetary and stellar observation	Large-scale precision
Coordinate-transformation	Astrolabes (planispheric, universal), equatorial	Coordinate conversion, qibla	Stereographic projection
Mathematical	Sine quadrants, trigonometric devices	Function evaluation	Numerical computation

Source: Compiled from Charette (2006), Berggren (1991), and King (2004).

Table 1 presents a functional taxonomy of Islamic astronomical instruments, organising them into four categories according to their primary operational purpose. The time-measuring category, comprising sundials and shadow quadrants, served the practical religious needs of determining prayer times, with calibration for latitude representing a key innovation (King, 2004). Angle-measuring instruments, including armillary spheres and parallactic rulers, enabled planetary and stellar observation through large-scale precision design, as exemplified by the 40-metre mural quadrant at Marāgha (Mozaffari, 2013). Coordinate-transformation instruments, particularly astrolabes, applied stereographic projection to convert between celestial coordinate systems and determine qibla direction (Charette, 2006). Mathematical instruments such as sine quadrants facilitated trigonometric function evaluation, supporting computational astronomy. This taxonomy demonstrates the

problem-driven nature of Islamic instrument design, where functional requirements dictated technical innovation (Mamat & Yusuff, 2025).

The Aleppo astronomer Ibn al-Sarrāj (early 14th century) devised semicircular and quadrant grids that could solve problems of spherical trigonometry (Charette, 2006). Ibn al-Shāṭir (1306–1375) created a universal astrolabe in which a grid of horizons rotates over a fixed stellar and ecliptic projection, and an astronomical compendium called *ṣundāq al-yawāqīt* for time-keeping at all latitudes and qibla determination (King, 2004). His most important contribution to the history of astronomy, however, was his planetary theory. In his *A Text of Final Inquiry in Amending the Elements*, the Ptolemaic eccentric deferent was eliminated completely and a second epicycle was introduced. Both the solar and lunar models are non-Ptolemaic, and what is of greatest interest is that the lunar theory is identical with that of Copernicus (1473–1543) except for trivial differences in parameters (Sarton, 1977). Ibn al-Shāṭir replaced Ptolemy's crank mechanism with a double-epicycle model which greatly improved the range of Earth-Moon distances while maintaining the longitudinal accuracy of the original model (Narayanan, 2013). There is no trace of the heliocentric concept in his treatise, but Ibn al-Shāṭir and Copernicus were compatible in their idea of utilizing only those celestial motions constructible by combination of uniform circular motions.

2.2 Observational Methods and Accuracy

Islamic astronomers achieved remarkable observational precision without telescopes. Al-Battānī's planetary observations achieved accuracies that Copernicus would cite centuries later (Saliba, 2007). The Marāgha observatory conducted systematic programmes of astronomical observation that generated corrected tables and constants. The precision of observations in the late Islamic period and the accuracy reached by the instruments constructed at Marāgha have been the subject of detailed scholarly analysis. According to a text written by Mu'ayyad al-Dīn al-'Urdī (d. 1266), one of the chief astronomers and instrument designers of the observatory, its astronomical equipment included a mural quadrant with a radius of about 40 metres, a solstitial armilla, an azimuth ring, a parallactic ruler (*triquetrum*), and an armillary sphere with a radius of about 160 cm (UNESCO Portal to the Heritage of Astronomy, n.d.). The central structure of the observatory is circular, with a diameter of 22 metres and a base of its enclosing wall 80 cm thick. A 1.5-metre-wide entrance opens into a 3.1-metre-wide corridor that marks the meridian line and contains the remains of the mural quadrant, of which 5.5 metres has survived. Outside the main building are five circular constructions where the smaller observational instruments were once mounted (Mozaffari, 2013).

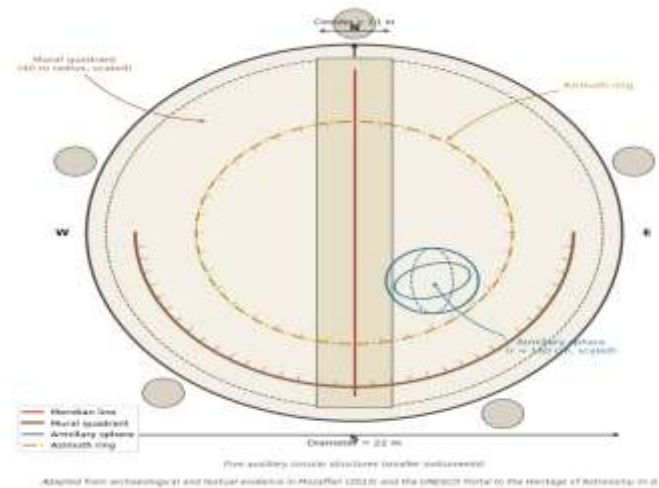


Figure 1. Schematic reconstruction of the Marāgha observatory's principal instruments.

