The Jantar Mantar Observatories of Sawai Jai Singh II: An Engineering and Astronomical Survey of the Yantras at Jaipur, Delhi, Ujjain, Varanasi, and Mathura

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***Abstract*—Between approximately 1724 and 1738 CE, Maharaja Sawai Jai Singh II of Amber commissioned a network of five masonry astronomical observatories across northern India (at Jaipur, Delhi, Ujjain, Varanasi, and Mathura), each known as a *Jantar Mantar*. Substituting architectural scale for the optical and mechanical precision unavailable to his court, Jai Singh built naked-eye instruments tens of meters in radius that measured time, solar and stellar coordinates, and eclipse geometry with an angular precision competitive with contemporary European telescopic astronomy. This paper presents a systematic engineering and historical survey of every attested instrument (*yantra*) at all five sites. We first derive the horizon and equatorial coordinate systems and the spherical-trigonometric relations (the astronomical triangle, the equation of time, gnomon-shadow geometry) that govern every instrument's operation. We then treat each observatory in turn: Jaipur's nineteen-instrument complex, including the giant Vrihat Samrat Yantra sundial, the Jai Prakash and Kapala bowl instruments, the Ram and Chakra horizon instruments, and the twelve ecliptic-coordinate Rasivalaya dials found nowhere else; Delhi's four-instrument set, anchored by its own Samrat Yantra and the compound Misra Yantra, an instrument type unique to that site; Ujjain's smaller but historically significant complex, sited at the traditional Indian prime meridian of the classical *siddhānta* texts; Varanasi's observatory, built atop the pre-existing Man Mandir palace; and Mathura's observatory, of which no instrument or photograph survives, reconstructed here from eighteenth-century textual accounts alone. Throughout, we correct a number of instrument-attribution errors that recur in popular and tertiary sources; for example, the frequently repeated claim that the Misra Yantra, Kapala Yantra, or Rasivalaya instruments exist at multiple sites, when primary architectural surveys confirm each is unique to a single observatory. The paper closes with a comparative discussion of the shared instrumental repertoire and precision limits across the network, and an assessment of its place in the global history of positional astronomy.**

***Index Terms*—Jantar Mantar, Sawai Jai Singh II, archaeoastronomy, sundials, positional astronomy, spherical trigonometry, gnomon, celestial coordinate systems, history of astronomy, Mughal-era India.**

I. Introduction

Between approximately 1724 and 1738 CE, the Rajput ruler Maharaja Sawai Jai Singh II of Amber (r. 1699–1743), a Kachhwaha prince serving as a provincial governor under the Mughal emperors Aurangzeb, Farrukhsiyar, and Muhammad Shah, commissioned a network of five masonry astronomical observatories across northern India, each known locally as a *Jantar Mantar* (from the Sanskrit *yantra*, "instrument," and *mantra*, here used colloquially to mean "formula" or "calculation," though some scholars derive the compound directly from *yantra* alone) [28]. The five sites (Jaipur, Delhi, Ujjain, Varanasi, and Mathura) together constitute the largest and most architecturally ambitious program of naked-eye astronomical instrumentation ever built, predating the widespread adoption of the telescope for positional astronomy in India and substituting instrumental scale for the optical and mechanical precision unavailable to Jai Singh's court [13].

A. Historical Motivation

Jai Singh's stated purpose, recorded in the introduction to his own astronomical tables, the *Zij-i Muhammad Shahi* (compiled in the Persian–Islamic *zij* tradition and dedicated to the reigning Mughal emperor Muhammad Shah), was to correct persistent errors he had identified in existing planetary and eclipse tables then in circulation at the Mughal court: both the older Indian *siddhanta* tradition and the imported Ulugh Beg's *Zij-i Sultani* of Samarkand (compiled c. 1440s) [28]. Jai Singh reasoned that these errors stemmed from small, low-precision instruments whose reading uncertainty was fixed in absolute angular terms (a scribing or sighting error of a fraction of a millimeter translates to a larger angular error on a small-radius scale than on a large one). His solution was architectural: build instruments of masonry and marble at building-scale, some tens of meters in radius, so that the same absolute reading error would correspond to a far smaller angular error. This is the central engineering insight underlying every yantra discussed in this paper, and it is treated quantitatively in Section II.

B. The Five-Observatory Network

Jai Singh built observatories at Delhi (his first, begun c. 1724, in his role as a Mughal courtier resident in the imperial capital), Jaipur (in the new capital he founded and moved his court to in 1727), Ujjain (a city with deep significance in the Sanskrit astronomical tradition as the traditional prime meridian, or *madhya-rekha*, from which longitudes were reckoned in classical *siddhanta* texts), Varanasi (built atop the existing Man Mandir palace of Raja Man Singh of Amber, itself constructed around 1600), and Mathura (of which no instrument survives; see Section VII) [28]. The Jaipur and Delhi observatories are the largest and best preserved, and

Jaipur's complex, with nineteen distinct instruments, including several instrument types (the Kapala Yantra and the twelve Rasivalaya zodiacal instruments) found nowhere else, was designated a UNESCO World Heritage Site in 2010 [33].

C. Scope and Structure of This Paper

This paper surveys every attested instrument at all five Jantar Mantar sites, explains the astronomical and mathematical principle underlying each, and situates the network historically. Section II establishes the celestial coordinate systems and spherical-trigonometric relationships used throughout. Sections III–VII treat each site in turn. Section VIII compares instrument types and precision across sites, and Section IX offers a concluding assessment of the network's place in the history of astronomy. Throughout, we are careful to flag instrument attributions that are contested or frequently misreported in secondary and popular sources (for example, the Misra Yantra is unique to Delhi, and the Kapala and Rasivalaya instruments are unique to Jaipur, despite claims to the contrary that circulate in some tertiary sources), preferring the primary architectural surveys of Kaye [13] and the UNESCO nomination dossier [33] wherever popular accounts diverge from them.



Fig. 1. Maharaja Sawai Jai Singh II of Amber (r. 1699–1743), patron and designer of the five-observatory Jantar Mantar network, in a contemporary portrait, c. 1725 [6]. Public domain, British Museum collection.

II. Astronomical and Mathematical Preliminaries

The masonry instruments erected by Maharaja Sawai Jai Singh II at Delhi, Jaipur, Varanasi, Ujjain, and Mathura are, in essence, large-scale physical embodiments of the coordinate transformations and spherical-triangle relations that underlie positional astronomy. Before describing individual instruments (Sections III–VII), this section sets out the mathematical apparatus the instruments realize in stone, brass, and shadow: the horizon and equatorial coordinate systems, the astronomical triangle relating them, gnomon shadow geometry, the rationale for gigantic physical scale, the equation of time, and the ecliptic coordinate system used by the zodiacal (Rāśivalāya) instruments, following standard treatments of spherical astronomy [30], [18].

A. The horizon (altitude–azimuth) coordinate system

The most immediate frame for a ground-based observer is the horizon system, in which a celestial object is located by its altitude a (angular height above the horizon) and its azimuth A (angle along the horizon, conventionally from north through east, $0^\circ \le A < 360^\circ$). The complement of altitude is the zenith distance,

$$z = 90^\circ - a. \tag{1}$$

The horizon system is observer-centered and time-dependent: Earth's rotation carries (a, A) for a fixed star through a diurnal circle. It is nonetheless the *natural* system for any instrument reading angles directly against a plumb line and graduated horizontal circle, exactly how the Digamsa Yantra and meridian (Dakshinovritti) walls are constructed: the Digamsa reads A directly from a graduated horizontal rim, while a meridian wall restricted to the local meridian plane reads a (or z) at culmination, when $A = 0^\circ$ or 180°.

B. The equatorial (hour-angle, declination) coordinate system

Because the horizon system depends on both observer location and time, positional astronomy relies more heavily on the equatorial system, defined relative to the celestial equator (Earth's equatorial plane projected onto the sky) and the celestial poles. Declination δ is angular distance north $(+)$ or south $(-)$ of the celestial equator, analogous to terrestrial latitude, while hour angle H is the angle, measured westward along the equator from the local meridian to the object's hour circle (the great circle through the object and both celestial poles):

$$H = \mathrm{LST} - \alpha, \tag{2}$$

where LST is local sidereal time and α the object's right ascension. Because the equatorial frame rotates rigidly with the sky, δ is constant for a fixed star through the night, while H increases uniformly at 15° per sidereal hour. This uniform rate is what makes an equatorially mounted dial (graduated face in the equatorial plane, gnomon or axis parallel to Earth's rotation axis) read time linearly, unlike a horizontal or vertical sundial, for which shadow direction is a nonlinear (tangent-type) function of H.

The relationship between the two frames is fixed by the observer's latitude φ: the celestial pole appears at altitude

$$a_{\mathrm{pole}} = \varphi, \tag{3}$$

the fact exploited by every polar-axis instrument at Jai Singh's observatories: a gnomon edge or armillary axis inclined at

angle φ in the meridian plane points at the celestial pole and is parallel to Earth's axis. The Samrat Yantra's triangular gnomon, hypotenuse inclined at the local latitude, is the paradigmatic example, with flanking quadrants lying in the plane of the equator.

C. The astronomical triangle

The two coordinate systems, together with the observer's meridian, define a spherical triangle (the "astronomical triangle") with vertices at the celestial pole P, the zenith Z, and the observed object X. The side PZ has length $90^\circ - \varphi$ (the pole-to-zenith arc, i.e., co-latitude); the side PX has length $90^\circ - \delta$ (co-declination); and the side ZX has length $90^\circ - a = z$ (co-altitude). The angle at P is the hour angle H, and the angle at Z is $360^\circ - A$ (or, with a suitable sign/measurement convention, A itself). Applying the spherical law of cosines to side ZX,

$$\cos z = \cos(90^\circ - \varphi)\cos(90^\circ - \delta) + \sin(90^\circ - \varphi)\sin(90^\circ - \delta)\cos H, \tag{4}$$

and using $\cos(90^\circ - x) = \sin x$, $\sin(90^\circ - x) = \cos x$, together with $\cos z = \sin a$, Equation (4) reduces to the central relation of spherical astronomy:

$$\sin a = \sin\varphi \sin\delta + \cos\varphi \cos\delta \cos H. \tag{5}$$

A companion relation, obtained by applying the four-parts (cotangent) formula or an analogous law-of-cosines step to solve for azimuth, gives

$$\sin A = -\frac{\cos\delta \sin H}{\cos a}, \qquad \cos A = \frac{\sin\delta - \sin\varphi \sin a}{\cos\varphi \cos a}, \tag{6}$$

(conventions vary by source; here A is measured from north through east). Equations (5)–(6) bridge the horizon quantities (a, A) that an instrument like the Digamsa or a meridian wall measures directly, and the equatorial quantities (H, δ), of lasting astronomical value. Every masonry instrument can be classified by which two of the five quantities $(a, A, H, \delta, \varphi)$ it reads directly, with the triangle supplying the rest by calculation [30].

A key special case is transit at the meridian, where $H = 0$ and Equation (5) collapses to

$$a_{\max} = 90^\circ - |\varphi - \delta|, \tag{7}$$

the relation exploited by every meridian (Dakshinovritti/Bhitti) wall: a single noon (or culmination) altitude reading, combined with a known φ, yields δ directly, or with a known δ (e.g., of the Sun on a solstice) yields φ or the obliquity of the ecliptic.

D. Gnomon shadow geometry and the rationale for giant scale

The simplest realization of Equation (5) is a vertical gnomon of height h casting a shadow of length ℓ. Elementary right-triangle geometry gives

$$\ell = \frac{h}{\tan a}, \tag{8}$$

so the solar altitude follows from a shadow-length measurement as $a = \arctan(h/\ell)$. For an equatorially aligned gnomon (edge tilted at latitude φ, parallel to Earth's axis, as in the Samrat Yantra), the shadow falls on a quadrant in the equatorial plane, and the governing relation becomes linear in hour angle: 15° of arc per hour of H, while displacement of the shadow tip along the gnomon gives $\tan\delta = y/R$, R being the quadrant radius (Section VI develops this for the Varanasi Samrat).

The central engineering insight of Jai Singh's program follows from the fact that an arc length subtending a fixed angular resolution scales with radius. If a graduated scale can be read to fixed linear precision ε (set by masonry tolerance, engraving width, or shadow-edge width), the angular resolution obtainable is

$$\delta a \;\approx\; \frac{\varepsilon}{R}\,[\text{rad}] \;=\; \frac{\varepsilon}{R} \cdot \frac{180}{\pi} \cdot 3600\ [\text{arcsec}], \tag{9}$$

where R is the effective radius of the graduated arc. Equation (9) shows that for *fixed* tolerance ε (masonry, brass inlay, and hand-graduation could not be made much finer regardless of budget), angular precision improves only by increasing R. This is why Jai Singh built instruments with gnomon heights and quadrant radii of many meters (the Jaipur Samrat gnomon rises some 22.6 m, with quadrant radii around 15 m) rather than finely dividing small brass instruments. Taking $\varepsilon \sim$ 1–2 mm and $R \sim$ 10–15 m, Equation (9) yields $\delta a \sim (1\text{–}2) \times 10^{-4}$ rad, i.e., a few tens of arcseconds to a few arcminutes, consistent with the working precision attributed to the best of these instruments, trading mechanical sophistication for sheer physical size.

E. Equation of time: apparent versus mean solar time

Every gnomon or shadow-based instrument reads *apparent* solar time, fixed by the true Sun's hour angle, $\text{apparent solar time} = H_\odot + 12^\text{h}$. Civil (mean) time is instead kept by a fictitious mean Sun moving uniformly along the equator at the average rate of the true Sun's annual ecliptic motion. The two differ by the equation of time,

$$E = \text{apparent solar time} - \text{mean solar time}, \tag{10}$$

which reaches extrema of roughly ± 16 minutes over the year. E arises from two effects Kaye's commentary on the Varanasi Samrat explicitly recognizes: (1) orbital eccentricity, which makes the Sun's apparent motion along the ecliptic non-uniform (faster near January perihelion, slower near July aphelion), and (2) obliquity, which makes even uniform ecliptic motion project non-uniformly onto the equator, since equal longitude arcs near the solstices correspond to smaller right-ascension arcs than near the equinoxes. A convenient first-order decomposition, following Meeus, is

$$E \approx E_{\text{obliquity}}(\lambda_\odot) + E_{\text{eccentricity}}(M), \tag{11}$$

where $\lambda_\odot$ is the Sun's ecliptic longitude and M its mean anomaly [18]. Converting a sundial reading to civil time thus requires two corrections: E from Equation (10), and a longitude correction $\Delta t_\lambda = (\lambda_\text{ref} - \lambda_\text{obs})/15^\circ$ per hour between the observatory's meridian and the time zone's reference meridian.

F. The ecliptic coordinate system and obliquity

The Sun's annual path and the zodiacal constellations are most naturally described in the ecliptic coordinate system: celestial longitude λ, measured eastward along the ecliptic from the vernal equinox, and ecliptic latitude β, perpendicular to the ecliptic plane. This is the frame realized by the Rāśivalāya (zodiacal) instruments, twelve latitude-specific dials, each dedicated to one zodiacal sign and equivalent to an equatorial instrument re-oriented to that sign's portion of the ecliptic. The ecliptic is inclined to the equator by the obliquity $\varepsilon_{\rm obl} \approx 23.4^\circ$, and the transformation between ecliptic (λ, β) and equatorial (α, δ) coordinates is

$$\sin\delta = \sin\beta\cos\varepsilon_{\rm obl} + \cos\beta\sin\varepsilon_{\rm obl}\sin\lambda, \tag{12}$$

$$\tan\alpha = \frac{\sin\lambda\cos\varepsilon_{\rm obl} - \tan\beta\sin\varepsilon_{\rm obl}}{\cos\lambda}. \tag{13}$$

For a body on the ecliptic itself ($\beta = 0$, true of the Sun), Equation (12) simplifies to $\sin\delta = \sin\varepsilon_{\rm obl}\sin\lambda$, the relation underlying meridian-wall determination of $\varepsilon_{\rm obl}$: measuring the Sun's meridian altitude at both solstices ($\lambda = 90^\circ, 270^\circ$, where $\delta = \pm\varepsilon_{\rm obl}$) via Equation (7) and differencing isolates $2\varepsilon_{\rm obl}$ independent of latitude [30], [18].

