

Architecture in the Service of Science

The Astronomical Observatories of Jai Singh II

Text and Photographs by Barry Perlus

Between 1724 and 1727, Jai Singh II, a regional king under the Mogul empire, constructed five astronomical observatories in his native territory of west central India. Passionately interested in mathematics and astronomy, Jai Singh adapted and added to the designs of earlier sight-based observatories to create an architecture for astronomical measurement that is unsurpassed.

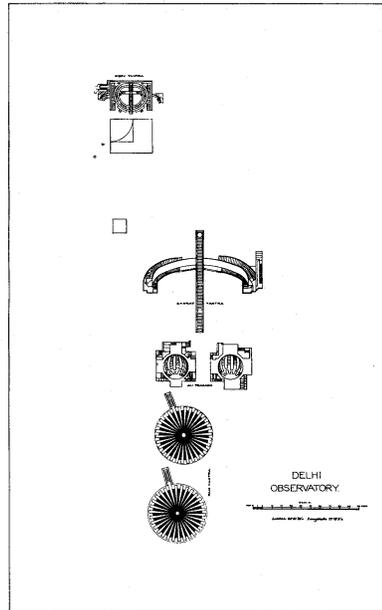
Jai Singh was influenced primarily by the Islamic school of astronomy, and had studied the work of the great astronomers of this tradition. Early Greek and Persian observatories contained elements that Jai Singh incorporated into his designs, but the instruments of the Jantar Mantar, as Jai Singh's observatories have come to be known, are more complex, or at a much

greater scale than any that had come before, and in certain instances, are completely unique in design and function.

Of the observatories originally built at Delhi, Jaipur, Mathura, Ujjain, and Varanasi, all but the Mathura observatory still exist. The condition of the instruments varies, due to the ravages of weather and lack of maintenance over time, but the observatories at Jaipur and Ujjain have had considerable restoration, and repairs have been made from time to time at each of the sites.



The Varanasi observatory was built on the roof of the Man Singh palace, overlooking the Ganges.



Plan of the Delhi Observatory. The site occupies an area of approximately five acres.



The Jantar Mantar at New Delhi, India. The red wash on the masonry structures stands in contrast to the lush green of its park-like setting in the midst of downtown New Delhi. A popular itinerary for foreign as well as national tourists, the site's open space and protected boundaries also offer the city's residents a quiet place for respite and contemplation.



Two of the twelve instruments known as the Rasivalaya Yantras, *foreground*, at the Jaipur observatory. Each of the Rasivalayas refers to one of the signs of the zodiac, and is designed to directly measure the latitude and longitude of a celestial object at the moment that the sign to which it refers crosses the meridian.



Above: Part of the Ujjain observatory. From left to right, the Samrat, Nadivalaya, and Digamsa Yantras.

Photographs and text © 2005 Barry Perlus
Illustrations of the principles of the instruments from Virendra Sharma: *Jai Singh and His Astronomy*, Motilal Banarsidass, publishers - used by permission.

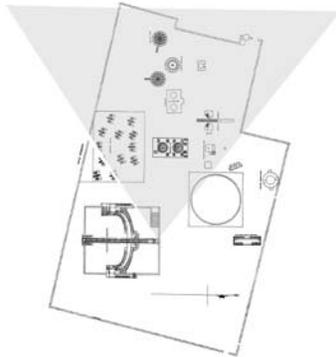
Site plans and elevation drawings, except where otherwise noted from G. S. Kaye: *The Astronomical Observatories of Jai Singh*, published by the Archaeological Survey of India.

The Jaipur Observatory

The city of Jaipur is located about 220 km south and west of New Delhi, in the State of Rajasthan. It was designed and built as a “new city” ca. 1727 by Jai Singh, and incorporated architectural and planning concepts that were advanced for their time. The city is also home to the largest and most elaborate of the five observatories, located just across from the Royal Palace.



The observatory at Jaipur, *above* seen from atop the gnomon of the Samrat Yantra (large sundial). The grey area in the site plan, *below*, indicates the area captured in the photograph.