Figure 1 illustrates the spatial arrangement of the mural quadrant, armillary sphere, and azimuth ring within the circular main building (diameter 22 m). The meridian line runs through the central corridor, with the mural quadrant embedded along its length. *Note: Adapted from archaeological and textual evidence presented in Mozaffari (2013).*

At Samarkand, Ulugh Beg's observatory (constructed 1424–1429) featured a giant sextant with a radius of 36–40 metres, embedded in a trench dug into a hill in the plane of the meridian (Nature, 2012). This instrument achieved arcminute-level scale divisions, with observational accuracy in practice reaching multi-arcminute levels. The observations carried out systematically from 1420 to 1437 resulted in a catalogue of 1018 fixed stars whose positions were largely determined through original observations (Sotheby's, 2019). Ulugh Beg's measurement of the tropical year—365 days, 6 hours, 10 minutes, and 8 seconds—represents an error of only 58 seconds compared to modern values. Using the sextant, astronomers at the observatory recalculated the positions of nearly 1,000 stars and compiled their results in the widely translated 1437 star catalogue *Zīj-i Sulṭānī*. The measurements were of unprecedented accuracy: the astronomers used them to recalculate trigonometric tables and to calculate the length of the sidereal year to within one minute of the measurement now accepted (Nature, 2012).

2.3 Knowledge Transmission

Islamic astronomy transmitted mathematical rigour, observational methods, and Arabic star names that remain in use today. The computational and observational techniques developed at Marāgha, Damascus, and Cairo were disseminated through both manuscript tradition and the circulation of instruments themselves. The Marāgha observatory pioneered a sustainable financial model by utilising endowments for ongoing expenses, setting a crucial precedent for future scientific institutions (Mokhtarzadeh, 2025). Tusi's creation of the *Zīj-i Īlkhānī* astronomical tables catalysed significant advancements in celestial studies across Asia, including China. The rich intellectual exchange between scholars in the Marāgha-Tabriz region and the University of Padua played a vital role in transmitting these ideas to Renaissance Europe (Mokhtarzadeh, 2025).

Table 2. Major Islamic observatories and their instrumental capabilities (9th–17th centuries)

Observatory	Date Founded	Patron	Principal Instruments	Radius/Aperture	Key Outputs
Baghdad (Shammāsiyya)	c. 830	al-Ma'mūn	Mural quadrant, armillary sphere	Not specified	<i>Zīj al-Ma'mūnī</i>
Marāgha	1259	Hūlāgū	Mural quadrant, armillary sphere, azimuth ring, triquetrum	40 m quadrant	<i>Zīj-i Īlkhānī</i>
Samarkand	1424	Ulugh Beg	Giant sextant, armillary sphere	36–40 m sextant	<i>Zīj-i Sulṭānī</i>

Istanbul (Tophāne)	1579	Murād III	Mural quadrant, azimuthally quadrant, astrolabe, armillary sphere, sextant	Not specified	Astronomical tables
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Source: Compiled from Mozaffari (2013), Mozaffari & Zotti (2013), and UNESCO Portal to the Heritage of Astronomy (n.d.).

Table 2 compares four major Islamic observatories across seven centuries, revealing a clear trajectory of instrumental scaling and institutional consolidation. The Baghdad observatory (c. 830), founded under al-Ma'mūn, established the prototype of state-patronised astronomical research, producing the *Zīj al-Ma'mūnī* (Saliba, 2007). The Marāgha observatory (1259) represents a quantum leap in precision instrumentation, with its 40-metre mural quadrant enabling unprecedented observational accuracy (Mozaffari, 2013). Samarkand (1424) under Ulugh Beg pushed scale further with a 36–40 metre sextant, yielding the *Zīj-i Sulṭānī* and a catalogue of 1,018 stars (Nature, 2012). The Istanbul observatory (1579) under Murād III consolidated diverse instruments but marked the tradition's twilight (Mozaffari & Zotti, 2013). This progression demonstrates the persistent correlation between patronage, instrumental scale, and scientific output in Islamic astronomy (Mokhtarzadeh, 2025).