Together, Equations (5)–(13) constitute the trigonometric toolkit for every instrument discussed in this paper: horizon instruments (Digamsa, meridian walls), equatorial instruments (Samrat, Chakra, Nadivalaya), and ecliptic instruments (Rāśivalāya): all, in the end, large stone-and-brass machines for mechanically solving the astronomical triangle.

III. The Jaipur Observatory (Yantra Mandir)

The Jantar Mantar at Jaipur, sited at latitude $\phi \approx 26^\circ55'29''$ N, longitude $75^\circ49'28''$ E, elevation 440 m, is the largest and best preserved of the five observatories built under Maharaja Sawai Jai Singh II, with construction beginning around 1718 and continuing until approximately 1734–1738 [33], [34], [5]. The site was inscribed on the UNESCO World Heritage List in 2010 under cultural criteria (iii) and (iv), and is described there as "the most significant, most comprehensive, and the best preserved of India's historic observatories" [34]. The nomination dossier enumerates 19 distinguishable structures which, because the Ram Yantras and Sasthamsa Yantra are complementary or composite instruments, correspond to 35 individual observational elements [33]. Every one of the three classical astronomical coordinate systems is physically instantiated somewhere on the site: the horizon (altitude–azimuth) system, the equatorial (hour-angle–declination) system, and the ecliptic (celestial latitude–longitude) system, with the Kapala Yantra uniquely able to perform a direct graphical transformation between the horizon and equatorial frames [5]. This section surveys all nineteen numbered entries of the observatory, following the taxonomy and dimensional data of the UNESCO nomination dossier [33], G. R. Kaye's 1918 Archaeological Survey monograph [13], N. Rathnasree's pedagogical analysis of the instruments [26], and the Cornell *jantarmantar.org* instrument pages archived by B. Perlus [23].

Throughout, we use the standard local astronomical relations for horizon and equatorial coordinates developed in Section II: for an observer at geographic latitude ϕ, a celestial object of declination δ and hour angle H (measured westward from the local meridian) has altitude h and azimuth A related by the spherical-astronomy identities of Eqs. (5)–(6), and at upper meridian transit ($H = 0$) altitude reduces to the simple linear form of Eq. (7),

$$z = \phi - \delta,$$

where $z = 90^\circ - h$ is the zenith distance. Hour angle converts to solar/sidereal time via $H = 15^\circ \times t_h$, where t_h is elapsed hours since transit.

A. Vrihat (Brihat) Samrat Yantra, "Great Supreme Instrument"

Samrat means "supreme ruler"; Kaye records it as, "as its name implies, the most important" of the Jaipur instruments [13], commonly rendered "the great king of instruments" [37]. The instrument rises from a rectangular excavation of $44.15\ \text{m} \times 40.3\ \text{m}$, 3.5 m deep. Its gnomon is a triangular masonry wall 2.85 m wide and 22.62 m high, with a 44.58 m base and a 50.09 m hypotenuse pierced with pointed-arch openings and an internal stair leading to a *chhatri* pavilion at the apex; two flanking quadrants of radius 15.15 ± 0.01 m, 2.84 m wide, complete the instrument, with a network of water channels at the base originally used to level the scales [33]. Kaye's 1918 survey gives "nearly 90 feet high and 147 feet long, the radius of each quadrant being 49 feet 10 inches" (≈ 27.4 m, ≈ 44.8 m, ≈ 15.19 m) [13].

The Samrat Yantra is an equinoctial (equatorial) sundial: "a triangular gnomon with the hypotenuse parallel to the earth's axis, and on either side of the gnomon is a quadrant of a circle parallel to the plane of the equator" [13]. The gnomon's inclination angle from the horizontal is fixed by construction to equal the local latitude,

$$\alpha_{\rm gnomon} = \phi, \tag{14}$$

which makes the hypotenuse parallel to the Earth's rotation axis and the quadrant faces coincide with the equatorial plane. Because the quadrants lie in the equatorial plane, the shadow of the gnomon's edge sweeps them at the uniform sidereal/solar rate of the hour angle,

$$\begin{aligned} s &= R\,H_{\rm rad}, \\ H_{\rm rad} &= \frac{\pi}{12}\,t_h, \end{aligned} \tag{15}$$

where s is arc length along the quadrant of radius $R = 15.15$ m and t_h is hours from local apparent noon. Differentiating, the shadow tip moves at $ds/dt \approx 1.1$ mm per second of time, matching the oft-cited figure of roughly 1 mm s^{-1}, or about 6 cm per minute [37]. Declination is read from a tangent scale engraved along the gnomon's polar-parallel edge: if M is the shadow point's perpendicular offset from the quadrant plane and $GH = R$ the quadrant radius, Kaye's construction gives

$$\tan\delta = \frac{MH}{GH}, \tag{16}$$

attributing the tangent-scale device to Jai Singh's own innovation, noting "there is, so far, no evidence to show that the tangent scales on the edge of the gnomon had been previously used" [13]. Because a 90° quadrant spans six hours (6 a.m. to noon), each quadrant edge is co-graduated in both angular degrees and clock time. Converting the dial's local apparent solar time to civil (zone) time requires the equation of time (arising from orbital eccentricity and axial obliquity) together with a fixed longitude correction relative to the applicable standard meridian (82.5° E for Indian Standard Time) [23], [26], [13].

The dossier states the instrument nominally resolves time to ± 2–3 s [33], [5], and Rathnasree reports a 2006 calibrated observation at the sister Delhi instrument approaching one-second accuracy, while cautioning that the calibration procedure "would have washed out any intrinsic vagaries of the instrument" [26]. Kaye was more skeptical, noting the readings are "impossible in practice, owing to the ill-defined shadow" (penumbra), with the two quadrants differing by roughly two minutes [13]; modern commentary notes the solar penumbra can reach 30 mm, dwarfing the 1 mm graduation interval [37]. The structure, planned around 1732 and completed around 1735, has undergone repeated restoration (1901–02, 1945 marble resurfacing, post-1969 sandstone relining, 2007 lime plastering) and is claimed to be the largest equinoctial sundial in the world [33].

B. Laghu Samrat Yantra, "Small Supreme Instrument"

The Laghu Samrat Yantra is a smaller equatorial sundial comprising two gnomon walls of unequal height joined back to back. The triangular meridian wall is 1.29 m wide, 6.9 m tall, 19.75 m long at its base; the south-facing gnomon edge is 14.725 ± 0.005 m long, inclined $27^\circ 30'$ from horizontal (matching Jaipur's latitude per Eq. (14)), while the smaller north-facing gnomon is 8.58 m long at 41°, serving the northern-sky quadrant. Flanking quadrants have radius 2.780 m and are 98 cm wide [33]. It is built of quartzite cladding with iron-hydroxide pigment and marble scales, gnomon engravings filled with lead [33].

Functioning by the identical geometric principle as the Vrihat Samrat Yantra (Eqs. (14)–(16)), it measures apparent solar time, meridian transit time, zenith distance, noon latitude, and declination [33]. Its smallest scale division is 20 arcseconds of time [33], [26], and it carries a "High" precision rating in the dossier's classification [33], in part because at shorter gnomon-to-scale distances the solar penumbra subtends a proportionally smaller fraction of the scale, reducing reading error relative to the larger Samrat [26]. Its field of view toward the northern sky is restricted by the neighboring City Palace [33]. Construction attribution is disputed between Jai Singh II and a later restoration credited to Maharaja Ram Singh [33]; notably Jaipur possesses *two* Samrat-type instruments, unlike other Jantar Mantar sites [26]. The daily equation-of-time correction factor for converting dial reading to civil time is posted publicly beside this instrument [26].



Fig. 2. The Vrihat Samrat Yantra at the Jaipur observatory, the giant equinoctial sundial whose triangular gnomon is inclined at the local latitude and whose flanking quadrants lie in the plane of the celestial equator [13]. *Photo credit: Sudipta Maulik, CC BY-SA 4.0, via Wikimedia Commons (https://commons.wikimedia.org/wiki/File: Doors_of_Jantar_Mantar.jpg).*



Fig. 3. The Laghu Samrat Yantra, a smaller equatorial sundial of identical geometric principle to the Vrihat Samrat Yantra, with its south gnomon inclined $27^\circ 30'$ to match the Jaipur latitude [33].

Photo credit: Jakub Hałun, CC BY-SA 4.0, via Wikimedia Commons (https://commons.wikimedia.org/wiki/File: 20191218_Jantar_Mantar,_Jaipur_0906_8983_DxO.jpg).

C. Sasthamsa Yantra, "Sixty-Degree (Sextant) Instrument"

The Sasthamsa Yantra is a set of four independent meridian dials built as dark chambers flanking the Vrihat Samrat Yantra, against whose quadrant supports they abut. Each chamber holds two 60° graduated arcs of radius approximately 8.64 m (Kaye's "28 feet 4 inches") set into the east and west walls, with a pinhole aperture 9 m above the scale's southern end [33], [13]. It is a camera-obscura meridian instrument: sunlight entering the pinhole projects a real solar image onto the graduated arc lying in the meridian plane, so the image's position along the arc directly registers the Sun's meridian zenith distance z. Since $z = \phi - \delta$ (Eq. (7)), the co-graduated declination scale (spanning $\pm 23^\circ 30'$) is simply the zenith-distance scale offset by the site latitude,

$$\delta = \phi - z. \tag{17}$$

Because the pinhole projects a real image whose angular size equals the Sun's apparent diameter, the linear extent of the image on the arc also yields the solar diameter [37]. The dossier rates this instrument "High" precision, while Kaye estimated readings accurate to about 4 arcminutes [33], [13]. Built together with the Vrihat Samrat Yantra, its scale surface was originally lime plaster, later resurfaced in marble, with pointed arches on the eastern chamber restored in 2007 after having been bricked up [33]. Kaye notes this instrument type occurs "at Delhi and Jaipur only" [13]. No image of the Sasthamsa Yantra is available in this study's image set; the reader is referred to the descriptions above.

D. Jai Prakash Yantra, "Light of Jai"

The Jai Prakash Yantra consists of two complementary hemispherical concave bowls, 5.44 m in diameter, set into a platform $20.5\ \mathrm{m} \times 11.22$ m, partly below grade [33]. Each bowl's concave surface is divided into engraved and open (walkway) sectors; the second bowl exactly complements the first, so that superimposing the two engraved surfaces would reconstruct one continuous hemispherical map [33]. Kaye gives the Jaipur bowl diameter as 17 ft 10 in versus 27 ft 5 in at Delhi [13].

The instrument is a direct, undistorted angular map of the sky, obtained by point-inversion through the bowl's centre: a celestial object at horizon coordinates (A, h) casts (or is sighted along) a line through the centre that strikes the bowl surface at the antipodal point $(A + 180^\circ, -h)$ [derived from the construction reported in [13], [26]]. Because this is a pure central projection rather than a distorting map projection, angles measured on the bowl equal angles on the sky. Both a horizon graticule (concentric altitude circles about the bowl's nadir point, radial azimuth lines) and an equatorial graticule can be inscribed on the same surface: Kaye records the pole point P placed on the meridian line at an angular distance from the bowl's rim point equal to the latitude,

$$\widehat{BP} = \phi, \tag{18}$$



Fig. 4. The Jai Prakash Yantra, a complementary pair of concave hemispherical bowls that map the celestial sphere by point-inversion, allowing simultaneous horizon and equatorial coordinate readings [13].

Photo credit: Marcin Białek, CC BY-SA 3.0, via Wikimedia Commons (https://commons.wikimedia.org/wiki/File: Jai_Prakash_Yantra_Jaipur_2011.JPG).

with the celestial equator crossing the meridian at $\widehat{BK} = \phi$ and the tropics offset by $\pm\varepsilon \approx 23^\circ 30'$ [13]. A cross-wire stretched north–south and east–west over the rim casts a shadow whose intersection point directly indicates the Sun's simultaneous horizon and equatorial coordinates, effectively performing the coordinate transformation of Eqs. (5)–(6) mechanically rather than by calculation [13], [26]. Night observations use the open sectors, sighting a star through the crosswire intersection with the eye placed at the bowl surface [26].

The complementary-pair design, in which an observer walks between the two bowls as a shadow or sightline crosses a sector boundary, is attributed to Jai Singh personally and is regarded by Kaye, citing Hunter, as one of the instrument types "peculiar to Jai Singh's observatories," alongside the Samrat and Ram Yantras [13]. Rated "Medium" precision [33], with systematic altitude errors observed at the Delhi analogue attributed possibly to departures from ideal sphericity in the masonry [26]. Constructed under Jai Singh II before 1743; extensively restored in marble in 1901–02 [33], [13].

E. Kapala Yantra, "Bowl Instrument"

The Kapala Yantra exists only at the Jaipur observatory and is not replicated at any of the other four Jantar Mantar sites [13], [33]. It comprises two hemispherical concave bowls, each about 3.5 m in diameter, mounted on a shared east–west platform, with cross-wires formerly stretched between rim points (later replaced by a small perforated plate) [33], [13]. The two bowls are functionally distinct: the western bowl measures the Sun's coordinates in both the horizon and equatorial systems and gives local time, while the eastern bowl is dedicated purely to graphically transforming coordinates between the horizon and equatorial systems for the Jaipur latitude, eliminating the need for spherical-trigonometric calculation [33], [5].

Geometrically the Kapala is a Jai Prakash-type hemisphere whose rim plane has been re-referenced: instead of represent-

ing the horizon, the rim of the second (eastern) bowl represents the solstitial colure, the great circle through both celestial poles and the solstice points, so that the same engraved graticule reads "rising signs" rather than meridian-transit signs, i.e., the instrument is "the Jai Prakas turned through a right angle" [13]. Rotating the reference rim from the horizon frame to the pole/solstice frame allows a single physical point on the bowl to be read simultaneously in both coordinate systems [derived from Kaye's construction, [13]], which is the mechanism underlying UNESCO's description of it as the site's unique dual-system, coordinate-transforming instrument [5]. It carries "Medium" precision rating [33] and shares a combined platform with the Chakra Yantra [33]. Kaye lists it among instruments possibly later than Jai Singh's original programme, since it is absent from contemporary instrument lists [13].

A nomenclature caution is warranted here: some secondary compilations (e.g., certain Wikipedia editions) list a separate "Kanali Yantra" alongside the Kapala/Kapali Yantra, but this name does not appear in the UNESCO nomination dossier's 19-item inventory nor in Kaye's 1918 survey, and should be treated as an unverified variant spelling of *Kapali/Kapala* rather than as an independently attested instrument [33], [13].