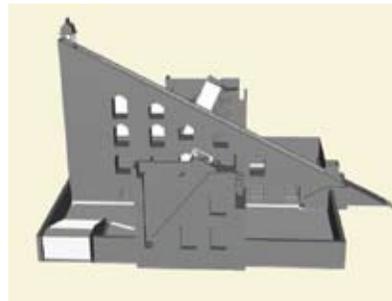
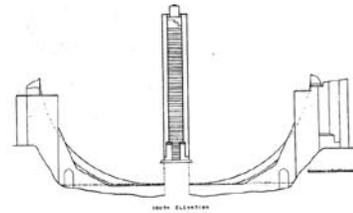
Site plan of the Jaipur observatory

Telling Time with the Largest Sundial in the World

The Samrat Yantra, pictured *far right* and in illustrations, *below*, is the largest sundial in the world. It's gnomon rises over 73 feet above its base, and the marble faced quadrants, 9 feet in width, create an arc that reaches 45 feet in height. According to Physicist V. N. Sharma, author of *Sawaiii Jai Singh and His Astronomy*:

The primary object of a Samrat is to indicate the apparent solar time or local time of a place. On a clear day, as the sun journeys from east to west, the shadow of the Samrat gnomon sweeps the quadrant scales below from one end to the other. At a given moment, the time is indicated by the shadow's edge on a quadrant scale.

In order to find time with the instrument at night, one has to know the time of the meridian transit of



Samrat Yantra section and model



View of the Samrat Yantra at Jaipur from the North East

a prominent star. This may be obtained from appropriate tables or calculated from the knowledge that a star returns to the meridian after 23 h, 56 min, 4.09 sec, the length of a sidereal day. The time at night is measured then by observing the hour angle of the star or its angular distance from the meridian. The readings then may easily be converted into the mean solar time. For measuring at night, a tube or slit is

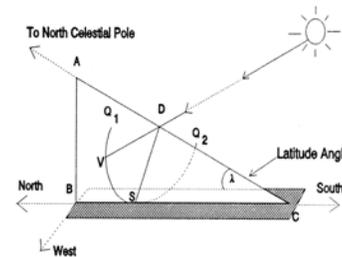


Figure 1
Samrat Yantra: Principle and Operation

used as a sighting device as Jagannatha suggests. With the quadrant edge as the vantage point, the observer looks at a prominent star through the device and moves the device back and forth along the quadrant edge SQ I (figure 1), until the star appears to graze the gnomon edge AC. The vantage point V on the quadrant edge then indicates the hour angle or meridian distance SV of the star, which after proper conversion gives the apparent solar time.

Because a Samrat, like any other sundial, measures the local time or apparent solar time and not the “Standard Time” of a country, a correction has to be applied to its readings in order to obtain the standard time. The correction for Indian Standard Time is as follows:

Indian Standard Time = Local Time \pm Equation of Time \pm Longitude difference.

How Does It Work?

Most of us are familiar with the brass sundials often used as ornaments in gardens. These designs, known as horizontal dials, cast the sun's shadow from a vertically mounted triangular plate across a horizontal surface scribed with lines indicating the hours of the day. Due to the projection of the sun's apparent circular motion across our sky onto a flat plane, the hour divisions are unequal, being more closely spaced towards the noon hour.

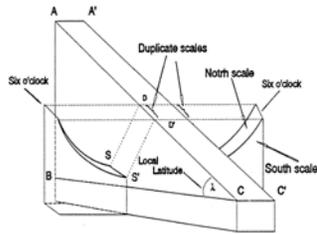


Figure 2

Samrat Yantra Perspective

When the surface upon which the sun's shadow falls is formed into a circular arc, and aligned perpendicular to the earth's axis of rotation, the passage of the sun overhead casts a shadow which moves across the surface in equal time increments. This type of dial, known as "equinoctial", was described as early as the 7th century and is the design used by Jai Singh for the Samrat Yantra.