On the eve of the Renaissance, Spain was the major interface between Muslim science and the rising European scientific activities. Many of the treatises written by Muslim scholars reached Europe via Spain, where they were translated into Latin. The astrolabe was re-introduced in the West through Spain in the 11th century. On the astrolabes of that period one finds typical sets of Arabic star names written in Gothic Latin letters, for example Vega, Altair, Rigel, and Alpheratz. Thus, as a result of the astrolabe tradition of Andalusian astronomy, most navigational stars today have Arabic names (Heydari-Malayeri, 2011). Copernicus knew of the results by Muslim scholars, and cites Battani as well as the Andalusians Zargālī and Ibn Rushd. He made use of the Tusi couple in his models in *De revolutionibus orbium coelestium*. There is growing consensus that Copernicus became aware of Tusi's result in some way, probably through Byzantine intermediaries, although an exact chain of transmission has not yet been identified (Heydari-Malayeri, 2011). In his *De revolutionibus* (1543), Copernicus explicitly referenced five Islamic astronomers, al-Battani, al-Zarqālī, Ibn Qurra, Ibn Rushd, and al-Bitruji, while also drawing upon the models of figures like al-Tūsī, al-'Urḍī, and al-Shāṭir, whose influence, though unmentioned by name, is evident in his work. Particularly, Book III of *De revolutionibus* is dedicated to the geometric models of planetary motion developed by Islamic scholars (Lee, 2024).

III. Research Methods

3.1 Present Phase: Contemporary Infrastructure and Research

a. Existing Observatories

Several Islamic countries have established significant astronomical observatories in recent decades, reflecting a renewed commitment to both scientific research and the practical requirements of Islamic astronomy (*falak*). The Kottamia Astronomical Observatory (KAO) in Egypt, established in 1964 as an extension of the historic Helwan Observatory (1903), houses the largest telescope in the Middle East and North Africa, a 74-inch (188 cm) reflector (National Research Institute of Astronomy and Geophysics). Located approximately 80 km from Cairo at an elevation of 450 metres, KAO benefits from around 250 clear nights annually and has contributed to major projects, including lunar surface observations for Apollo landing site selection. The observatory was upgraded over the past two decades with modern CCD cameras, spectrographs, and computerised control systems.

In Saudi Arabia, the Sharjah Academy for Astronomy, Space Sciences and Technology (SAASST) constructed the first solar radio spectrometer in the Middle East, operating since December 2021 with a bandwidth of 30 MHz (25.5–55.5 MHz) (Alrefay et al., 2022). This system enables advanced studies of solar radio emission and contributes to space weather awareness programmes (Alrefay et al., 2022). Educational radio telescopes optimised for hydrogen-line astronomy have also been replicated across five Saudi universities at a unit cost of under US\$2,500, integrating practical radio astronomy into undergraduate curricula (Alrefay et al., 2023).

In Malaysia, the Bintulu Falak Centre in Tanjung Batu, Sarawak, was officially opened in August 2025, marking a new chapter in Islamic astronomy and space science (Bernama, 2025). The centre occupies the former site of the Bintulu moon sighting station and is positioned as a science education hub, astronomical research reference centre, and science-spiritual tourism destination (Bernama, 2025). The Perak State Observatory in Manjung has received RM38.65 million (approximately US\$8.6 million) in allocated funding for construction across 94 hectares, designated as the state's official Islamic astronomy observation centre (The Borneo Post, 2024). This development complements the existing Tan Sri Harussani Observatory at INSTUN in Behrang, creating an integrated *falak* ecosystem (The Borneo Post, 2024).

In Morocco, the Oukaïmeden Observatory has emerged as a significant research facility, deploying the Single Star SCIDAR (SSS) instrument for real-time vertical profiling of atmospheric turbulence up to 22 km altitude (Habib et al., 2006). This instrument, designed for compatibility with small-aperture telescopes (~40 cm), addresses a critical gap in site characterisation for adaptive optics applications (Habib et al., 2006).

Table 3. Selected contemporary astronomical observatories and facilities in the Islamic world

Observatory/Facility	Country	Established	Principal Instrument	Aperture/Scale	Primary Function
Kottamia (KAO)	Egypt	1964	Reflector telescope	188 cm (74 in)	Research, lunar observation
Oukaïmeden	Morocco	—	Single Star SCIDAR	~40 cm	Turbulence profiling
Sharjah (SAASST)	UAE	2021	Solar radio spectrometer	30 MHz bandwidth	Solar radio astronomy

Bintulu Falak Centre	Malaysia	2025	Falak observation facilities	—	Falak, education, tourism
Perak State Observatory	Malaysia	2026 (planned)	Falak observation centre	94 hectares	Falak, public engagement

Sources: NRIAG (n.d.); Habib et al. (2006); Alrefay et al. (2022); Bernama (2025); The Borneo Post (2024).

Table 3 surveys five contemporary astronomical facilities across the Islamic world, revealing a dual trajectory of research capability and *falak* applications. Kottamia Observatory (Egypt, 1964) remains the region's largest optical facility, with its 188 cm reflector supporting research and lunar observation (NRIAG, n.d.). Oukaimeden (Morocco) exemplifies specialised instrumentation, deploying the Single Star SCIDAR for atmospheric turbulence profiling (Habib et al., 2006). Sharjah's SAASST (UAE, 2021) represents a new generation of solar radio astronomy capability (Alrefay et al., 2022). The two Malaysian entries, Bintulu Falak Centre (2025) and the planned Perak State Observatory, demonstrate the integration of Islamic astronomical practice with education and public engagement (Bernama, 2025; The Borneo Post, 2024). Collectively, these facilities illustrate a regional shift from purely observational functions toward diversified instrumentation and heritage-linked outreach.