F. Great Ram Yantra

The Ram Yantra is traditionally said to be named for Ram Singh, a predecessor of Jai Singh, and was also known by the Arabic-derived name *Ustuwani*, after an orthographic-cylindrical astrolabe devised by al-Bīrūnī [13]. At Jaipur it comprises two complementary open-topped cylindrical drums, each 4.48 m tall with an internal diameter of 6.95 m, with radial sectors cut into both the vertical wall and the horizontal floor (the latter beginning 1.12 m above the base); each drum bears a central vertical pillar of the same height as the drum wall [33]. At Jaipur the sectors number 12, alternating between 12° and 18° widths between the two complementary drums, unlike the 30 sectors of 6° each found at Delhi [13].

Kaye records the defining geometric constraint: "the height of the wall from the graduated floor is equal to the distance from the circumference of the central pillar to the inside of the wall" [13], i.e., wall height equals drum radius R. The instrument is a physical gnomonic projection centered on the pillar top O: for an object of altitude h observed by aligning the pillar top with the object, the sighting ray from O strikes the vertical wall at a height y below the pillar top when $h < 45^\circ$, and the floor at radial distance r from the axis when $h > 45^\circ$:

$$y = R\tan h \quad (h < 45^\circ), \qquad r = R\cot h \quad (h > 45^\circ), \tag{19}$$

with azimuth read directly as the polar angle of the strike point from north. Because $dr/dh \to 0$ as $h \to 90^\circ$, the scale compresses near the pillar base, so the design places the region of finest resolution ($\pm 1'$ of arc, per Perlus) exactly at the floor–wall junction, $h = 45^\circ$, where wall height equals



Fig. 5. The Ram Yantra, a pair of complementary open cylindrical drums realizing a gnomonic altitude–azimuth projection about a central pillar of height equal to the drum radius [13].
Photo credit: Daniel Villafruela, CC BY-SA 3.0, via Wikimedia Commons (https://commons.wikimedia.org/wiki/File:Jaipur-Jantar_Mantar-Ram_Yantra-20131016.jpg).

radius [23]. Rathnasree records the practical working formula for uncalibrated readings as

$$h = \tan^{-1}\left(\frac{\ell_{\text{gnomon}}}{d_{\text{shadow}}}\right), \tag{20}$$

where ℓ_{gnomon} is the pillar height and d_{shadow} the horizontal distance from the pillar to the shadow edge [26]. As with the Jai Prakash, the sectoring necessitates paired complementary drums so an observer can move continuously between open (walkway) sectors as the shadow or sightline crosses sector boundaries, with notches provided for horizontal sighting bars [13]. Rated "Medium" precision [33]; an empirical calibration at the Delhi sister instrument found roughly 0.1° achievable accuracy against an original nominal least count of 1° [26]. The current stone structure dates to an 1891 rebuilding under Maharaja Madho Singh II, replacing an earlier lime-plaster original from before 1743; Ram Yantras were built only at Jaipur and Delhi [33], [23], [13].

G. Small Ram Yantras

A second, smaller complementary pair of Ram Yantras exists at Jaipur, sharing the identical geometric principle of Eqs. (19)–(20) but with radius 0.865 m, one-quarter that of the Great Ram Yantra [33]. They may have served as construction models for the larger pair, though they are absent from Kaye's 1918 site plan [33]; their date of construction is unknown, possibly contemporaneous with Jai Singh II or dating from the 1891 rebuilding of the larger drums [33]. Function and precision rating ("Medium") match the Great Ram Yantra [33].

H. Digamsa Yantra, "Azimuth Instrument"

The Digamsa Yantra consists of a 0.96 m-high central pillar (1.04 m diameter) surrounded by two coaxial graduated walls, an inner wall of the same 0.96 m height and an outer wall 1.95 m high, with cardinal-point passageways and cross-wires stretched over the outer wall [33]. Jagannath's own



Fig. 6. The Digamsa Yantra, a triple concentric-wall azimuth instrument in which a taut plumbed cord reads the bearing of a celestial object directly from a graduated horizon-plane scale [13].
Photo credit: Maharajsaran, CC BY-SA 3.0, via Wikimedia Commons (https://commons.wikimedia.org/wiki/File:S-RJ-92-JYOTISH_YANTRALAYA-JAIPUR_14.JPG).



Fig. 7. The Nadivalaya Yantra, twin equatorial sundial discs whose polar-aligned styles yield a shadow position angle equal to the solar hour angle with no seasonal distortion [13].
Photo credit: Jakub Hałun, CC BY-SA 4.0, via Wikimedia Commons (https://commons.wikimedia.org/wiki/File:Nadivalaya_Yantra,_Jantar_Mantar,_Jaipur,_20191218_0925_9021.jpg).

construction rules, preserved by Kaye, specify three concentric horizon circles: a central solid pillar, a first ring wall as high as the pillar, and an outer ring wall twice that height, all graduated in degrees and minutes with cardinal lines marked by taut cross-threads [13].

The instrument measures azimuth only, via a taut string running from the pillar's centre, over a weight suspended at the outer rim: this string defines the vertical plane containing the observer and the target object, and its intercept on the graduated outer rim reads the azimuth A directly as a plane angle from north,

$$A = \theta_{\text{rim}}, \tag{21}$$

requiring no trigonometric reduction since altitude is not sensed at all [derived from Jagannath's construction procedure, [13]]. Stated resolution is 6 arcminutes, with "Medium" precision rating [33]. Kaye notes the type also occurs at Ujjain and Benares but not at Delhi [13]. Constructed under Jai Singh II before 1743 [33].

I. Nadivalaya Yantra, "Circular/Equinoctial Dial"

The Nadivalaya consists of two large stone discs embedded in masonry, facing north (3.70 m diameter) and south (3.74 m diameter) respectively, both oriented parallel to the plane of the equator, with a storage chamber between them [33]. At the centre of each face an iron style projects perpendicular to the disc, i.e., parallel to Earth's rotation axis, surrounded by concentric hour circles graduated in hours/minutes and in the traditional units *ghati/pala* (1 ghati = 24 minutes, 1 pala = 24 seconds) [13].

Because the style is parallel to the polar axis and the dial plane is perpendicular to it, the shadow's position angle on the disc equals the Sun's hour angle exactly, with no seasonal distortion:

$$\theta_{\text{shadow}} = H = 15^\circ\, t_h, \tag{22}$$

the defining property of an equatorial (equinoctial) dial [derived from the construction reported in [13], [26]]. Since the Sun illuminates only the disc facing it, the north face is lit for the roughly six months following the vernal equinox and the south face for the six months following the autumnal equinox; the changeover occurs precisely when the solar declination δ changes sign, which is why the instrument "shows very effectively the passage of the sun across the equator" [13], [26]. Rated "Low" precision [33]; Rathnasree presents measured time errors from this "low precision" instrument, and Jagannath himself is quoted by Kaye as considering it of limited value because (at Benares) it serves only northerly observations, a criticism Kaye states does not apply at Jaipur or Ujjain [26], [13]. Only the northern half (*Uttari Gola*) was original; the southern half and storage chamber were added, per an inscribed plaque, in a 1771 restoration under Maharaja Pratap Singh [33], [13].

J. Horizontal Sundial atop the Nadivalaya

Mounted on the roof of the Nadivalaya's northern plate, reached by a steep stair, this small horizontal (*palabha*-type) sundial has a right-triangular brass gnomon 13 cm high with a 24.2 cm base and a 27.5 cm hypotenuse inclined $28^\circ 15'$ from horizontal, with time scales engraved on the flanking platform [33].

Unlike the equatorial dials described above, a horizontal dial produces hour lines that are *not* uniformly spaced in angle. If θ is the angle of the hour line from the noon line, ϕ the latitude, and H the hour angle, the governing relation is

$$\tan\theta = \sin\phi\, \tan H \tag{23}$$

[derived from standard horizontal gnomonics applied to the construction reported in [33]], in contrast to the uniform 15°

per hour of the equatorial Nadivalaya immediately below it. The dossier notes a significant construction anomaly: the gnomon's $28°15'$ inclination is more than a full degree away from Jaipur's latitude ($\approx\ 26°55'$) and lies closer to the latitude of Delhi, suggesting the piece may originally have been fabricated for the Delhi observatory [33]. Rated "Low" precision; possibly installed during the 1771 restoration, later covered by a protective cage that was removed during the 2007–2008 restoration to permit renewed observation [33].

K. Dakshinottara Bhitti Yantra, "North–South Wall Instrument"

This meridian-wall instrument comprises two independent graduated systems inscribed on parallel walls of a narrow north–south chamber, each wall 5.41 m long and 7.22 m high. The east-facing wall carries two intersecting quadrants with iron sighting bars near the top marking the arc centres; the west-facing wall carries a semicircle with a central iron bar [33]. Kaye measured the east-face quadrant radii at 20 ft (≈ 6.1 m) and the west-face semicircle radius at 10 ft 10 in (≈ 3.3 m) [13].

Functionally equivalent to a modern transit-circle mural quadrant, it measures the altitude of an object at meridian transit, down to within $3°$ of the horizon [33], [13]. A pin or sighting bar at the arc's centre allows the observer to read the object's meridian altitude h or zenith distance z directly off the graduated wall; applying Eq. (7),

$$\delta = \phi - z = \phi - (90° - h), \tag{24}$$

converts the observed meridian altitude into declination once the site latitude is known, or, applied to solstitial solar transits, allows determination of ϕ and the obliquity ε [derived from the transit-circle function described in [13], [33]]. It is rated "High" precision [33]. The present structure, built in 1876 with lead-filled marble engravings, replaced a dilapidated 1728 original by Jai Singh II that stood elsewhere on the site; Kaye notes the equivalent Delhi instrument had already been destroyed by his time [33], [13]. No image of this instrument is available in this study's image set.

L. Unnatamsa Yantra, "Altitude Instrument"

From *unnata* ("elevated"), this is a large brass altitude circle: an outer-diameter 5.35 m graduated ring, fabricated from moulded brass sections and weighing over 600 kg, suspended from a wooden beam between two masonry pillars roughly 7 m tall, themselves inclined $12°$ from the north–south line. The ring carries orthogonal cross-beams and can rotate freely about a vertical axis within a stepped circular pit [33], [13].

A sighting tube mounted at the ring's centre is aligned with a celestial object, and the object's altitude is read from a pointer on the graduated limb of the ring [33]. Because the ring rotates about a vertical axis, bringing it into the vertical plane through the object first sets the azimuth, after which the alidade pivoted at the ring's centre reads altitude h directly as a plane angle,

$$h = \theta_{\text{limb}}, \qquad A = \theta_{\text{ring-bearing}}, \tag{25}$$



Fig. 8. The Unnatamsa Yantra, a large suspended brass altitude circle that rotates about a vertical axis to bring the sighting alidade into the object's vertical plane before its limb is read for altitude [33].
Photo credit: Swapnil.Karambelkar, CC BY-SA 4.0, via Wikimedia Commons (https://commons.wikimedia.org/wiki/File: Unnatamsa_yanta_at_Jantar_mantar_Jaipur_India.jpg).

requiring no trigonometric reduction, functionally equivalent to a large armillary altitude circle [derived from the construction described in [33], [13]]. As a metal instrument it is not assigned a masonry precision rating in the dossier's table [33]; Kaye generally regarded the metal instruments as observationally inferior to the masonry ones [13]. Built under Jai Singh II before 1743; the sagging original wooden beam was consolidated rather than replaced during the 2007 restoration owing to the unavailability of a matching timber [33].

M. Chakra Yantra, "Ring Instrument"

The Jaipur Chakra Yantra (to be distinguished from the differently designed Varanasi/Benares Chakra Yantra) consists of two brass ring instruments mounted between the Kapala bowls on three posts aligned north–south, each ring pivoted to rotate about a diameter parallel to Earth's axis, with a 51 cm graduated brass plate at the southern pivot lying parallel to the equatorial plane [33]. Kaye records the Jaipur rings as 6 ft in diameter, describing the type as "an equatorial" [13].

Since the ring's rotation axis is set parallel to the Earth's axis, the ring always lies in an hour circle (a great circle through both celestial poles). Sighting an object through a tube pivoted on the ring gives the angular distance of the object from the equatorial plane along that hour circle directly, i.e., its declination δ, while the ring's rotational bearing read on the graduated equatorial plate gives the hour angle H:

$$(\delta, H) \ \longrightarrow\ \alpha = \mathrm{LST} - H, \tag{26}$$

where the object's right ascension α follows once the local sidereal time (LST) is known [derived from the construction described in [33], [13]]. Two duplicate rings permit cross-checking of readings [33]. It shares a combined platform with the Kapala Yantra; no construction date is recorded [33]. A widely repeated misattribution describes the Jaipur Chakra Yantra as a set of four semicircular world-time arcs corresponding to Greenwich, Zurich, and other meridians. This description in fact belongs to the *Misra Yantra*, an instrument



Fig. 9. The Jaipur Chakra Yantra, a pair of polar-axis-mounted brass equatorial rings that read declination along the ring and hour angle from a graduated equatorial plate at the southern pivot [33].

Photo credit: Jakub Hałun, CC BY-SA 4.0, via Wikimedia Commons (https://commons.wikimedia.org/wiki/File: Rama_Yantra_gnomon_and_Chakra_Yantra,_Jantar_Mantar,_ Jaipur,_20191218_0928_9028.jpg).

unique to the Delhi observatory and not present at Jaipur [13], [36]; the Jaipur Chakra Yantra is the brass equatorial ring pair described above [33].

N. Krantivritta Yantra I and II, "Ecliptic Instrument"

Two related instruments at Jaipur bear the name Krantivritta ("ecliptic"). The first (Krantivritta I) is an incomplete masonry *torquetum*: a circular plate 3.39 m in diameter, oriented parallel to the equatorial plane, with a central metal rod, but lacking the mobile superstructure that would complete the instrument [33]. Kaye identifies its intended type as "the Torquetum of Regiomontanus," rejected by Tycho Brahe as unwieldy, designed for direct measurement of celestial latitude and longitude [13]. A complete torquetum is a nested chain of graduated circles that steps between reference frames: a base plate in the equatorial plane carrying an hour-angle scale; a second disc tilted from it by the obliquity of the ecliptic,

$$\varepsilon \approx 23.5^\circ, \tag{27}$$

which defines the ecliptic plane and carries an ecliptic-longitude (λ) scale; and a perpendicular arm reading ecliptic latitude (β) [derived from the standard torquetum design as described in [13], [33]]. The Jaipur instrument preserves only the equator-parallel base stage, and was never completed; its precision is recorded as "Not clear" [33].

Krantivritta II is a later working brass model consisting of two pivoted circles: one moving in the equatorial plane, the other, the ecliptic scale proper, inclined at $23^\circ 27'$ to it, with a bar carrying sighting quadrants at each end, rotating about a perpendicular axis through the ecliptic scale's centre [33], [13]. Rotating the ecliptic circle to an object's longitude λ and reading the perpendicular sighting quadrant gives ecliptic latitude β without any separate coordinate transformation, mechanically substituting for the spherical-trigonometric relation between equatorial and ecliptic coordinates,

$$\sin\delta = \sin\beta\cos\varepsilon + \cos\beta\sin\varepsilon\sin\lambda \tag{28}$$

[derived; the equivalent right-ascension relation is likewise avoided by direct mechanical reading, per the construction in [33], [13]]. Kaye judged this demonstration instrument "more suitable for demonstration purposes than for actual observation"; it was built in 1901–02 by the restorer Major Arthur Garrett specifically to illustrate the function the original, incomplete Krantivritta I could not perform [13], [33], [37]. Neither instrument has an available image in this study's figure set.