Accuracy and Scale

When Jai Singh designed the observatories, one of his foremost objectives was to create astronomical instruments that would be more accurate and permanent than the brass instruments in use at the time. His solution was to make them large, *really large*, and to make them of stone and masonry. This simple yet remarkable de-

cision brought forth a collection of large scale structures for the measurement of celestial position and movement that is unequalled today. Among the many startling impressions for a visitor to one of the observatories, is the scale of the instruments. One is literally enveloped, and



Time subdivisions on the quadrant scale. The smallest subdivisions, visible in the lower right corner, represent intervals of two seconds.

confronted with a space that is both aesthetic and mathematical. The time scale of the Samrat Yantra at Jaipur, for example, includes subdivisions as fine as two seconds, and as one watches, the motion of the gnomon's shadow becomes a palpable experience of earth's cosmic motion.

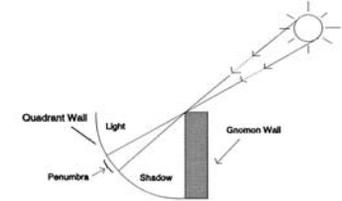
The Problem of the Penumbra

While the enormous size of the Samrat Yantra generates large scales with fine divisions, a problem arises due to the fact that the sun is not a single point in the sky, but rather a disc, with finite diameter. Expressed in angular degrees, the sun's penumbra (the edge of the sun's shadow) is one-half degree. As a consequence, the shadow edge is not a sharp, abrupt change from light to dark, but changes gradually over a distance of several centimeters.

Virendra Sharma writes:

The first and foremost factor affecting the precision of time measurements, and which is inherent in the very design of the instrument, is the width of the penumbra. For large Samrats, such as those at Delhi and Jaipur, the penumbra could be several centimeters wide. The sun, because of the finite width of its disc, casts diffused shadows of objects. As a result, pinpointing the exact location of the shadow-edge becomes a difficult as well as a subjective matter. The penumbra at the Great Samrat of Jaipur, at mid-morning on a clear day, can be as wide as 3 cm or more, making it difficult to read

time with accuracies better than ± 15 seconds. However, when the sun is strong, the difficulty may be eliminated and the procedure of measuring time made objective. This is done by superimposing on the penumbra the shadow of a thin object



The penumbra of the sun is one-half degree wide. The figure shows a highly exaggerated version of the effect.



Panoramic view of the Samrat Yantra from ground level at the west quadrant.



Detail of Quadrant with shadow

such as a needle or a string.

By holding a one to two cm long taut string parallel to the shadow edge, about one cm or so above the instrument's surface, and reading the scale where the string's shadow merges with the shadow of the gnomon edge, we could repeat our readings with an accuracy of ± 3 sec or better. The author believes that

the astronomers of Jai Singh must have used some device similar to that of the string for overcoming the problem of the penumbra.



Observing the center of the penumbra

Other Measurements

In addition to marking local time, the Samrat or “Great” Yantra was used to determine the sun’s declination and the right ascension (RA) of any celestial object.

According to Virendra Sharma:

to measure the declination of the sun with a Samrat, the observer moves a rod over the gnomon surface AC up or down (Figure 1) until the rod’s shadow falls on a quadrant scale below. The location of the rod on the gnomon scale then gives the declination of the sun. Declination of a star or planet requires the collaboration of two observers. One observer stays near the quadrants below and, sighting the star through the sighting device, guides the assistant, who moves a rod up or down along the gnomon scale. The assistant does this until the vantage point V on a quadrant edge below, the gnomon edge above where the rod is placed, and the star—all three—are in one line. The location of the rod on the gnomon scale then

indicates the declination of the star. In this exercise, in addition to two observers, a torch bearer may also be necessary to shine light on the rod on the gnomon edge for the principal observer near the quadrants below to see it clearly.