3.2 Case Study: AlUla Manara

The most significant contemporary development in Islamic astronomical infrastructure is AlUla Manara, approved by the Royal Commission for AlUla (RCU) in June 2026. Located more than 70 kilometres north of AlUla in Saudi Arabia, between the Harrat Uwayrid Reserve and the Gharameel site, the location was selected for its exceptionally dark skies and low levels of light pollution (Royal Commission for AlUla, 2026). The facility will house a main telescope with a four-metre diameter mirror, alongside two additional two-metre telescopes, placing it among the largest observatories in the world (Royal Commission for AlUla, 2026).

The project includes a state-of-the-art observatory, a world-class research centre, observation platforms, interactive exhibitions, and educational facilities designed to expand public engagement with astronomy and space science (Royal Commission for AlUla, 2026). RCU is working in partnership with the Saudi Space Agency, King Abdulaziz City for Science and Technology (KACST), and the SETI Institute to position AlUla Manara as a centre for innovation and scientific advancement (Royal Commission for AlUla, 2026). The observatory's design draws inspiration from the surrounding desert landscape and celestial themes, with locally sourced sandstone to integrate the complex into AlUla's natural environment (Royal Commission for AlUla, 2026).

Table 4. Site characterisation parameters for AlUla Manara

Parameter	Value	Method	Source
Median nighttime seeing	1.5 arcsec	Differential Image Motion Monitor (DIMM)	Lombardi et al. (2024)
Median cold-season PWV	3.2 mm	ERA5 reanalysis	Lombardi et al. (2025)
Clear-sky fraction	>79% nighttime hours	Satellite and ground data	Lombardi et al. (2024)

Latitude/Longitude	~27°N, ~38°E (AlUla region)	Geodetic survey	Royal Commission for AlUla (2026)
Primary telescope aperture	4.0 m	Design specification	Royal Commission for AlUla (2026)

Sources: Lombardi, G., Fildes, G., Cuevas, O., Alrefay, T. Y., & Almalik, N. (2024). Preliminary characterization of the AlUla Manara astronomical site. *Proceedings of SPIE*, 13094, 130944K. <https://doi.org/10.1117/12.3017967>; Lombardi et al. (2025). Assessment of the AlUla Manara astronomical site using ECMWF ERA5 reanalysis data. *Journal of Astronomical Telescopes, Instruments, and Systems*, 11(3), 034005. <https://doi.org/10.1117/1.jatis.11.3.034005>

Table 4 consolidates the site characterisation parameters for AlUla Manara, demonstrating its suitability for a 4-m-class optical-infrared telescope. The median nighttime seeing of 1.5 arcsec, measured via Differential Image Motion Monitor, indicates atmospheric stability comparable to established world-class observatories (Lombardi et al., 2024). The median cold-season precipitable water vapour of 3.2 mm, derived from ERA5 reanalysis, confirms favourable infrared observing conditions (Lombardi et al., 2025). A clear-sky fraction exceeding 79% of nighttime hours provides ample observing time (Lombardi et al., 2024). The site's location at approximately 27°N, 38°E places it within a dark-sky region between the Harrat Uwayrid Reserve and Gharameel (Royal Commission for AlUla, 2026). The planned 4.0 m primary aperture positions AlUla Manara among the world's largest observatories (Royal Commission for AlUla, 2026).

Preliminary site characterisation indicates a median nighttime seeing of 1.5 arcsec, median cold-season precipitable water vapour (PWV) of 3.2 mm, and over 79% of nighttime hours with clear sky conditions (Lombardi et al., 2024). A separate assessment using ECMWF ERA5 reanalysis data evaluated the site's suitability for hosting a 4-m-class optical-infrared telescope, confirming its potential as a world-class observing location (Lombardi et al., 2025).

Figure 2 bar chart showing median seeing (arcsec) and clear-sky fraction (%) for AlUla Manara, Ward Mountain, and Dubba Mountain, based on ERA5 reanalysis and DIMM measurements. AlUla Manara presents a median seeing of 1.5 arcsec, while Ward Mountain and Dubba Mountain show higher values at their respective elevations. Data from Lombardi et al. (2025) and Lombardi et al. (2024).