O. Yantra Raj, "King of Instruments" (Great Astrolabe)

The Yantra Raj comprises three masonry pillars, 3.3 m high, supporting two beams that carry two large brass/iron discs. The principal disc is an astrolabe measuring 2.43 m vertically (with crown) and 2.115 m horizontally, described by the nomination dossier and the UNESCO heritage portal as the largest instrument of its kind in the world, fabricated from a single piece of moulded brass patched with lead and weighing over 400 kg; a second, less clearly understood plate of riveted iron sheets, roughly 2.1 m in diameter with a central sighting hole, stands alongside it [33], [5], [13]. The pillars are aligned 23° from the meridian plane [33].

The astrolabe is engraved specifically for a latitude of 27° N, essentially that of Jaipur, and functions via stereographic projection of the celestial sphere from the south celestial pole onto the equatorial plane. Stereographic projection is conformal and maps every circle on the celestial sphere to a circle (or line) in the plane, which is what permits the compass-drawn engraving of horizon almucantars, azimuth lines, the celestial meridian, diurnal circles, and the ecliptic all on a single *tympan*, above which a rotating *rete* carries the ecliptic scale and pointers for bright stars, one full rotation corresponding to one day [35], [33]. Rotating the rete against the plate mechanically performs the equatorial-to-horizon transformation of Eqs. (5)–(6) for a chosen local sidereal time, and reading the ecliptic scale against the horizon line yields the rising degree (ascendant) used for calendrical and astrological determinations, including the 4th, 7th, and 10th houses of the zodiac [derived from standard astrolabe theory applied to the Jaipur instrument, [35], [33]]. The astrolabe measures altitude, zenith distance, declination, longitude, local time, and the ascendant, and per Wikipedia is used once yearly to calculate the Hindu calendar [33], [37]. No firm construction date is recorded, though the 1750s traveller Tieffenthaler mentions three large metal astrolabes suspended on iron rings at the site; the 2007 restoration repaired the masonry and replaced damaged timber beams [33]. No image of the Yantra Raj is available in this study's image set.

P. Rasivalaya Yantras, "Zodiac-Sign Dials" (a set of twelve)

The twelve Rasivalaya instruments exist only at the Jaipur observatory, forming "a unique group of 12 gnomon-dials" with no counterpart at any other Jantar Mantar site [5],

[23]. They stand together on a masonry floor $41\ \mathrm{m} \times 39\ \mathrm{m}$, each built on the Samrat Yantra principle, with gnomon lengths ranging from 4.22 m (Gemini) to 6.21 m (Aries) and quadrant radii of either 1.24 m or 1.68 m; each instrument's orientation and gnomon inclination differ according to its assigned zodiacal sign, and the Cancer instrument uniquely uses unplastered ashlar masonry with double round arches rather than pointed arches [33].

Kaye gives the clearest geometric statement: "each instrument is exactly of the same type as the Samrat Yantra, but the quadrants lie, not in the plane of the equator, but in the plane of the ecliptic when the particular sign is on the horizon [meridian], and the edge of the gnomon then points to the pole of the ecliptic" [13]. Each dial is therefore a Samrat Yantra whose polar axis has been re-pointed from the celestial pole to the ecliptic pole, valid only at the specific sidereal instant when the first point of its assigned zodiacal sign transits the meridian. Because the ecliptic pole traces a diurnal circle of radius $\varepsilon \approx 23.5^\circ$ about the celestial pole, and because the ecliptic itself is inclined to the meridian at the moment of transit, the required gnomon inclination varies across the twelve instruments from roughly 3.5° to 50.5°, with azimuth orientation varying up to $\pm 26^\circ$ from north, as reported by Perlus [23]. At the correct sidereal moment, the gnomon-edge shadow on the ecliptic-parallel quadrant reads ecliptic longitude λ (an hour-angle analogue referenced to the ecliptic pole), while the tangent scale along the gnomon edge reads ecliptic latitude β (a declination analogue),

$$\lambda \leftrightarrow H_{\text{ecliptic pole}}, \qquad \beta \leftrightarrow \delta_{\text{ecliptic pole}}, \tag{29}$$

directly paralleling Eqs. (15)–(16) for the ordinary Samrat Yantra [derived from Kaye's construction and Perlus's description, [13], [23]]. This makes the Rasivalaya group the only masonry instrument set anywhere that measures natively in the ecliptic coordinate system [5], [23].

Rated "Medium" precision, with a documented authenticity caveat: angular alterations of up to $0^\circ 29'$ in azimuth and $2^\circ 28'$ in altitude were introduced during Major Garrett's 1901–02 restoration [33]. The set is not mentioned in contemporary lists from Jai Singh's own time and was first securely documented by Tieffenthaler's 1750s visit; it was repaired in the 1870s under Maharaja Ram Singh and again in 2008 [33], [13].

Q. Dhruva Darsaka Yantra, "Pole-Star Indicator"

A small trapezoidal masonry structure, 3.07 m long and 54 cm wide, whose lower end stands 76 cm and upper end 2.32 m above the ground, oriented so that its upper surface points at the pole star [33]. Its function is purely demonstrative: "to show the pole star to a lay person" [33]. The inclined sightline's altitude above the horizon equals the site latitude,

$$h_{\text{pole}} = \phi, \tag{30}$$

the fundamental relation between the altitude of the celestial pole and the observer's geographic latitude [derived; the reported rise of $2.32 - 0.76 = 1.56$ m over a 3.07 m base gives $\arctan(1.56/3.07) \approx 26.9^\circ$, consistent with Jaipur's latitude of $\approx 26^\circ 55'$, per [5], [33]]. Kaye separately describes a related portable brass *Dhruva Bhramana Yantra* ("circumpolar instrument"), a nocturnal-type device with a slotted sighting plate and weighted rotating index: when the pole star and β Ursae Minoris (Kochab) are sighted through the slit, an index pointer indicates sidereal time in *ghatis*, since the position angle of the Kochab–Polaris line is a linear function of local sidereal time as the pair circles the pole once per sidereal day [13]. Rated "Low" precision, and first securely documented in a 1902 visitor account [33]. No image of this instrument is available in this study's figure set.



Fig. 10. One of the twelve Rasivalaya (zodiac) instruments at Jaipur, each a Samrat-type gnomon dial re-oriented to the ecliptic pole for the meridian transit of a specific zodiacal sign [13].

Photo credit: Wikimedia Commons contributor, CC BY-SA, via Wikimedia Commons (https://commons.wikimedia.org/wiki/Category:Rashivalaya_Yantra).

R. Disha Yantra / "Jai Singh's Seat", "Direction Instrument"

The Disha Yantra is a large circular engraving on red stone slabs, roughly 30 m in diameter, inscribed on a low platform 15–35 cm above grade; recent restoration revealed stone concentric rings beneath the lime-mortar surface [33]. Its function is explicitly disputed in the primary source literature: variously described as a horizontal dial, as the former site of a water-lifting machine, or, per one hypothesis favored by the dossier, as a template used to cut the marble cladding pieces for the Vrihat Samrat Yantra's quadrants, which share the same radius as the Disha Yantra's circle; the purpose of its concentric rings remains speculative, possibly connected to ground-levelling via water channels [33]. The UNESCO nomination dossier explicitly classifies the Disha Yantra, together with the Astronomer's House, as a structure *not* used for astronomical observation, and assigns it a precision rating of "Not clear" [33]; a popular description of it as a direction-finding instrument is not supported by the dossier's own analysis [33], [37]. No image of this structure is available in this study's figure set.

S. Synthesis

Taken together, the nineteen entries of the Jaipur Yantra Mandir instantiate all three classical celestial coordinate systems in monumental masonry and brass form: the horizon (altitude–azimuth) system in the Ram Yantras, Digamsa Yantra, Unnatamsa Yantra, and Dhruva Darsaka Yantra; the equatorial (hour-angle–declination) system in the two Samrat Yantras, the Sasthamsa, Nadivalaya, Dakshinottara Bhitti, and Chakra Yantras; and the ecliptic (celestial-latitude–longitude) system uniquely in the twelve Rasivalaya Yantras and the two Krantivritta instruments, with the Jai Prakash, Kapala, and Yantra Raj instruments performing direct mechanical transformation between systems [5], [33]. The Kapala Yantra and the complete set of twelve Rasivalaya instruments are, among all Jantar Mantar sites, attested only at Jaipur [13], [5], [23], underscoring Jaipur's role as the most elaborated and functionally complete of Jai Singh II's observatories.

IV. The Delhi Observatory (Jantar Mantar, New Delhi)

The Delhi observatory, in the former Jaisinghpura quarter south of Shahjahanabad, was the first of the five masonry observatories erected by Maharaja Sawai Jai Singh II of Amber–Jaipur, the others following at Jaipur, Ujjain, Varanasi and Mathura [13], [36]. It was raised at the instance of the Mughal emperor Muhammad Shah as part of Jai Singh's programme to compile a new set of astronomical tables, the *Zij-i Muhammad Shahi* [13], [29]. Jai Singh's own account, preserved by Kaye, states that he first constructed brass instruments of the astrolabe type "in accordance with the Muslim books," found them unsatisfactory owing to their small size, worn axes and shifting planes, and therefore resolved to build large immovable instruments of stone and lime [13]. The observatories were also conceived as teaching laboratories, a purpose stated explicitly in the preface to the *Zij-e-Muhammadshahi* [7].

Dating. Two dates compete in the historical record: Pandit Gokal Chand's A.D. 1710 and Sa'id Ahmad Khan's statement that the observatory was built "in accordance with the orders of the Emperor Muhammad Shah in the seventh year of his reign," corresponding to A.H. 1137, i.e. A.D. 1724–25. Kaye's critical assessment favours 1724 as the founding date, noting that the 1710 figure derives from a mistaken 1910 restoration plaque that was nonetheless still repeated by visitors decades later [13], [31].

Site coordinates. Kaye's adopted elements place the observatory at latitude $28^\circ 37'$ N, longitude $77^\circ 13'$ E of Greenwich, using $28^\circ 37' 35''$ in his instrument computations [13]. A modern GPS survey at the Samrat Yantra gives $28^\circ 37' 36''$ N, $77^\circ 12' 59''$ E, with a constant longitude correction of $+20^{\mathrm{m}}08^{\mathrm{s}}$ to be added to local sundial time to obtain Indian Standard Time [7].

On the instrument inventory. Kaye's site plan and later architectural surveys agree that the surviving Delhi complex comprises four principal instruments (the Samrat Yantra, the paired Jai Prakash bowls, the paired Ram Yantra cylinders, and the compound Misra Yantra), together with the Shashthamsa arc built into the masonry of the Samrat itself [13], [1], [42]. This is stated here explicitly because the widely circulated claim that Delhi "consists of 13 architectural astronomical instruments," including a Kapala Yantra and twelve Rasivalaya Yantras, is *not* supported by the primary literature [36]. Kaye's instrument census places the Rasi Valaya and the Kapala at Jaipur only [13], and the UNESCO nomination dossier for the Jaipur observatory states in its comparative table that the Kapala was "invented specially in Jaipur observatory, absent in the others" and that the Rasivalaya Yantra exists "only at Jaipur observatory" [33]. The popular "13 instruments" figure for Delhi should accordingly not be used as a basis for scientific description of the site.

The observatory was plundered and largely dismantled by the Jats under Jawahir Singh before 1795, fell into serious disrepair through the nineteenth century, was partially repaired at the request of the Delhi Archaeological Society in 1852, and underwent a full restoration under Pandit Gokal Chand, sanctioned by the Maharaja of Jaipur and completed in 1910 [13], [42], [1]. The Niyat Chakra component of the Misra Yantra received the last major instrument-level renovation, in 1951 [7].

A. Samrat Yantra ("Supreme Instrument")

The Samrat Yantra is the central, and largest, structure of the Delhi complex. Kaye describes it as "an equinoctial dial... in principle one of the simplest 'equal hour' sundials" [13]. Its foundations occupy a quadrangular excavation 15 ft deep, 123 ft east–west by 120 ft north–south; the completed structure stands 68 ft high (60.3 ft above the surrounding ground), and each of the two quadrant walls has a radius of 49.5 ft [13]. Popular sources give a base length of 114 ft, a thickness of 10 ft and a hypotenuse of 128 ft (39 m) [36], while architectural documentation records the triangular gnomon's base as roughly 35 m with an internal staircase about 1.5 m wide rising through three storeys, spanned by Mughal keel-arch openings [1]. A circular pillar surmounts the gnomon, probably intended originally for rough azimuth sighting and now bearing a small European-style sundial likely added during the 1910 restoration [13].

Gnomon geometry. The gnomon is a triangular wall whose hypotenuse is inclined at an angle equal to the observatory's terrestrial latitude, $\varphi \approx 28^\circ 37'$, so that this edge lies parallel to the Earth's rotation axis and points toward the celestial pole. The two quadrant walls are erected at right angles to the gnomon face and therefore lie in planes parallel to the celestial equator [13]. Because the shadow of the polar edge consequently sweeps the equatorial quadrant at a constant angular rate, the hour angle H of the Sun is read directly and linearly from the position of the shadow:

$$H = 15^\circ \times t_h, \qquad (1\ \text{hour} \equiv 15^\circ) \tag{31}$$

where t_h is elapsed local apparent solar time in hours measured from noon [13], [26]. When the shadow reaches the top of the western quadrant it is 06:00 local time; at solar noon the shadow vanishes from the western quadrant and reappears at the base of the eastern one; by 18:00 it has travelled to the top of the eastern scale [26], [31].

Declination from the tangent scale. Declination is not read from a uniformly divided scale but from a scale of tangents engraved along the gnomon edge. Following Kaye's construction, let AB be the polar edge of the gnomon, with $\angle ABC = \varphi$ (the latitude), and let GH be the radius of a quadrant. If a sighting rod is raised or lowered along the gnomon edge until its shadow coincides with the edge of the quadrant, the resulting angle $\angle HGL$ gives the Sun's declination δ through

$$\tan(\angle HGL) = \frac{HL}{GH}, \qquad \delta \equiv \angle HGL, \tag{32}$$

where HL is the linear displacement measured along the gnomon from the equatorial reference point [13]. Equation (32) is precisely why the gnomon edges are graduated with non-uniform tangent divisions rather than a linear scale: equal increments of arc length HL correspond to progressively larger increments of δ as $|\delta|$ grows. Readings are taken upward from the equatorial line for northern declinations and downward for southern ones [31].

Right ascension and civil time. Right ascension is obtained differentially: the hour angle of a target star and of a reference star of known right ascension are measured (by eye, sighting along the gnomon edge from a point on the quadrant) at the same physical instant, and the difference of hour angles is added to or subtracted from the reference star's right ascension [10]. Because a sundial reads only local apparent solar time T_{app}, conversion to mean/civil time requires both the equation of time E (which encodes the combined effects of orbital eccentricity and the obliquity of the ecliptic) and a fixed longitude correction $\Delta\lambda$:

$$T_{\text{IST}} = T_{\text{app}} + E + \Delta\lambda, \tag{33}$$

with $\Delta\lambda \approx +20^{\text{m}}08^{\text{s}}$ at Delhi's longitude relative to the Indian Standard Meridian [13], [7].

Precision. Sharma's assessment gives a design precision of $\pm 2^{\text{s}}$ in time, $\pm 15''$ in right ascension and $\pm 1'$ in declination, noting that "the great Samratas of Jaipur and Delhi are both capable of achieving a precision of $\pm 1'$ of arc, the limit for the unaided eye," although both instruments "suffer from a number of constructional defects" [29]. In practice the dominant limitation is the penumbra of the Sun's roughly half-degree angular diameter, which smears the shadow edge over several centimetres; a taut string held parallel to and just above the shadow edge, its own shadow read against the gnomon's, restores repeatability to about $\pm 3^{\text{s}}$ or better [10].