The right ascension or RA of an object is determined by simultaneously measuring the hour angle of

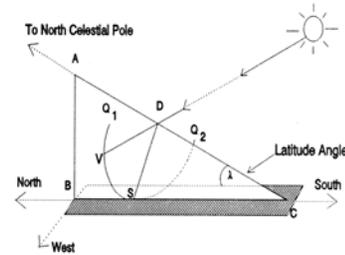


Figure 1

Samrat Yantra: Principle and Operation

the object and the hour angle of a reference star. From the measurements, the difference between the right ascensions of the two is calculated. By adding or subtracting this difference to the right ascension of the reference star, the RA of the object is determined.

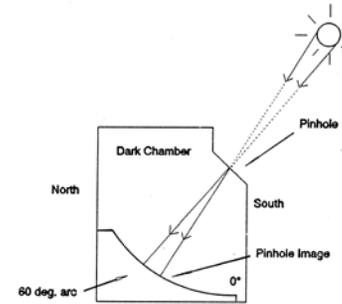
Shasthansa Yantra

A secondary instrument, built within the towers that support the quadrant scales, gives extremely accurate measurements of the zenith distance, declination, and diameter of the sun. Called the *Shasthansa Yantra*, as Virendra Sharma describes, it is essentially:

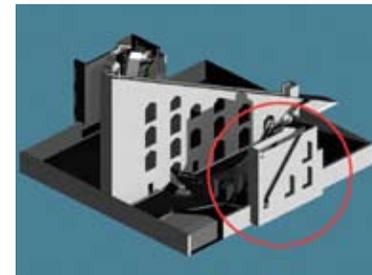
... a 60 degree arc facing south, within a dark chamber. The arc is divided into degrees and minutes. High above the arc, at its center on the south wall, is a pinhole to let sunlight in. As the sun passes across

the meridian at noon, its pinhole image falling on the Shasthansa scale below enables the observer to measure the zenith distance, declination, and the diameter of the sun.

The figure below shows the principle of its operation.



The principle of the Shasthansa Yantra



The Shasthansa Yantra is built within the towers that support the great quadrant, as seen in this model.

I visited the Shasthansa Yantra at Jaipur in December 2004 and made time lapse studies of the sun’s meridian transit. The chamber is entered from the north wall of either the east or west tower (there are duplicate instruments, one in each tower). The interior of the chamber is about 15 feet wide by 30 feet long, and is open to a height of about 40 feet. The upper areas

of the chamber are home to dozens of bats who gain entrance through ventilation grills in the upper section of the tower. A platform about 12 feet above floor level provides access to observe the sun’s image on the quadrants. A bamboo ladder is used to reach the platform.



Interior of the *Shasthansa Yantra*



Detail of the *Shasthansa* quadrant with the pinhole image of the sun at noon

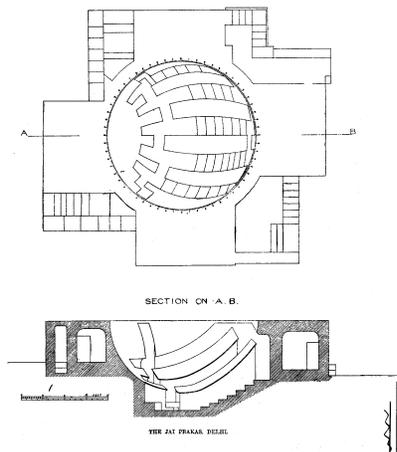
The Jai Prakash Mirror of the Heavens

The Jai Prakash may well be Jai Singh's most elaborate and complex instrument. It is based on concepts dating to as early as 300 B.C. when the Greco-Babylonian astronomer Berosus is said to have made a hemispherical sundial. Hemispherical dials also appear in European Church architecture during the Middle Ages, and at the observatory in Nanking, China in the late 13th-century. The Jai Prakash, however, is much more elaborate, complex, and versatile than any of its predecessors.

How it Works

The Jai Prakash is a bowl shaped instrument, built partly above and partly below ground level, as can be seen in the drawing below.