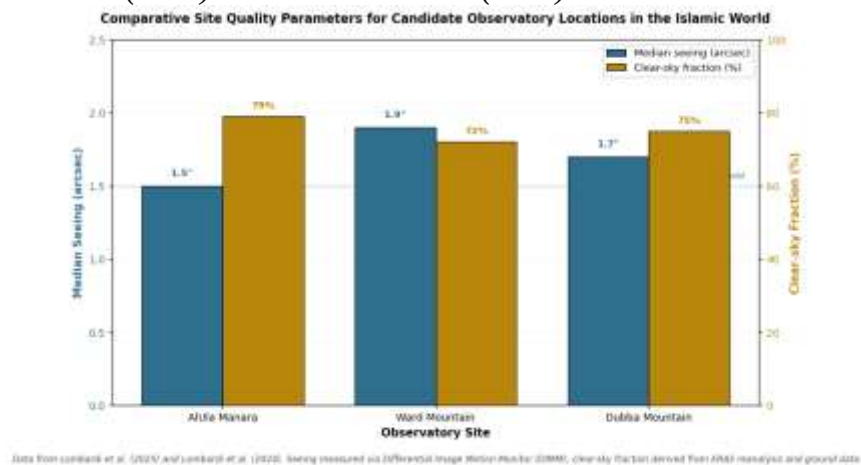


Figure 2. Comparative site quality parameters for candidate observatory locations in the Islamic world.

3.3 Regional Site Prospecting and Methodological Challenges

Beyond individual facilities, systematic efforts are underway to identify optimal observatory sites across the Middle East and North Africa (MENA) region. A comparative study using NCEP/NCAR reanalysis data evaluated astroclimatic parameters across MENA, identifying promising values for the Deriba site (coherence time of 8.77 ms) and the Aklim site (average seeing of 0.50 arcsec) (Hach et al., 2026). These analytical tools are crucial for large-scale site prospecting in the absence of in situ measurements (Hach et al., 2026).

Contemporary astronomical research in the Islamic world nonetheless faces several structural challenges. While some facilities are world-class, regional collaboration and data-sharing frameworks remain underdeveloped (Hach et al., 2026). The comparative analysis of the historical and contemporary periods reveals that the institutional models of the Golden Age—large-scale, state-funded observatories with integrated research programmes—offer instructive parallels for modern infrastructure planning (Saliba, 2007; Mozaffari, 2013). Historical observatories typically fell into two categories: those serving as educational institutions and those dedicated solely to astronomical observation (Mokhtarzadeh, 2025). Key factors contributing to the success of historical observatory development include rulers' support, intellectual dedication, and political stability (Mokhtarzadeh, 2025). These factors remain relevant for contemporary initiatives.

A further challenge concerns the integration of classical and modern instrumental traditions. The digital era has witnessed a significant leap in astronomical instrumentation, with traditional instruments largely replaced by software applications and digital devices (Mamat & Yusuff, 2025). While this transformation makes astronomy more inclusive and applicable, it also risks breaking the chain of historical knowledge if not balanced with the preservation of classical instruments and their working principles (Mamat & Yusuff, 2025). Bridging classical heritage and contemporary technology remains an urgent task for astronomical education and research in the Islamic world.

IV. Result and Discussion

4.1 Comparative Analysis: Historical Models and Contemporary Practice

a. Institutional Continuity

The Marāgha observatory represents a particularly instructive historical model. Established around 1259 CE under the patronage of Hūlāgū, it was not merely an observatory but a scientific institute with a main building for observational equipment, auxiliary buildings, accommodation quarters, and a library said to have contained about 400,000 volumes (Mokhtarzadeh, 2025; Cambridge University Press, 2018). A team of astronomers, most of them invited from different parts of the Islamic world, were responsible for the design and construction of astronomical instruments, as well as for conducting observations and performing calculations (Mozaffari, 2013). The observatory pioneered a sustainable financial model using endowments, integrated philosophical sciences with astronomy, and provided stipends to scholars (Mokhtarzadeh, 2025; İhsanoğlu, 2020).

These institutional features, state patronage, integrated research and education, international recruitment, sustainable funding, and instrument design and construction as core activities, reappear in the AIUla Manara project, albeit adapted to contemporary governance and funding structures (Royal Commission for AIUla, 2026). This continuity suggests that the organisational principles of Islamic mega-science are historically persistent.

Table 5. Comparative institutional features: Marāgha (1259) and AlUla Manara (2026)

Institutional Feature	Marāgha Observatory	AlUla Manara
Patronage	Hūlāgū (Ilkhanid court)	Royal Commission for AlUla (Saudi government)
Primary function	Research, education, instrument design	Research, astro-tourism, public engagement
Funding model	Waqf endowments	Government allocation + partnerships
International collaboration	Scholars from across Islamic world	SETI Institute, GRANTECAN, Saudi Space Agency
Instrument capability	40 m mural quadrant, armillary sphere	4 m primary telescope, 2 × 2 m telescopes
Knowledge output	<i>Zīj-i Īlkhānī</i>	LaserSETI installation, research data

Sources: Mokhtarzadeh (2025); Royal Commission for AlUla (2026); SETI Institute (2024).