Condition. By 1918 the lower structure stood seasonally below the local water table, submerging the lower quadrants and rendering the instrument "useless for astronomical purposes"; a later cemented platform installed to combat this seepage destroyed the adjoining quadrant segments, so that the Delhi Samrat today carries no legible original graduations [13], [26]. A 2006 Nehru Planetarium calibration campaign, using roughly 450 public timing observations at the winter solstice, demonstrated that the surviving structure, part oriental equinoctial dial, part improvised horizontal dial near the cemented platform, remains intrinsically capable of second-level timing if properly re-marked [26], [7].



Fig. 11. The Samrat Yantra at Delhi, with the compound Misra Yantra visible in the background.

Comparatively, Jaipur possesses two Samrat instruments (the giant Vrihat/Brihat Samrat and a smaller Laghu Samrat) against one each at Delhi and Ujjain, and Delhi's gnomon inclination of $28°37'$ contrasts with Jaipur's latitude of approximately $26°55'$ [13], [26].

Image credit: Pallav.journo, CC BY-SA 4.0, https://commons.wikimedia.org/wiki/File:Jantar_Mantar_Samrat_Yantra_Misra_Yantra.jpg

B. Jai Prakash Yantra ("Light of Jai")

The Jai Prakash Yantra, "invention of Jai," called by the court astronomer Jagannatha the "crest jewel" of the instruments, consists of two complementary concave hemispherical bowls set immediately south of the Samrat Yantra [13]. Hunter's 1799 account gives a diameter of "twenty-seven feet five inches," describing "a concave hemispherical surface, formed of mason work, to represent the interior hemisphere of the heavens... divided by six ribs of solid work and as many hollow places" [13]. Modern surveys give a rim diameter of about 8.33 m at Delhi (against 5.4 m at Jaipur), with each Delhi bowl set on its own individual platform, unlike the shared platform at Jaipur [33], [1]. Only one complete hemisphere is strictly required for the geometry; the second is engraved with pathways complementary to the first so that, superimposed, an observer standing in either bowl's cut-away walkways can access the full spherical surface without walking on the graduated zone itself [13].

Geometry. The concave surface functions as an inverted map of the celestial hemisphere: the rim represents the local horizon, the lowest interior point represents the zenith, and two graticules are engraved on the surface. The horizon graticule consists of a meridian great circle through the north and south rim points and the zenith point, azimuth lines radiating from the zenith point to the rim, and altitude circles concentric about the vertical axis. The equatorial graticule places the (inverted) north celestial pole at a point on the meridian below the south rim point, offset by an amount fixed by the latitude φ; the celestial equator lies $90°$ further along the meridian from the pole; diurnal circles (declination parallels) are drawn parallel

to the equator, and hour circles radiate from the pole to the rim [10]. In addition, Jai Singh is credited with introducing "circles of the signs of the zodiac" cutting the diurnal circles at the meridian, so that the shadow crossing such a circle signals which zodiacal sign is culminating [13].

An observer reads the Sun's position from the shadow cast by cross-wires stretched north–south and east–west over the rim; at night, sighting is performed with the eye placed at the spherical surface in the cut-away sectors [13], [26]. Because both the horizon and equatorial graticules are simultaneously present, the instrument allows direct visual conversion between the two coordinate systems: for a body observed at hour angle H and declination δ, the corresponding altitude a and azimuth A satisfy the standard spherical transformation

$$\sin a = \sin\varphi \sin\delta + \cos\varphi \cos\delta \cos H, \tag{34}$$

$$\cos A = \frac{\sin\delta - \sin\varphi \sin a}{\cos\varphi \cos a}, \tag{35}$$

which the Jai Prakash renders as a direct graphical reading rather than a computation, since both graticules are engraved on the same physical surface [10], [13].

Precision. At the analogous Jaipur instrument, Sharma reports time accurate to $\pm\frac{1}{2}$–1 min, zenith distance and declination each to about $\pm 3'$, and azimuth or right ascension to between $\pm 3'$ and $\pm 1^\circ$, describing the precision as "rather limited for the kind of precision Jai Singh had in mind" [29]. Observations with the Delhi bowls show systematic altitude errors that likely reflect departures of the masonry surface from true sphericity [26].

The Jai Prakash is one of three instruments (with the Samrat and Ram Yantra) that Jai Singh personally claimed to have devised, and Kaye traces its conceptual roots to a manuscript description by Abdul Ali Birjandi (d. 1523), crediting Jai Singh's original contribution as the complementary double-bowl construction and the zodiacal culmination lines [13]. The Delhi bowls were substantially reconstructed during the 1910 restoration, with the original cross-wires replaced by galvanized iron pipes at the bowl centres [13]. A related but architecturally distinct instrument at Jaipur, the Kapala, operates on a similar principle but is used chiefly to demonstrate the transformation between coordinate systems and, as already noted, is peculiar to Jaipur [13], [33].

C. Ram Yantra

The Ram Yantra comprises two large complementary open-topped cylindrical structures south of the Jai Prakash bowls, said by local tradition to be named for Ram Singh, Jai Singh's grandfather [13]. Each building consists of an outer circular wall and a central pillar, the wall/pillar height above the graduated floor being set equal to the inner radius: 24 ft 10 in at Delhi, with a central pillar diameter of 5 ft 3.5 in [13]. Kaye's comparative table gives an internal diameter of 54 ft 7.5 in and height of 24 ft 8 in at Delhi, roughly twice the corresponding Jaipur dimensions (23 ft 1 in diameter, 11 ft 4 in height); modern metric surveys give 16.65 m inner diameter at Delhi against 6.9 m at Jaipur [13], [33]. At Delhi the floor is divided into 30 graduated sectors of 6° each, separated by equal open gaps, subdivided finely enough to read azimuth to about 1°; at Jaipur there are only 12 sectors of unequal width [13], [7].

Geometry. Because the wall (and pillar) height is set equal to the inner radius R, the instrument forms an isosceles right-triangle cross-section between the pillar top, the wall top, and the wall/floor junction. Concentric circular scales on the floor and continuing up the inner wall read azimuth directly; radial lines from the pillar to the wall, continued vertically up the wall, read altitude, with the zero mark at the top of the wall and 90° at the pillar base. For a shadow (by day) or sightline (by night) whose horizontal distance from the pillar axis is x, the altitude a of the observed body follows from the elementary gnomon relation

$$a = \arctan\left(\frac{h_{\text{pillar}}}{x}\right), \tag{36}$$

where h_{pillar} is the pillar's height, equal by design to the wall height R [26]. Because $h_{\text{pillar}} = R$, the shadow of the pillar's top lands exactly at the wall/floor junction when $a = 45^\circ$: readings above this altitude fall on the vertical wall face, and readings below it fall on the horizontal floor moving outward from the pillar [31]. As with the Jai Prakash, the complementary pairing of the two Ram Yantra buildings means that wherever one instrument presents an open gap the other presents a graduated sector, so that superimposing the pair yields a notionally complete cylindrical scale; only the zenith point directly above the pillar cannot be observed by either [7], [31].

Precision. The instrument is most accurate near the 45° floor/wall junction, where markings are widest, giving about $\pm 1'$ of arc; precision degrades toward high altitudes near the pillar base to roughly $\pm 1^\circ$ [10]. Sharma similarly places theoretical precision at $\pm 1'$ for altitudes of 40°–50° at Jaipur, degraded in practice by penumbral shadow-blurring to about $\pm 6'$ [29]. Modern student observation campaigns at Delhi, using an original least count of 1°, have nonetheless achieved roughly 0.1° precision in both altitude and azimuth, with no detectable departure of the masonry from its intended geometry [26].

The Ram Yantra, like the Jai Prakash, exists only at Delhi and Jaipur; Kaye considered the Jaipur example comparatively modern and regarded the Delhi instrument's chief originality as lying in its scale and the duplication of the structure into a complementary pair [13]. As of 2025, the Archaeological Survey of India was preparing a restoration of the Delhi Ram Yantra under a Supreme Court directive, having found the pillar's engraved scale entirely eroded and the calibrated floor arcs and radial lines nearly vanished [25].

Image credit: Subeesh Balan, CC BY-SA 3.0, https://commons.wikimedia.org/wiki/File:Jantar_Mantar_New_Delhi.jpg

Image credit: Thomas Daniell / William Daniell, *c.* 1789, public domain, https://commons.wikimedia.org/wiki/File:Samrat_Yantra_and_Jai-Prakash_Yantra,_Jantar_Mantar,_Delhi,_early_19th_century.jpg

D. Shashthamsa Yantra ("sixty-degree arc")

The Shashthamsa (or Sasthamsa) Yantra is a 60° graduated arc built in the meridian plane inside a dark chamber within



Fig. 12. General view of the Jantar Mantar, New Delhi, showing the Ram Yantra structures in the observatory grounds.



Fig. 13. Historic aquatint engraving of the Samrat and Jai Prakash Yantras at Delhi, by Thomas and William Daniell, *c.* 1789. This is a period engraving from the Daniells' publication, not a modern photograph, and is included for its documentary value in showing the instruments' early-19th-century condition.

the masonry that supports the east quadrant of the Samrat Yantra [13]. Kaye records the Vrtti Shastamsa as occurring at Delhi and Jaipur only [13]; the UNESCO dossier notes the Delhi example is now in ruins, with an estimated radius of about 8 m, compared with four functioning Jaipur units of 8.65 m radius [33].

Principle: the aperture (pinhole) meridian instrument. A small orifice some 30–40 ft above the arc admits a narrow beam of sunlight which, as the Sun crosses the meridian, projects a solar image onto the graduated arc below, functioning as a pinhole camera in the meridian plane [13]. The position of the projected image on the arc gives the Sun's meridian zenith distance z directly. Declination follows from the standard meridian-transit relation

$$\delta = \varphi - z \tag{37}$$

for a transit south of the zenith, where φ is the observatory's latitude [31]. The 60° arc length suffices because the Sun's meridian zenith distance at Delhi's latitude never exceeds this range over the course of a year. Sharma places the Sasthamsa, together with the Samrat, among the highest-precision instruments in the corpus, capable in principle of maintaining Jai Singh's target of $\pm 1'$ of arc [29].

The Delhi chamber housing the instrument was sealed during the 1910 restoration and remained inaccessible when Kaye surveyed the site in 1918; he recommended it be reopened and returned to working order once the Samrat's persistent water-table problem was resolved [13]. The World Monuments Fund counts the Shashthamsa among the four instruments of the original Delhi construction phase [42].

E. Misra Yantra ("Mixed Instrument"): Unique to Delhi

The Misra Yantra, "mixed instrument," combines several distinct sub-instruments within a single symmetric structure. It is essential to state explicitly, given a recurring error in secondary and encyclopedic sources, that **the Misra Yantra exists only at the Delhi observatory**: it is absent from Jaipur, Ujjain, Varanasi and Mathura alike [13], [11]. Some popular accounts and even certain photograph captions on Wikimedia Commons mislabel Misra Yantra images as depicting a Jaipur instrument; no such structure exists at Jaipur, and Kaye's independent site-by-site inventories confirm the Misra Yantra appears in neither of the contemporary lists of Jai Singh's own instruments [13]. Indeed, the Misra Yantra was not built by Jai Singh at all: Kaye attributes it to his son and successor Madho Singh (r. 1751–65), "who inherited no small portion of his father's love of science," a dating corroborated by internal chronological evidence discussed below [13], [1].

The structure stands roughly 140 ft north-west of the Samrat Yantra, measuring about 25 m east–west by 12 m north–south, organized symmetrically about a central wall 8 m high whose upper edge is inclined at the same angle as the Samrat's hypotenuse. Four semicircular scales, executed in white marble strips about 0.5 m wide, in contrast to the plain lime-plastered surfaces used elsewhere at Delhi, are supported on individually curved walls reached by internal staircases [1]. Kaye describes the building as combining "four separate instruments" in total: the Niyat Chakra at the centre, two half-Samrat (equinoctial) dials flanking it, the Agra Yantra (a horizontally faced quadrant) on the west, the Dakshinovritti/Dakshinottara arc on the east wall, and the Karka Rasi Valaya on the inclined north wall [13]; later inventories (e.g. Wikipedia's account of the Mishra Yantra) enumerate the same components slightly differently, as five named sub-instruments [39].

Image credit: Anaga elsa, CC BY-SA 3.0, https://commons.wikimedia.org/wiki/File:Jantar_mantar..jpg

1) The Laghu Samrat halves: On either side of the Niyat Chakra, half of an equinoctial dial is attached, constructed on the same principle as the great Samrat Yantra: a gnomon inclined at the local latitude, divided into a central gnomon and two flanking side-gnomons, casting shadows onto graduated quadrant surfaces to the east and west. These half-dials give local time and solar declination by the same tangent-scale geometry as Equations (31)–(32), with the Niyat Chakra physically separating the morning and afternoon halves [13], [26].



Fig. 14. The Misra Yantra at Delhi, showing the compound arrangement of the Niyat Chakra, Laghu Samrat half-dials and inclined Karka Rasi Valaya wall. (Note: despite the Wikimedia Commons filename, this photograph has been verified to depict the Delhi instrument, the Misra Yantra being unique to that site.)

Observational calibration of these quadrants and gnomons by Nehru Planetarium staff was completed by January 2007 [7].

2) Niyat Chakra ("fixed circles"): The Niyat Chakra consists of a gnomon flanked by four graduated marble semicircles, whose centres lie on the hypotenuse of the central wall [13], [1]. Each semicircular plane is inclined to the Delhi meridian at a different angle, reported by local pandits as $77°16'$ W, $66°34'$ W, $68°7'$ E and $76°54'$ E, though contemporary engineering surveys gave somewhat different values that Kaye found difficult to reconcile [13].

Geometry. Let AB denote the polar edge of the Delhi gnomon, with ABD lying in the plane of the Delhi meridian. Let ABE be a second plane making an angle S with ABD; this plane represents the meridian of a distant locality whose longitude differs from Delhi's by S. If CX denotes the direction toward the Sun at the moment it lies in plane ABE, i.e. at local apparent noon for that distant locality, then the arc EQ subtended on the corresponding marble semicircle measures the Sun's declination δ at that instant:

$$\delta_{\odot}(t_{\text{noon},\,S}) = \text{arc } EQ, \qquad S = \lambda_{\text{Delhi}} - \lambda_{\text{remote}}, \tag{38}$$

where λ denotes terrestrial longitude [13]. Each semicircle is graduated north and south from its zero point E purely for reading declination; the Delhi meridian plane ABD itself carries no scale. In effect, each of the four marble arcs is a dedicated Samrat-type declination dial pre-rotated to correspond to a fixed hour-angle offset (equivalently, longitude difference) from Delhi.

The four reference localities. Tradition, as recorded by Kaye and by Tomkins, names the four places as Greenwich Observatory, the observatory at Zurich, a village identified as "Notkey" in Japan (latitude $43°33'$ N, longitude $145°17'$ E), and a locality on the Pacific island of "Serichew" (latitude $48°6'$, longitude $163°13'$ E) [13]. Kaye notes that the implied longitude of Delhi relative to Greenwich, $77°16'$ E, is close to the modern value of $77°13'$ E, lending some credibility to the tradition, but he also observes a decisive chronological difficulty: the Zurich observatory was not founded until 1759, sixteen years after Jai Singh's death in 1743, which independently corroborates the instrument's post-Jai Singh, Madho Singh-era construction [13]. The Niyat Chakra received the observatory's last major instrument-specific renovation, in 1951 [7].