The diameter at the rim of the bowl is 17.5 feet for the Jaipur instrument, and 27 feet at Delhi. The interior surface is di-



Plan and section of one of the Jai Prakash pairs at the Delhi observatory. Jai Prakash were built only at Jaipur and Delhi.



"Unwrapped" spherical panorama from within the Jai Prakash at the Jaipur observatory. The sighting guide is visible against the sky.

vided into segments, and recessed steps between the segments provide access for the observers. A taut crosswire, suspended at the level of the rim, holds a metal plate with circular opening directly over the center of the bowl. This plate serves as a sighting device for night observations, and casts an easily identifiable shadow on the interior surface of the bowl for solar observation.

The surfaces of the Jai Prakash are engraved with markings corresponding to an inverted view of both the azimuth-altitude, or horizon, and equatorial coordinate systems used to describe the position of celestial objects. See figure 4, right.

Virendra Sharma gives a detailed description of the design of the Jai Prakash:

In the azimuth-altitude system, the rim of each hemispherical surface represents the local horizon and the bottom most point, the zenith.

Cardinal points are marked on the rim, and cross wires are stretched between them. A great circle drawn between the north and the south points and passing through the zenith on the instrument's surface represents the meridian. From the zenith point a number of equal azimuth lines are drawn up to the rim or horizon. Next, a number of

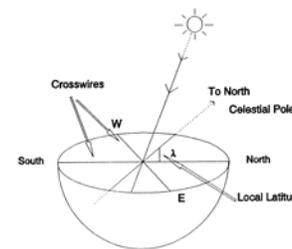


Figure 4

The principle of the Jai Prakash.

equally-spaced circles with their centers on the vertical axis passing through the zenith are inscribed on their surface. These circles are parallel to the rim and intersect the equal azimuth lines at right angles.

For the equatorial system, a second set of coordinates is inscribed. For these coordinates, a point on the meridian, at an appropriate distance below the south point on the rim, represents the north celestial pole. At a distance of 90° further down, a great circle intersecting the meridian at right angles represents the equator. On both sides of the equator, a number of diurnal circles are drawn. From the pole, hour circles radiate out in all directions up to the very rim of the instrument.

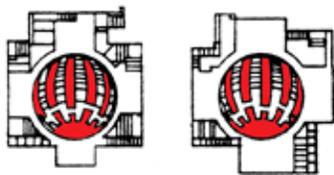
On a clear day, the shadow of the cross-wire falling on the concave

surface below indicates the coordinates of the sun. These coordinates may be read either in the horizon or in the equator system as desired. The time is read by the angular distance from the meridian measured along a diurnal circle.

Jai Singh's Ingenuity: The Jai Prakash built as Complementary Pairs

As described earlier, the design of the Jai Prakash was based on earlier hemispherical sundials. But Jai Singh modified this design to be able to make night time observations. He did this by removing the area of the concave surface between alternate hour circles and providing steps for the observer to move around freely to take readings. Working at night, the observer sights the object in the sky through the circular aperture plate at the intersection of the cross-wires. With the aid of a sighting device attached to the concave surface the position of the sky object is then read from the engraved coordinates.

A second instrument was built next to the first, identical in all respects except that the hour circles corresponding to the steps in the first have a solid, engraved surface, and the hour circles corresponding to the



Plan view of the Jai Prakash at Delhi.

engraved surface of the first are removed to provide steps. As seen in the plan view, the instruments are exact complements of each other, and if the engraved surfaces (tinted red) of one were to be transposed



Panoramic view of the interior of the Jai Prakash at Jaipur. At far left is the passageway to the companion instrument, and at far right, exit steps to the outside. At center is the opening between hour segments of the hemispherical surface, with steps leading down to the center of the bowl.

above the other, they would represent a single complete surface. In practice, when the shadow of the sun cast by the cross-wire, or the coordinates of a celestial body observed at night moves past the edge of one of the engraved surfaces, the observer walks to the other instrument and continues the observation there.