Table 5 compares the institutional architectures of the Marāgha observatory (1259 CE) and AlUla Manara (2026 CE), revealing striking structural continuities across nearly eight centuries. Both institutions were established under state patronage, Hūlāgū's Ilkhanid court and the Royal Commission for AlUla, respectively (Mokhtarzadeh, 2025; Royal Commission for AlUla, 2026). The funding models differ in mechanism but converge in principle: Marāgha relied on waqf endowments for sustainability, while AlUla Manara combines government allocation with international partnerships (İhsanoğlu, 2020; SETI Institute, 2024). International collaboration characterises both: Marāgha recruited scholars from across the Islamic world, whereas AlUla Manara partners with the SETI Institute and GRANTECAN (Mokhtarzadeh, 2025; SETI Institute, 2024). Instrumental capability has scaled dramatically, from a 40 m mural quadrant to a 4 m telescope, yet the principle of precision instrumentation persists (Mozaffari, 2013). Knowledge outputs similarly evolved from the *Zīj-i Īlkhānī* to LaserSETI research data.

b. Instrumental Continuity

The instrumental tradition of Islamic astronomy exhibits a remarkable continuity of design principles. The astrolabe, the most iconic instrument of the classical period, was substantially reworked and improved by Muslim scientists between the 8th and 14th centuries (King, 2004; Charette, 2006). The principle of precision instrumentation, achieving the highest possible accuracy through careful design, large scale, and systematic calibration is evident in both the mural quadrant at Marāgha and the four-metre telescope planned for AlUla Manara (Mozaffari, 2013; Royal Commission for AlUla, 2026).

The historical emphasis on problem-driven instrumentation, designing instruments to solve specific astronomical problems, such as timekeeping, qibla determination, and planetary prediction, finds contemporary expression in the LaserSETI collaboration at AlUla Manara, which applies optical instrumentation to the search for extra-terrestrial intelligence (SETI Institute, 2024). LaserSETI monitors the sky for laser flashes that could indicate the presence of extra-terrestrial technology, representing a continuation of the Islamic astronomical tradition's engagement with fundamental questions about the universe (SETI Institute, 2024). The collaboration also includes SETI Institute support for data analysis systems, hardware and instrument development, and educational outreach, a

modern analogue of Marāgha's integrated research and teaching mission (SETI Institute, 2024).

Figure 3 shows the timeline plots major observatories (Baghdad, Marāgha, Samarkand, Istanbul, AIUla Manara) against key instrumental innovations (astrolabe refinement, universal astrolabe, giant sextant, four-metre telescope). The visualisation highlights the persistence of large-scale, state-patronised observatory construction across twelve centuries. *Data from Mozaffari (2013), Mokhtarzadeh (2025), and Royal Commission for AIUla (2026).*

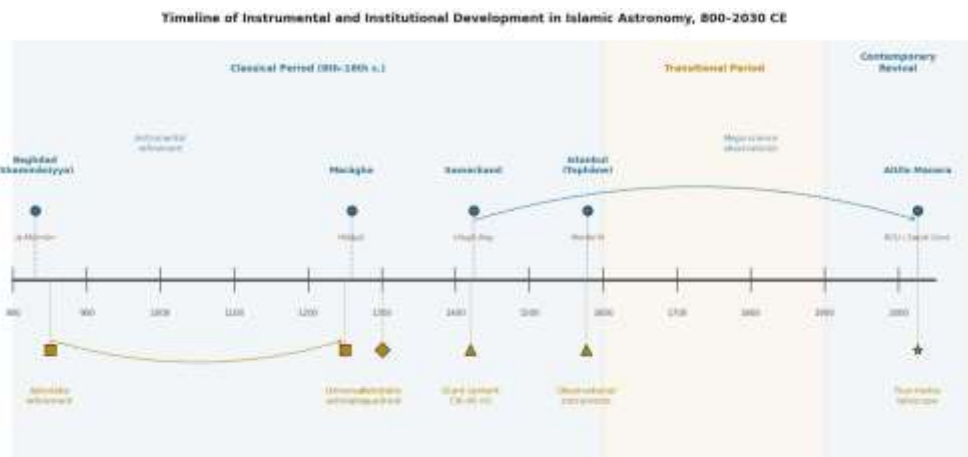


Figure 3. Timeline of instrumental and institutional development in Islamic astronomy, 800–2030 CE.