3) Dakshinottara Bhitti / Dakshinovritti Yantra: On the east wall of the Misra Yantra is a graduated semicircle used to obtain meridian altitudes, functionally equivalent to the mural quadrants of medieval Islamicate and European observatories and corresponding to the modern transit circle [13], [39]. The UNESCO dossier records versions of the Dakshinottara Bhitti Yantra at Jaipur, Delhi, Ujjain and Varanasi, comparing the type to the mural quadrants of Ray, Maragheh, Ulugh Beg's Samarkand observatory, and Tycho Brahe's Uraniborg [33].

Geometry. The instrument operates purely in the meridian plane. A rod or sighting device pivoted at a fixed centre pin is adjusted until, at the moment of the Sun's meridian transit, its shadow (or sightline) falls at the corresponding point on the graduated scale, yielding the meridian altitude $a_{\text{mer}} = 90° - z$. Declination is then recovered from the meridian relation of Equation (37), using the known latitude $\varphi \approx 28°37'$ [31]. Note that this component is architecturally distinct from, and considerably smaller than, the free-standing Delhi mural quadrant recorded by Hunter (1799) west of the Misra Yantra, which measured one degree as 2.833 in (implying a radius near 13.5 ft) and with which Jagannatha determined the latitude of Indraprastha (Delhi) as $28°39'$ N and the obliquity of the ecliptic as $23°28'$ in 1729; that free-standing instrument had already been destroyed by Kaye's time [13]. In October 2024 the Archaeological Survey of India announced conservation work on the Dakshinottara Bhitti and Karka Rasi Valaya components of the Misra Yantra, with plans to re-cut markings in marble rather than plaster [16].

4) Karka Rasi Valaya ("Circle of the Sign of Cancer"): The north wall of the Misra Yantra is deliberately inclined from the vertical by an angle of $5°$ and bears a large graduated circle, the Karka Rasi Valaya, with a sighting peg at its centre [13], [31].

Geometry of the summer-solstice ring. The inclination is not arbitrary but is fixed by the geometry of the summer solstice at Delhi's latitude. With the observatory's latitude $\varphi = 28°37'35''$ and the obliquity of the ecliptic $\varepsilon = 23°27'02''$ (as adopted by Kaye), the Sun's meridian zenith distance at the summer solstice, when $\delta_{\odot} = +\varepsilon$, is

$$z_{\text{solstice}} = \varphi - \varepsilon = 28°37'35'' - 23°27'02'' \approx 5°10'33''. \tag{39}$$

Because this residual zenith distance is small and directed toward the north, the noon Sun at midsummer passes just north of the zenith and consequently shines *over* the top of the north wall for a short interval centred on the solstice, illuminating the wall's northern face rather than the ground before it. The wall is tilted from the vertical by very nearly this same angle ($5°$, Kaye's rounded figure) so that its graduated face lies in a plane parallel to the ecliptic at the solstitial epoch, rather than parallel to the equator. Consequently the shadow of the central pin, projected onto this ecliptic-parallel plane, does not read equatorial hour angle or declination but instead reads directly

the Sun's *ecliptic longitude* $\lambda_\odot$ in the vicinity of the summer solstice point ($\lambda_\odot = 90^\circ$, the first point of Cancer):

$$\lambda_\odot \approx 90^\circ + \Delta\lambda_\odot(\text{pin-shadow position on Karka Rasi Valaya}). \tag{40}$$

This is confirmed by the 1910 restoration tablet recorded by Kaye: "Kark Rashi Balay Yantra. Restored A.H. 1910, tested by Jotish Gokul Chand for finding the longitude of the Sun when the Cancer or the point 90 in the ecliptic comes over the plane of the meridian" [13], and by Tomkins's independent description of the instrument as "used for determining the longitude of the Sun when the sign of Cancer was on the meridian" [31]. The instrument is thus a rare surviving example of an ecliptic-coordinate (rather than equatorial- or horizon-coordinate) masonry device among Jai Singh-era instruments, and Kaye speculates it may correspond to the "northern dial" mentioned in Jagannatha's own writings [13].

The Karka Rasi Valaya is one of only two Delhi surfaces (with the Misra Yantra's quadrants) for which a modern observational database exists, published by Rathnasree, Garg, Pandey and Chikara as "Karka Rasi Valaya: The Instrument on the Backwall of the Misra Yantra," *Indian Journal of History of Science* 43(3), 425–436 (2008) [26].

5) Agra Yantra (western quadrant, "amplitude instrument"): On the west side of the Misra Yantra building stands a second quadrant, distinguished from the Samrat-type quadrants by having a horizontal rather than axis-parallel face. Kaye records that its use "does not seem to have been understood by the restorers" of 1910 and notes that Hunter's late-eighteenth-century account makes no mention of it at all, again suggesting a post-Jai Singh addition [13]. Because amplitude is a horizon-system quantity, the angular displacement of a body's rising or setting point from the due east or west point of the horizon, this component belongs to the horizon coordinate system rather than the equatorial framework of the rest of the Misra Yantra. For a body of declination δ observed at latitude φ, the amplitude $\mathcal{A}$ at rising or setting satisfies

$$\sin\mathcal{A} = \frac{\sin\delta}{\cos\varphi}. \tag{41}$$

All Misra Yantra graduations were executed in lime plaster as of Kaye's 1918 survey, in contrast to the white marble scales seen on the structure today, which reflect subsequent refacing [13], [1].

F. Ancillary structures

Several minor features complete the documented Delhi instrument set. A measuring platform in front of the Misra Yantra, 47 ft by 43 ft, bears traces of a 20-ft-radius quadrant and was judged by Kaye to have been used for measurements during construction or repair of the instruments, rather than for astronomical observation itself [13]. Two stone pillars 17 ft apart stand south-west of the Misra Yantra, their connecting line oriented 35° east of north; absent from all historical textual accounts, Kaye speculated they may originally have supported one of Jai Singh's portable brass instruments of the type still found at Jaipur, such as the Unnatamsa Yantra or the large Yantra Raj astrolabe, the latter surviving today only at Jaipur, possibly having been relocated there from Delhi [13], [33]. Finally, the circular pillar atop the Samrat gnomon, discussed in §IV-A, likely served an azimuth-sighting function in its original form before acquiring its 1910-era European dial [13].

It is worth recording, for comparative purposes, which instrument types are conspicuously *absent* from Delhi: the Dhruva Darsaka, Krantivritta, Yantra Raj, Chakra Yantra, Digamsa, Unnatamsa, Rasivalaya, Kapala and the Disha Yantra ("Jai Singh's Seat") are all recorded by the UNESCO comparative analysis, and independently by Kaye's census, as present only at Jaipur or at Jaipur together with Varanasi and/or Ujjain, never at Delhi [33], [13]. This underscores that Delhi's astronomical repertoire, while smaller in instrument count than Jaipur's, includes two forms found nowhere else: the Misra Yantra as a whole, and its Karka Rasi Valaya sub-component in particular.

V. The Ujjain Observatory (Vedh Shala)

The Ujjain observatory, known locally as the Vedh Shala and today administered as the Government Jiwaji Observatory, stands in the Jaisinghpura quarter on the bank of the Shipra (Sipra) river. G. R. Kaye's 1918 Archaeological Survey of India monograph records the site's elements as latitude $23^\circ 10'$ N, longitude $75^\circ 46' 00''$ E of Greenwich, elevation 1600 ft, magnetic declination $0^\circ 40'$ E, and a local apparent-time offset of $26^{\mathrm{m}}53^{\mathrm{s}}$ from Indian Standard Time [13]. Modern coordinates are given as 23.1713° N, 75.7665° E [40]. The founding date is unsettled: sources variously give 1719 (while Jai Singh was governor of Malwa), 1725, 1725–30, or Kaye's own conclusion of "probably between A.D. 1728 and A.D. 1734" [32], [40], [13]; Jai Singh's five observatories as a group (Delhi, Jaipur, Ujjain, Mathura and Varanasi) were completed between 1724 and 1735 [38].

Ujjain as the traditional Indian prime meridian. Ujjain occupies a distinctive place in the history of Indian astronomy as the conventional zero-longitude reference of classical Sanskrit astronomical treatises, the *siddhāntas*. The district administration states that the *Sūrya Siddhānta* and the *Pañcasiddhāntikā* were composed at Ujjain, that Indian astronomers traditionally place the Tropic of Cancer through the city, and that from around the fourth century BC Ujjain carried the reputation of being "India's Greenwich" [32]. Kaye documents the textual basis for this tradition directly: the *Pañcasiddhāntikā* (xiii, 17) states that "Ujjayinī is near to Laṅkā, being situated to the north on the same meridian; hence the noon of the two places occurs at the same time," giving the latitude (v. 19) as 24° N; and the *Sūrya Siddhānta* (i, 62) places Ujjain (Avanti) on the same meridian as the mythical mountain seat of the gods [13]. Kaye additionally quotes al-Bīrūnī: "all the canons of the Hindus agree in this, that the latitude of Ujain is 24 degrees, and that the sun culminates over it at the time of the summer solstice" [13]. This traditional identification should, however, be read as a Siddhāntic convention rather than a physically exact statement: Kaye himself judged it "doubtful whether there ever was a fixed position in ancient Ujjain which was considered as of zero longitude" [13], the

observatory's actual latitude is close to $23^\circ 10'$ rather than 24°, and precession of the equinoxes has since shifted the zero-shadow (Tropic) line roughly 30 km north of the city, to Dongla [20]. Modern civil practice nonetheless preserves the convention: Hindu horoscopes and the *pañcāṅga* (almanac) continue to be reckoned on Ujjain local time, approximately 29 minutes behind Indian Standard Time [22].

On the instrument inventory. It must be stated explicitly that the frequently repeated claim that the Ujjain site "consists of 13 architectural astronomy instruments" [40], [19] is a conflation error, not a documented instrument count. The figure of "13" originates with V. N. Sharma's statement that Jai Singh built thirteen different *types* of instrument in total, across all five of his observatories combined (Delhi, Jaipur, Ujjain, Mathura and Varanasi), not thirteen instruments at Ujjain alone [29]. Kaye's own 1918 survey found only **four** masonry instruments standing at Ujjain: the Samrat, the Dakshinovritti (Bhitti), the Nāri Valaya, and the Digamsa [13]; the observatory's own modern signage lists **five** yantras, adding the Shanku Yantra, itself a twentieth-century addition discussed in §V-E and not an original Jai Singh-era instrument [12]. Ujjain's genuine instrument count is thus four to five, roughly a third of the oft-cited figure.

A. Samrat Yantra ("Supreme Instrument")

Kaye records the Ujjain Samrat Yantra as "practically of the same size as the one at Benares and the smaller one at Jaipur, namely, 22 feet high, the edge of the gnomon 47½ feet, and the radius of each quadrant 9 feet 1 inch" [13]. In Hunter's time (*c.* 1796) the quadrants were divided into *ghaṭīs* (a traditional Indian time unit) and subdivisions, with tangent scales marked along the gnomon edges; by 1918 these graduations had entirely disappeared, leaving only "a skeleton" of the structure [13]. Present-day reporting from the observatory gives the same 22-ft height, with the gnomon inclined at $23^\circ 10'$, the local latitude, and quarter-circle quadrants to east and west graduated in hours, minutes and thirds [21].

Geometry. The instrument follows the same equatorial-coordinate principle as the Delhi and Jaipur Samrat Yantras. With AB the gnomon edge and $\angle ABC = \varphi$ the observatory's latitude, and with GH the radius of a quadrant, Kaye's construction gives the time before noon as the arc KG and the Sun's declination as the angle $\angle HGL$, defined by the tangent relation

$$\tan(\angle HGL) = \frac{HL}{GH}. \tag{42}$$

Kaye notes there is no earlier precedent for tangent scales engraved on a gnomon edge, so the device may be an original contribution of Jai Singh himself [13]. Because the gnomon hypotenuse is inclined at $\varphi = 23^\circ 10'$, it lies parallel to the Earth's rotation axis, and the quadrant faces lie in the equatorial plane; the shadow of the gnomon edge therefore sweeps the quadrant at the uniform rate

$$\frac{dH}{dt} = 15^\circ\,\text{hour}^{-1}, \tag{43}$$

so that hour angle H maps linearly onto arc length along the quadrant. Declination is recovered from the perpendicular displacement d of the shadow edge, measured along the gnomon at distance R (the quadrant radius):

$$\delta = \arctan\!\left(\frac{d}{R}\right), \tag{44}$$

identical in form to Equation (42) and to the Delhi construction, and again requiring a non-uniform tangent graduation of the gnomon edge. Converting the local apparent reading to Indian Standard Time requires the equation of time together with the fixed longitude correction of $26^{\mathrm{m}}53^{\mathrm{s}}$ relative to the 82.5° E standard meridian, for which a correction table is posted beside the instrument [12], [13].

Precision. The Samrat class of instrument belongs to Sharma's high-precision category, with a design target of $\pm 2^{\mathrm{s}}$ in time, $\pm 15''$ in right ascension and $\pm 1'$ in declination, degraded in practice by construction defects to ± 10–90^{s} in time and $\pm 1'$ to $\pm 15'$ in declination [29].

The Sun-Dial (Samrat) is listed among the four instruments built by Jai Singh himself at Ujjain [32]. It was already ruined by 1918, when Kaye recommended restoration "on the same lines as the Benares instruments," cautioning that "European graduations and symbols should not be employed" [13]. It remains operational today as a display and teaching dial [22].

B. Nadi Valaya Yantra ("circular dial")

Kaye describes the Nadi Valaya as situated a few feet south of the Samrat Yantra: "a cylinder 7½ feet long, 3 feet 7½ inches in diameter, whose axis is fixed horizontally in the plane of the meridian, the faces of the cylinder being cut parallel to the plane of the equator," each face originally carrying a central iron style surrounded by a circle graduated into *ghaṭīs* and subdivisions; both styles and graduations had vanished by 1918 [13].

Geometry. The cylinder's axis is the polar axis, inclined at the latitude $\varphi = 23^\circ 10'$ to the horizontal, so each circular face lies in a plane parallel to the celestial equator. The style at the centre of each face is parallel to the polar axis, and its shadow on the corresponding face rotates at the uniform equatorial rate of Equation (43), giving local apparent time directly from the shadow position, calibrated in *ghaṭīs* (1 *ghaṭī* = 24 min) and *palas* (1 *pala* = 24 s) [13]. The instrument additionally functions as a binary detector of the Sun's hemisphere: the north face is illuminated only while the solar declination $\delta_\odot > 0$, and the south face only while $\delta_\odot < 0$; at either equinox, when $\delta_\odot = 0$, sunlight grazes both faces edge-on and neither is illuminated. This behaviour is still used for public equinox demonstrations at the observatory, which reports that "before September 23 … the round part of the northern edge of the Nadivalaya Yantra received sunlight. On September 23, no sunlight will be visible on the northern and southern edges and from September 24 … the sunlight will fall on the southern circle" [8].

One of the four instruments attributed to Jai Singh at Ujjain, the Nadi Valaya was found stripped of its styles and graduations by Kaye in 1918, who recommended their replacement [32], [13]. Sharma classes the Nāḍīvalaya, together with the Dhruva Paṭṭikā, as an instrument "clearly designed with a

layman in mind… of little value to a researcher" [29]. It has since been restored and remains in demonstrative use [8].

C. Bhitti Yantra / Dakshinovritti Yantra ("meridian wall instrument")

Kaye records this instrument at Ujjain as the Dakshinovritti Yantra, describing the generic type as being "like the mural quadrants found in most mediaeval observatories… essentially a wall in the meridian… corresponds to the modern transit circle" [13]. The Ujjain observatory itself refers to it today as the Bhitti Yantra [12]. Some tourism sources describe the Bhitti Yantra as unique to Ujjain, but this is contradicted by Kaye, who documents Dakshinovritti-type instruments at Jaipur, Ujjain and Varanasi, and records that a further example originally stood at Delhi before being destroyed [13], [22].

The instrument consists of a wall lying in the meridian, its east face carrying a double quadrant whose two centres, near the top corners of the wall, are 25 ft apart; traces of a tangent scale survive on the ledge below the quadrants. A flight of steps on the west side leads to a narrow platform bearing a small 2-ft-diameter pillar recorded by Hunter as the Agra Yantra, used for observing the amplitude of rising and setting bodies (cf. Equation (41) for the underlying relation), plus a further small parapet projection bearing a horizontal dial he called the "Puchlia Yantra." By 1918 the masonry survived largely intact, but all graduations had disappeared and the wall itself had come to lean about 5° from the vertical [13].

Geometry. The instrument operates in the local horizon system restricted to the meridian plane, which at the moment of transit is exactly convertible to the equatorial system. Two sighting pegs are fixed at the top of the wall, one used for bodies transiting south of the zenith and one for bodies transiting north of it. For an upper culmination south of the zenith,

$$z = \varphi - \delta, \tag{45}$$

and for one culminating north of the zenith,

$$z = \delta - \varphi, \tag{46}$$

so that in either case

$$\delta = \varphi \mp z, \qquad a_{\text{mer}} = 90^\circ - z, \tag{47}$$

which is precisely why two peg-centres, rather than one, are provided. The tangent scale recorded on the ledge below the quadrants is the graphical equivalent of $z = \arctan(x/R)$ for a linear shadow offset x at scale radius R [13].

Kaye judged the Bhitti Yantra the most difficult Ujjain instrument to conserve, remarking that "the only solution seems to be to take it down and rebuild it stone by stone on a secure foundation" [13]. It remains standing and interpreted for visitors today [22].

D. Digamsa Yantra (azimuth instrument): Rebuilt 1974

Kaye's 1918 description of the Ujjain Digamsa records it as similar to the Benares example, situated close to the Samrat Yantra on its east side, and consisting of an outer circular wall 36 ft 10 in in diameter and 8 ft 10 in high, concentric with an inner wall 24 ft 4 in in diameter and 4 ft 6 in high; a central pillar, since removed, originally stood at the centre, with cross-wires stretched north–south and east–west over the outer wall and arched openings at the four cardinal points of both walls [13]. Generically, Kaye describes the Digamsa type as "a fixed large circular protractor": a central pillar (typically about 4 ft high) surrounded by two graduated circular walls, the outer twice the height of the inner, with cross-wires stretched from the cardinal points [13].

Geometry. The instrument works purely in the horizon (altitude–azimuth) coordinate system. The graduated outer wall is a materialized horizon circle of radius approximately 18 ft, read from the intersection of a sightline with the rim [13]. With the auxiliary Turīya Yantra mounted on the central rod, both azimuth A and altitude a of a body can be read; these are related to the equatorial coordinates (H, δ) at the observatory's latitude $\varphi = 23^\circ 10'$ by the standard transformation

$$\sin\delta = \sin\varphi \sin a + \cos\varphi \cos a \cos A, \tag{48}$$

with the companion relation for hour angle obtained from the analogous cosine rule. Kaye's own assessment of practical performance was that "by the aid of a movable string and an assistant, azimuth (horizontal angles) observations can be made with fair accuracy," though such wall-and-cross-wire designs rank below the Samrat and Shaṣṭhāṃśa in precision [13], [29].

Explicit note on reconstruction. Hunter, visiting in 1792–93, found the Digamsa building already "roofed with tiles and converted into the abode of a Hindu deity," showing that the instrument had fallen out of astronomical use well before Kaye's survey; Kaye himself found the walls badly cracked, their foundations exposed by drainage erosion, and recommended replacing the cross-wires and diverting the adjacent nullah [13]. The district administration's own account states plainly that, "having arrived at the last moments of its position, the Digansh Yantra was re-constructed in 1974" [32]. This 1974 date is corroborated by the discrepancy between Kaye's 1918 outer-wall diameter of 36 ft 10 in and the outer-wall diameter of 32 ft 10 in reported by the observatory in 2025 [13], [21]: **the Digamsa Yantra visible at Ujjain today is therefore a twentieth-century reconstruction, not the original Jai Singh-era fabric**, and this distinction should be preserved in any historical or metrological use of the instrument's dimensions.

E. Shanku Yantra (gnomon dial): A 1982 Addition, Not by Jai Singh

The Shanku Yantra is a vertical gnomon (śaṅku) fixed at the centre of a horizontal circular platform, from whose shadow tip seven curves are traced, jointly representing the twelve tropical zodiacal months (saṅkrāntis) [12]. It must be stated explicitly that **this instrument was not built by Jai Singh**: the district administration records that "the Shanku (Gnomon) Yantra has been prepared under the direction of (Late) Shri G. S. Apte," the observatory's first modern superintendent, and that it "was re-built in 1982" [32]. It therefore postdates the observatory's



Fig. 15. General view of the Vedh Shala (Government Jiwaji Observatory), Ujjain, showing the Samrat Yantra and surrounding instrument platforms.

eighteenth-century instruments by more than 250 years and represents a modern didactic addition rather than an original component of Jai Singh's design.

Geometry. For a vertical gnomon of height h casting a noon shadow of length s, the Sun's zenith distance is

$$z = \arctan\!\left(\frac{s}{h}\right), \qquad a = 90^\circ - z, \tag{49}$$

and at local apparent noon the zenith distance is related to declination and latitude by

$$z = \varphi - \delta. \tag{50}$$

At an equinox, $\delta = 0$, so Equations (49)–(50) combine to give the observatory's latitude directly from the equinoctial noon shadow,

$$\varphi = \arctan\!\left(\frac{s_{\text{equinox}}}{h}\right), \tag{51}$$

exactly as claimed on the observatory's own interpretive signage [12]. The seven engraved curves are the loci of the shadow tip (in general hyperbolae, degenerating to a straight line only at $\delta = 0$) for the solstitial, equinoctial and intermediate *saṅkrānti* declinations; because each non-zero declination is shared by an ascending and a descending solar month, twelve zodiacal months are represented by only seven distinct curves [2]. The Shanku Yantra is thus a direct physical embodiment of the classical Siddhāntic method of expressing terrestrial latitude via the equinoctial shadow of a gnomon, the same method underlying Ujjain's traditional shadow ratio of 310/720, corresponding to

$$\varphi_{\text{Siddhāntic}} = \arctan\!\left(\frac{310}{720}\right) \approx 23^\circ 17' 40'' \tag{52}$$

as recorded by Kaye [13].

Despite being a later addition, the Shanku Yantra is today the most actively used instrument at the site: it is paired with the Nadi Valaya for public equinox demonstrations [8], and an example at the associated Varahamihira observatory at Dongla was used to observe a zero-shadow (Sun-overhead) event at 12:28 p.m. on 21 June 2025 [20].

Image credit: Bernard Gagnon, CC BY-SA 3.0, https://commons.wikimedia.org/wiki/File:Vedh_Shala,_Ujjain_01.jpg

F. Summary

Ujjain's surviving instrument set is modest relative to Jaipur's but historically significant on two distinct grounds: it is the site of the traditional Indian prime meridian referenced throughout the classical *siddhānta* literature, and its Samrat, Nadi Valaya and Bhitti Yantras represent original eighteenth-century masonry embodiments of equatorial- and meridian-coordinate astronomy under Jai Singh's direct patronage [13], [32]. Two important caveats bear repeating for any quantitative or historical use of the site: the popularly cited "13 instruments" figure conflates Sharma's five-observatory instrument-type count with Ujjain's actual four-to-five-instrument inventory [29], [13], [12]; and two of the instruments seen by visitors today, the Digamsa (rebuilt 1974) and the Shanku Yantra (built 1982 by G. S. Apte), are twentieth-century constructions rather than original Jai Singh-era fabric, notwithstanding their integration into the observatory's present didactic presentation [32].

VI. The Varanasi Observatory (Man Mandir)

A. Site and historical framing

The Varanasi instruments stand on the roof of the Man Mandir, a palace built near Manikarnika Ghat on the Ganges by Raja Man Singh of Amber, who died in 1614, a century before any astronomical instrument was added [14]. Jai Singh II placed his instruments on this rooftop around A.D. 1737 (Williams's date, accepted by Kaye), with Delhi dated to roughly 1724 and Jaipur to 1734 [14]. Site constants recorded by Kaye after the 1912 restoration are $\varphi = 25^\circ 18' 24.9''$N, longitude $83^\circ 00' 46.1''$E, elevation 360 ft [14]. Jai Singh described the Mathura, Varanasi, and Ujjain instruments as built "in order to confirm the observations made at Delhi"; Kaye calls Varanasi confirmatory rather than primary [14], adding it "has long since ceased to be used for practical purposes" [14].

Unlike the open-ground layouts at Delhi and Jaipur, the instruments here are compressed onto a constrained rooftop, shaping the final inventory: two Samrat dials, two meridian (Dakshinovritti) walls, one Digamsa, one Chakra, and one Nadivalaya, with no Jai Prakash, Ram Yantra, Shashtamsa, Misra, or Rāśivalāya ever built here [14], [13]. The constraint is explicit in Kaye's account of a lost second Nadivalaya, removed because "at the present time there is no space to accommodate such an instrument" [14].

B. Samrat Yantra: the equinoctial sundial

The larger Samrat Yantra ("Supreme Instrument") is, in Kaye's words, "of the same type as those at the other observatories, and is the same size as that at Ujjain and the smaller one at Jaipur" [14]. Its gnomon stands 22 ft 3.5 in (6.79 m) high with a hypotenuse of 39 ft 8.5 in (12.10 m), flanked by two quadrants of radius 9 ft 1.5 in (2.78 m), faced in sandstone and carefully graduated [14]. The Wikiversity heritage dossier gives compatible metric figures: a wall 10.973 m long, 1.372 m broad, rising from 1.937 m to 6.795 m so as to "point directly to the North Pole" [41].



Fig. 16. The Samrat Yantra at the Man Mandir observatory, Varanasi. The triangular gnomon's hypotenuse is inclined at the local latitude ($\varphi \approx 25.3°$N) so as to lie parallel to Earth's rotation axis, with flanking quadrants in the equatorial plane [14]. Photo: Nandanupadhyay, CC BY-SA 3.0 (https://commons.wikimedia.org/wiki/File:Samrat_Yantram_at_Observatory_of_Man_Singh.jpg).

Geometrically, this is an equatorial (equinoctial) sundial: the gnomon hypotenuse is inclined to the horizontal by $\varphi = 25°18'24.9''$, making it a polar axis, while the two quadrants lie in the plane of the equator [14]. Because the shadow-receiving surface is the equatorial plane, the shadow sweeps the quadrant scale *uniformly* at $15°$ per hour of H, the linear-in-H behavior described in Section II, and the reason Kaye classes the Samrat as an "equal-hour" dial, unlike a horizontal or vertical dial [14]. Declination is read separately, along the gnomon edge: with R the quadrant radius (2.78 m) and y the shadow-tip displacement along the gnomon,

$$\tan\delta = \frac{y}{R}, \tag{53}$$

so the gnomon edge is a tangent scale for declination whose resolution degrades as $|\delta|$ grows [14]. In Kaye's notation, with GH the quadrant radius and HL the gnomon displacement, "$\tan HGL = HL/GH$" [14], identical in substance to Equation (53).

Converting a Samrat reading to civil time requires the two corrections of Section II: the equation of time, which Kaye attributes to "the eccentricity of the earth's orbit" together with "the obliquity of the ecliptic," and a longitude correction to Indian Standard Time's reference meridian, $82.5°$E [14]. Kaye's recorded offset of 2 min 03 s between Varanasi local and standard time follows from $(83°00'46'' - 82°30')/15°$ per hour, matching his figure exactly [14].

The finite gnomon-wall thickness duplicates the dial into morning and afternoon instruments on its east and west faces [14], and at 2.78 m quadrant radius the Varanasi Samrat is markedly smaller than Jaipur's Brihat Samrat, whose gnomon rises 22.6 m with quadrant radii of 15.15 m, reading to 2 seconds of time [5], illustrating, per Equation (9), how a 5.4-fold radius increase buys finer resolution for the same graduation tolerance.

C. Laghu Samrat Yantra: the small equinoctial dial

The smaller Samrat Yantra stands 8 ft 3 in (2.51 m) high with quadrants of radius 3 ft 2 in (0.97 m) [14]. It is identical in principle to the larger Samrat, reading apparent solar time, hour angle, and declination via the tangent-scale construction of Equation (53), but roughly 2.9 times coarser given its smaller radius, making it a rapid-reference rather than precision instrument [14]. Comparison of an 1773 drawing with the present layout suggests both this dial and the Nadivalaya have been displaced from their original positions [14].

D. Dakshinovritti Yantra: the meridian walls

Two meridian (Dakshinovritti, "south-circle") instruments exist at Varanasi. The first is a double quadrant on the east wall of the great Samrat's gnomon, each quadrant of radius 10 ft 7 in (3.23 m); a fixed pin atop each quadrant casts a noon shadow, or is sighted along at night, giving the zenith distance of a culminating body [14]. Apparently absent in an 1773 drawing but present by 1865, it is a later addition or rebuild [14]. The second is a free-standing meridian wall south of the Samrat, with two quadrants of radius 7 ft 9.75 in (2.38 m) on its east face; an 1777 account by Sir Robert Barker describes larger, differing radii, suggesting substantial later rebuilding [14]. The entrance mural quadrant, a wall 3.353 m high and 2.775 m broad, is "now in ruins" [41].

Both instruments operate in the horizon system restricted to the meridian plane, where azimuth collapses to $0°$ or $180°$ and a single reading gives a or $z = 90° - a$ at culmination [14]. Applying Equation (7), a culmination altitude with known $\varphi = 25.3°$N yields declination directly, $\delta = \varphi - z$ south of the zenith. Because the Sun's declination never exceeds $\varepsilon_{\rm obl} \approx 23.4° < \varphi$, the noon Sun always culminates south of the zenith at Varanasi; the northern quadrant instead serves high-declination stars, circumpolar objects, and the Moon [14]. Kaye likens its function to "the modern transit circle" [14]; a modern account notes it "could even measure the Moon's position by utilizing the faint gnomon shadow cast by moonlight" [27].

E. Nadivalaya Yantra: the cylindrical equatorial dial

The Nadivalaya ("circular dial"), inscribed on-site as "Uttara-dakshino Gola" (north-and-south dial), is a cylindrical instrument whose axis runs north–south with two circular faces parallel to the equatorial plane; an iron style at the center of each face is surrounded by circles graduated in hours and in traditional ghati/pala units [14]. Since each face is parallel to the equatorial plane, its normal, the style, is the polar axis, inclined $\varphi = 25.3°$ to the horizontal; Kaye's phrase "horizontal and pointing north and south" is best read as describing orientation on the roof rather than a literal horizontal style [14].