4.3 Knowledge Transmission Continuity

The transmission of astronomical knowledge from the Islamic world to Europe during the medieval period is well documented. The rich intellectual exchange between scholars in the Marāgha-Tabriz region and the University of Padua played a vital role in this scientific renaissance, with the Marāgha astronomers' theoretical frameworks laying groundwork for heliocentric models that later influenced European astronomers like Copernicus (Mokhtarzadeh, 2025). The mathematical tools developed at Marāgha, including the Tusi Couple and Urdu Lemma—are found in Copernicus's *De Revolutionibus*, and his model of the Moon's motion is mathematically identical to that of Ibn al-Shāṭir (fourteenth-century Damascus) (Mokhtarzadeh, 2025; Rose, 2017).

Less examined is the reverse transmission; the integration of contemporary international astronomical practices into the Islamic world's research infrastructure. The AIUla Manara project exemplifies this two-way exchange: it incorporates international expertise (SETI Institute, GRANTECAN) while positioning itself as a centre for regional scientific advancement (Royal Commission for AIUla, 2026; SETI Institute, 2024). The historical precedent for this model of international collaboration lies in the Marāgha observatory's recruitment of scholars from across the Islamic world, creating a multicultural hub for scientific exchange (Mokhtarzadeh, 2025).

Table 6. Knowledge transmission: Historical and contemporary patterns

Dimension	Classical Period (9th–15th c.)	Contemporary Period (21st c.)
Direction	Islamic world → Europe	International → Islamic world + regional
Mechanism	Manuscript translation, instrument circulation	Institutional partnerships, data sharing

Key agents	Toledo translators, Padua scholars	SETI Institute, GRANTECAN, Saudi Space Agency
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Sources: Rose (2017); Mokhtarzadeh (2025); SETI Institute (2024).

Table 6 contrasts knowledge transmission patterns between the classical and contemporary periods, revealing a reversal in directional flow alongside persistent mechanisms of exchange. During the classical period, transmission moved predominantly from the Islamic world to Europe through manuscript translation and instrument circulation, with Toledo translators and Padua scholars serving as key agents (Rose, 2017; Mokhtarzadeh, 2025). The outputs—*Almagest* translations and planetary models, directly shaped the European Renaissance (Saliba, 2007). In the contemporary period, the direction has inverted: international expertise now flows into the Islamic world and outward regionally through institutional partnerships and data sharing (SETI Institute, 2024; Royal Commission for AlUla, 2026). The key agents, SETI Institute, GRANTECAN, and the Saudi Space Agency—represent a new model of collaborative mega-science. Outputs have likewise diversified from textual translation to LaserSETI instrumentation, telescope technology, and educational capacity-building (SETI Institute, 2024).

4.4 Future Directions: A Research Agenda for Heritage-Informed Instrumentation

a. Regional Observatory Networks

The most promising pathway for advancing astronomical research in the Islamic world lies in the development of regional observatory networks. Historical precedent suggests that collaborative infrastructure, such as the Marāgha observatory's integration of observational, computational, and educational functions can serve as a model for modern consortia (Mozaffari & Zotti, 2013). A networked approach would enable resource-sharing for instrumentation, data archiving, and researcher mobility across countries that individually may lack the critical mass for certain research programmes. The contemporary resurgence of Islamic astronomy signals the potential for renewed contributions to astrophysics, provided it is supported by regional observatory networks and space-based research initiatives (Royal Commission for AlUla, 2026). The inclusion of three comparative sites, Volcanic Top, Ward Mountain, and Dubba Mountain, in recent site characterisation studies demonstrates the potential for multi-site assessments to inform national and regional infrastructure planning (Lombardi et al., 2025). These sites, located between 33 km and 218 km from AlUla Manara, exhibit favourable turbulence conditions that merit further investigation, though their availability for astronomical development remains uncertain due to archaeological and accessibility constraints (Lombardi et al., 2025).

b. Computational Reconstruction of Historical Instruments

A distinctive research direction proposed here is the application of computational methods to the design and reconstruction of historical Islamic instruments. The stereographic projection underlying astrolabe design can be modelled computationally to assess precision and identify the relationship between design parameters and observational accuracy. The anonymous Persian treatise *al-Risāla al-Ghāzāniyya fī 'l-ālāt al-raṣādiyya* ("Ghāzān's Treatise on the Observational Instruments"), which describes the structure, construction, and functions of twelve "new" observational instruments proposed during the reign of Ghāzān Khān, provides a substantial corpus for such analysis (Mozaffari & Zotti, 2013). Mathematical instrumentation in fourteenth-century Egypt and Syria, documented in richly illustrated Arabic treatises describing the construction of over 100 various astronomical instruments, offers further material for systematic digital reconstruction. This approach could be extended to the instruments described in Arabic manuscripts, many of

which remain unstudied. The large sextant at Samarkand, with its arc divisions where 70.2 cm represented one degree and marks only 1 mm apart represented five seconds, demonstrates the precision achievable through careful design and construction.