As an equatorial-plane sundial, shadow azimuth about the style equals the Sun's hour angle exactly, a uniform $15°$ per hour, or 60 ghatis per day so 1 ghati $= 6° = 24$ minutes [14]. Because sunlight strikes the north face only when $\delta_\odot > 0$ and the south face only when $\delta_\odot < 0$, the instrument



Fig. 17. The Digamsa Yantra, a large circular azimuth instrument at Varanasi, described by Kaye as "a large circular protractor" [14]. Photo: Nandanupadhyay, CC BY-SA 3.0 (https://commons.wikimedia.org/wiki/File:Digansa_Yantra_at_Observatory_of_Man_Singh.jpg).

doubles as an equinox detector, "show[ing], very effectively, the passage of the sun across the equator" [14]. A now-lost second Nadivalaya, 6 ft 2 in (1.88 m) diameter, stood southeast of the Digamsa, attested by Williams, Hunter (1797), and Bapu Deva Sastri (1865), gone by Kaye's time for lack of roof space [14]. Kaye's 1918 volume flags the surviving example as "quite modern" (substantially rebuilt) and possibly originally built for northern-hemisphere use only, echoing Jagannath's own criticism that it "is not of much value, because it only gives readings for northerly observations" [13], [14].

F. Digamsa Yantra: the azimuth circle

The Digamsa ("azimuth instrument") is the large circular structure at the east of the terrace, with an exterior diameter of 31.5 ft (9.60 m), an inner diameter of 21 ft (6.40 m), an outer wall 8 ft 4 in (2.54 m) high, and an inner wall and central pillar each 4 ft 2 in (1.27 m) high, topped by an iron rod matching the outer wall's height [14], [13]. This makes the Varanasi Digamsa the largest-diameter example of the three surviving instruments of its type, exceeding those at Jaipur (27 ft/17 ft) and Ujjain (30 ft 10 in/24 ft 4 in) [13]. It is also the only Varanasi instrument visible from street level, its curved outer wall glimpsed above the riverfront balconies [15], [13].

The Digamsa's construction, quoted by Kaye from the astronomer Jagannatha's instructions, prescribes three concentric graduated horizon circles with cardinal cross-wires and a taut "thread of vision" from the central pillar to the outer rim [13]. The rim graduation crossed by this thread, or by the central gnomon rod's shadow, gives azimuth A directly and linearly in degrees, with $A_{\mathrm{sun}} = \text{shadow bearing} + 180^\circ$ [14], [13]. The Digamsa supplies only one of the two horizon coordinates of Equation (6); altitude is not measured, which is why it complements the meridian quadrants and equatorial instruments on the same roof [14]. Kaye already recorded in 1920 that it was "of little practical use, owing to its being surrounded on all sides but one by buildings," a limitation only worsened by later urbanization [14], [15].

G. Chakra Yantra: the equatorial armilla

The Chakra ("circle") Yantra is an iron declination circle 3 ft 7 in (1.09 m) in diameter, 1 in thick and 2 in broad, faced in brass and graduated in degrees and minutes, mounted to revolve about an axis parallel to Earth's rotation axis; a separate graduated hour circle sits at the southern end of this axis on the supporting pillar [14]. Kaye classes the Chakra with the equatorial-armillary family common to medieval observatories, tracing the type to the Islamic *dhāt al-ḥalaq* armillary tradition [13]. At 1.09 m diameter, the Varanasi ring is only about 60% the diameter of the two Jaipur rings (each 6 ft), again reflecting the rooftop's scale constraint [13].

Because the moving ring is mounted as an hour circle, a great circle through both celestial poles, rotating it until the target body is bisected in its sighting tube sets the ring to the body's declination directly on its own graduated rim, while the fixed equatorial circle at the base simultaneously reads the hour angle H [13]. Right ascension then follows from Equation (2), $\alpha = \mathrm{LST} - H$. Because the mounting axis is itself the polar axis, a single rotation tracks the diurnal motion of any object, and both equatorial coordinates are read without further transformation [13].

The instrument's accuracy was doubted in its own time: Hunter's 1797 account, quoted by Kaye, complains that "the index is not furnished with sights; and the pin by which it is fixed to the centre of the circle is so prominent, that the eye cannot look along the index itself" [14]. That pin survives as a striking material-culture detail: the fastening wedge is carved into the rough shape of a horse's head, a form Kaye identifies as the Arabic *faras* ("horse") wedge, concluding "there is evidence to show that the horse shaped design of the wedge was brought to India by the Muslims," interesting "as evidence of the persistence of a traditional design, and in some degree as evidence of the ultimate source of the design of Jai Singh's instruments" [14]. This fitting is one of the strongest concrete indications of Islamic and Persian astronomical-instrument transmission into Jai Singh's designs.

H. Condition, protection, and current status

The Samrat, Digamsa, Chakra, Nadivalaya, and both meridian walls underwent complete restoration in 1911–12 under the Maharaja of Jaipur's court astronomer Pandit Gokal Chand, commemorated by an on-site marble plaque [14], [41]. The site has been protected since 1958 under the Ancient Monuments and Archaeological Sites and Remains Act, listed by the Archaeological Survey of India as the "Observatory of Mansingh" [41], [3]. Despite this, the Astronomical Society of India's outreach program reports the Varanasi instruments, with those at Delhi, "are in a state of disrepair," graduation markings largely illegible, though "yet in a condition to be used for Astronomy observations and teaching" [4]. A Virtual Experiential Museum was inaugurated at the site in February 2019 [24]. Figure 18 shows the rooftop setting above the city.

VII. The Mathura Observatory: A Lost Instrument (Historical Reconstruction)

Of the five observatories built by Sawai Jai Singh II, the Mathura installation is the only one to have vanished entirely.



Fig. 18. View over Varanasi from the Man Mandir observatory rooftop, illustrating the dense urban surroundings that Kaye and later observers cite as limiting several instruments' sky access [14], [15]. Photo: Nandanupadhyay, CC BY-SA 3.0 (https://commons.wikimedia.org/wiki/File:View_of_Varanasi_city_from_the_roof_top_of_Observatory_of_Man_Singh.jpg).

No instrument, wall, wedge, or graduated arc survives above ground, and, crucially, *no photograph, sketch, or measured drawing of any Mathura instrument is known to exist*. This section is therefore necessarily reconstructive: every claim about what the observatory contained rests on secondhand textual description, chiefly by the eighteenth-century Jesuit missionary-geographer Joseph Tieffenthaler and, more briefly, by the British official Hunter, rather than on surviving physical or visual evidence.

A. Site and destruction

The observatory stood atop the fort at Mathura, on a site associated with the Kans Qila ("Kansa's Fort"), rebuilt in the historical period by Raja Man Singh of Amber and later used occasionally by Jai Singh [9]. Kaye situates Mathura as the last of Jai Singh's observatories, implying a construction date of roughly 1737–1743, since Boudier's Jesuit account of an early-1734 visit to Delhi and Jaipur mentions neither Varanasi nor Mathura [13]. Other secondary sources place construction earlier, around 1723–1725, so the date should be treated as uncertain within the 1720s–1730s range [17].

The destruction is documented in blunt terms by F. S. Growse, in his 1883 district memoir of Mathura: "The whole of the Mathurā observatory has now disappeared. A little before the mutiny the buildings were sold to the great Government contractor, Joti Prasad, who destroyed them for the sake of the materials. Certainly, they had ceased to be of any practical use; but they were of interest, both in the history of science and as a memorial of one of the most remarkable men in the long line of Indian sovereigns and their inconsiderate demolition is a matter for regret" [9]. "The mutiny" refers to the Indian Rebellion of 1857, so the masonry was salvaged for building material shortly before that uprising. No systematic survey, measured plan, or photographic record was made before demolition, unlike Varanasi, Jaipur, and Delhi, documented by Barker and Campbell in the 1770s and photographed extensively thereafter. Everything known about the Mathura instruments' form and dimensions therefore derives from a handful of pre-demolition textual witnesses.

B. The textual record: Tieffenthaler and Hunter

The principal source is Joseph Tieffenthaler, an Austrian Jesuit missionary and geographer who traveled through northern India in the mid-eighteenth century and left a description of the Mathura instruments, later excerpted in Kaye's compilation. Tieffenthaler describes a gnomon of limestone construction, reportedly some 13 Paris feet in extent, and equinoctial dials of about 5 spans, though the transcribed digits are not fully reliable given the condition of the surviving copies [13], [17]. He offers a comparative judgment of quality, describing it as "only a feeble imitation of that at Djepour [Jaipur]" [13].

A second, briefer witness is Hunter's account, published around 1799, enumerating the instruments observed at several of Jai Singh's sites, including Mathura, in a numbered list; the Mathura entry is terse compared to Hunter's treatment of Delhi and Jaipur [17]. A UNESCO nomination dossier prepared for the Jaipur observatory notes that a Nadivalaya (cylindrical equatorial dial) and a Dakshinottara Bhitti (meridian wall) were "known to be present at Mathura," suggesting overlap with the equatorial and meridian instrument types documented at Varanasi (Section VI) rather than a wholly novel design [17]. The dossier bluntly summarizes the instruments' fate: "The ones at Mathura and Ujjain are completely lost while Benaras is in a poor condition" [17].

Beyond these two witnesses, no other pre-demolition eyewitness description has been located. Because Tieffenthaler and Hunter wrote as external observers, and their texts survive only through subsequent transcription and uncertain OCR of archival copies, any numerical dimension attributed to a Mathura instrument should be treated as approximate and provisional, unlike Kaye's authoritative measured values for Varanasi after its 1912 restoration.

C. Historiographical caution

Several disagreements complicate the record and are stated explicitly rather than resolved by conjecture. First, the construction date is variously given as 1723, 1725, or (per Kaye) after 1734 [17]. Second, sources disagree whether Mathura or Jaipur was Jai Singh's last observatory, Kaye favoring Mathura and other compilations favoring Jaipur [17]. Third, Hunter misattributes the fort's construction to Jai Singh himself, whereas Kaye and Growse are explicit it was built by Man Singh I of Amber, with Jai Singh only later adding instruments [9], [17]. Given the complete loss of the instruments and the thinness of the surviving descriptions, no attempt is made here to reconstruct precise dimensions, materials, or a site plan beyond what Tieffenthaler and Hunter explicitly state.

D. The modern site

The presumed site survives only as part of the Kans Qila mound, a ruin in Mathura where little more than fragments of outer walls remain [17]. The mound is protected at the state level by Uttar Pradesh (reference S-UP-91), but is *not* among

the Archaeological Survey of India's centrally protected monuments [17]. No historical marker or signage identifies it as a former Jantar Mantar, and no museum display commemorates Jai Singh's work there, in marked contrast to the restored, museum-equipped observatories at Varanasi, Jaipur, and Delhi [17]. Because no image of any instrument or of the site in its observatory-era state is available, this section relies solely on the textual record above and includes no illustrative figure.

VIII. Comparative Discussion

Table I summarizes the instrument inventory across the four surviving Jantar Mantar sites (Mathura is excluded, as no instrument survives there; see Section VII). Several patterns emerge from a cross-site comparison.

TABLE I
Comparative instrument inventory across the surviving Jantar Mantar observatories [13], [33], [28].

Site	Instr. count	Distinguishing instruments
Jaipur	19	Kapala Yantra and 12 Rasivalaya (zodiacal) instruments, unique to this site
Delhi	5 major (Misra Yantra is compound, with 5 sub-components)	Misra Yantra, unique to this site
Ujjain	4–5	Traditional Indian prime meridian; Digamsa rebuilt 1974, Shanku added 1982 (not original)
Varanasi	6	Built atop a pre-existing 1600 CE palace; Chakra Yantra shows Islamic instrument-design influence

A. Shared Design Logic

Despite differing in instrument count, all four surviving sites share the same underlying engineering logic described in Section II: angular precision is achieved through physical scale rather than fine mechanical graduation. Every site includes at least one Samrat Yantra (a giant equatorial sundial whose gnomon is inclined at the local latitude), confirming that Jai Singh regarded this instrument as the indispensable core of each observatory, from which local apparent solar time could be read directly to a claimed precision of about two seconds [13].

B. Duplication versus Site-Specific Instruments

The Samrat Yantra, Jai Prakash Yantra (or its close relatives Kapala/Dakshinovritti), Ram Yantra (or Chakra/Digamsa horizon instruments), and Nadivalaya-type polar-axis dials recur at multiple sites in modified form, suggesting a standard instrumental repertoire that Jai Singh's astronomers adapted to each site's available space and to the specific latitude of construction (compare, for instance, the differing gnomon angles of the Samrat Yantra at each site, which must equal local latitude, as derived in Section II). By contrast, the Misra Yantra (Delhi only) and the Kapala/Rasivalaya group (Jaipur only) represent site-specific instrumentation, and Jaipur's status as Jai Singh's purpose-built capital observatory, constructed with more available land and resources than the constrained urban sites at Delhi and Varanasi, likely explains why it alone hosts the ecliptic-coordinate Rasivalaya instruments described in Section III.

C. Sources of Error and Historical Assessment

Even instruments of this scale were subject to systematic errors beyond simple reading precision: masonry settling, thermal expansion of marble and stone facings, refraction near the horizon (relevant to low-altitude readings on the Digamsa and Chakra instruments), and small errors in the initial alignment of the meridian line itself. Kaye's 1918 survey found several instruments measurably out of true alignment by the early twentieth century, likely from foundation settling over nearly two centuries [13]. Modern surveys using GPS and precision theodolites have largely confirmed that, when new, the primary gnomon angles were cut to within a few arcminutes of the theoretically correct local latitude [33], a remarkable achievement for masonry construction supervised without the aid of the telescope.

IX. Conclusion

The Jantar Mantar network represents a distinctive episode in the global history of astronomy: the deliberate substitution of architectural scale for optical and mechanical precision, undertaken at the exact historical moment, the second quarter of the eighteenth century, when European observatories were moving decisively in the opposite direction, toward smaller telescopic instruments of ever-finer mechanical graduation. Jai Singh II's five observatories were not built in ignorance of the telescope; contemporary accounts indicate his court was aware of European instruments, and he is known to have consulted Portuguese Jesuit sources and possibly obtained European ephemerides [28]. Rather, the masonry instruments reflect a considered engineering choice suited to available materials, skilled labor, and the specific goal of correcting tabulated planetary positions and eclipse predictions to the accuracy the naked eye could achieve at large scale.

Of the four surviving sites, Jaipur remains the most complete expression of Jai Singh's design program, preserving instrument types, the Kapala Yantra and the twelve Rasivalaya, found nowhere else, while Delhi's Misra Yantra demonstrates a willingness to combine several measurement functions into a single compound structure. Ujjain's observatory, though smaller, carries particular significance as the site of the traditional Indian astronomical prime meridian, linking Jai Singh's eighteenth-century instrumentation to a much older tradition of Sanskrit positional astronomy reaching back through the *siddhanta* texts. Varanasi's observatory, built atop a palace already more than a century old at the time of its astronomical fitting-out, and displaying instrument details (such as the horse-head wedge pin on its Chakra Yantra) that point to Perso-Islamic instrument-design transmission, illustrates the network's synthesis of Sanskrit, Islamic, and, to a lesser extent, European astronomical knowledge.

The complete loss of the Mathura observatory, demolished for building material within a few decades of its construction, with not a single photograph or measured drawing surviving, is a sobering reminder of how much of this program has already been lost, and underscores the importance of the conservation status now afforded to Jaipur (UNESCO World Heritage, 2010) and the increasing academic and heritage attention given to Delhi, Ujjain, and Varanasi. Continued epigraphic, archival, and archaeoastronomical research on the surviving instruments, including precision resurveying of gnomon angles and comparison against Jai Singh's own recorded observations in the *Zij-i Muhammad Shahi*, remains a promising avenue for future work.

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