4.5 Heritage Science and Instrument Preservation

The preservation of astronomical heritage, both tangible (instruments, observatory remains) and intangible (manuscripts, observational records), requires integrated heritage-science approaches. Ulugh Beg's observatory in Samarkand, inscribed as part of the World Heritage Site Samarkand—Crossroads of Cultures in 2001, represents a model for the protection of astronomical heritage under UNESCO's highest level of cultural protection (UNESCO Portal to the Heritage of Astronomy, n.d.). The site comprises the remains of a meridian arc that originally formed part of the 15th-century observatory, with the colossal quadrant's white marble slabs containing incised Arabic symbols and numerals (UNESCO Portal to the Heritage of Astronomy, n.d.). Future research should develop standardised protocols for the documentation, conservation, and digital archiving of Islamic astronomical instruments and manuscripts, building on existing UNESCO frameworks and the AlUla Manara project's commitment to safeguarding dark skies as both natural and cultural heritage (Royal Commission for AlUla, 2026).

4.6 Education and Public Engagement

The historical connection between astronomy and Islamic religious practice; prayer times, qibla direction, and crescent moon observation, provides a unique framework for science education and public engagement. The AlUla Manara project exemplifies this integration through its inclusion of visitor and research centres, interactive exhibitions, and observation platforms designed for stargazing and contemplation (Royal Commission for AlUla, 2026). The project's alignment with Saudi Vision 2030 goals, including economic diversification, local job creation, and skills development, demonstrates how astronomical infrastructure can serve broader societal objectives (Lombardi et al., 2024). Future initiatives should build on this connection to create a pipeline from public engagement through university education to professional research, utilising smart applications, digital observatories, and visual media to explain the evolution of Islamic astronomical knowledge and its relationship with modern sciences.

Table 7. Research agenda for heritage-informed instrumentation in the Islamic world

Research Domain	Priority Actions	Expected Outcomes	Timeline
Regional networks	Develop data-sharing protocols; establish consortium governance	Integrated multi-site observing campaigns	2026–2030
Computational reconstruction	Digitise manuscript instrument descriptions; model stereographic projections	Validated design parameters; precision assessments	2026–2028
Heritage science	Standardise conservation protocols; create digital archives	Preserved instruments; accessible manuscript corpus	2026–2032
Education	Develop curriculum linking historical and modern astronomy	Trained workforce; public engagement	2026–2035

Space-based astronomy	Integrate ground and space facilities	Multi-wavelength capability	2030–2040
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Table 7 outlines a five-domain research agenda for heritage-informed instrumentation, sequenced across a fifteen-year horizon. The regional networks domain prioritises data-sharing protocols and consortium governance, targeting integrated multi-site observing campaigns by 2030 (Lombardi et al., 2025). Computational reconstruction—digitising manuscript instrument descriptions and modelling stereographic projections—offers the shortest timeline (2026–2028) and yields validated design parameters for historical astrolabes and quadrants (Mozaffari & Zotti, 2013). Heritage science focuses on conservation protocols and digital archives, preserving instruments and manuscript corpora through 2032 (UNESCO Portal to the Heritage of Astronomy, n.d.). Education builds curriculum bridges between historical and modern astronomy, producing a trained workforce by 2035. Space-based astronomy, the longest-term domain, integrates ground and space facilities for multi-wavelength capability by 2040 (Royal Commission for AlUla, 2026).

V. Conclusion

This comparative assessment has demonstrated that the astronomical tradition of the Islamic world is characterised by a continuity of instrumental and methodological principles that spans twelve centuries. The astrolabe, mural quadrant, and giant sextant of the classical period were not merely historical artifacts but expressions of a research paradigm that valued precision instrumentation, systematic observation, and problem-driven design. The AlUla Manara project, with its four-metre telescope and integrated research centre, represents a contemporary expression of this same paradigm, adapted to modern governance, international collaboration, and technological capability.

The historical record offers instructive lessons for contemporary practice. The Marāgha observatory's model of state patronage, integrated research and education, international recruitment, and sustainable endowment funding provides a template that remains relevant today. The Samarkand observatory's achievement of 58-second accuracy in tropical year measurement through a 40-metre sextant demonstrates that precision is a function of design and systematic method, not merely technological sophistication. These historical precedents suggest that the contemporary revival of astronomy in the Islamic world has deep roots and can draw on a rich institutional and instrumental heritage.

The research agenda proposed here, regional observatory networks, computational reconstruction of historical instruments, heritage-science protocols, integrated education, and space-based astronomy, offers a framework for realising this potential. The heritage of Islamic astronomy is not a static artifact to be commemorated but an active epistemological resource capable of informing contemporary scientific practice. By connecting the instruments of the past with the infrastructure of the future, the Islamic world can reclaim its historical role as a bridge between scientific traditions and a contributor to global astronomical knowledge.

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