The Jai Prakash at Jaipur. The pattern of alternating areas of surface and void can be seen by careful comparison.

Kapala Yantra Predecessor to the Jai Prakash

According to maps of the Jaipur observatory dating to the early years of its construction, Jai Singh built two small hemispheric dials, with a diameter of 11 feet, before constructing the Jai Prakash. These instruments, named Kapala Yantras, were built side by side on a masonry platform. Named Kapala A and Kapala B, the two hemispheric bowls have very different functions. Kapala A has engravings similar to the Jai Prakash, but lacks the cutaways and size that would permit night observations. Kapala B serves only to transform graphically the horizon system of coordinates into the equator system and vice versa. It is the only instrument at Jaipur not meant for observing.



The Kapala A at Jaipur. The crosswire, center plate, and its shadow can be clearly seen in the inset.

Ram Yantra

The Ram Yantra is a cylindrical structure built in pairs like the Jai Prakash. Its primary function is to measure the altitude and azimuth of celestial objects, including the sun. In the Islamic and Hindu schools of astronomy there were no instruments like the Ram Yantra prior to Jai Singh's creations.

Virendra Sharma gives this description of the principle and operation of the Ram Yantra:

The cylindrical structure of Rama yantra is open at the top, and its height equals its radius. To understand the principle, let us assume that the instrument is built as a single unit as illustrated in Figure 4. The cylinder, as illustrated in the figure, is open at the top and has a vertical pole or pillar of the same height as the surrounding walls at the center. Both the interior walls and the floor of the structure are engraved with scales measuring the angles of azimuth and altitude. For measuring the azimuth, circular scales with their centers at the axis of the cylinder are drawn on the floor of the structure and on the inner surface of the cylindrical walls. The scales are divided into degrees and minutes. For measuring the altitude, a set of equally spaced radial lines is drawn on the floor. These lines emanate from the central pillar and terminate at the base of the inner walls. Further, vertical lines are inscribed on the cylindrical wall, which begin at the wall's base and terminate at the top end. These lines may be viewed as the vertical extension of the radial lines drawn on the floor of the instrument. The radial and the vertical lines are inscribed with scales for measuring the altitude of a celestial object, and are graduated

such that the zero mark is at the top, and the 90° mark is at the base of the central pillar. If the preference is to measure the zenith distance, then the markings would have to be reversed, i.e., the top end would now denote a 90° mark and the base of the pillar, zero.

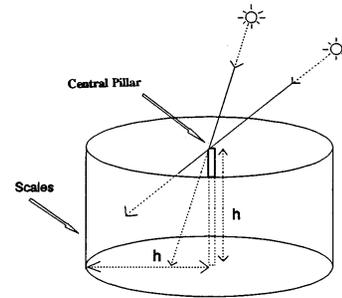
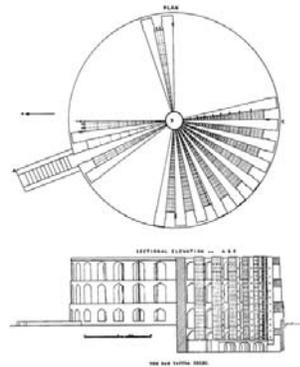


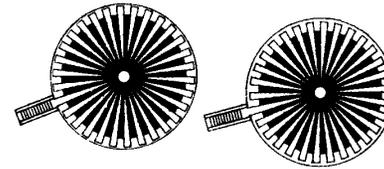
Figure 4

Principle of the Ram Yantra, *above*, and a plan and elevation of the Ram Yantra at Delhi, *below*.



In daytime the coordinates of the sun are determined by observing the shadow of the pillar's top end on the scales, as shown in the figure. The coordinates of the moon, when it is bright enough to cast a shadow, may also be read in a similar manner. However, if the moon

is not bright enough, or if one wishes to measure the coordinates of a star or planet that does not cast a shadow, a different procedure is followed. To accomplish this, the instrument is built in two complementary units.



Plan view: Ram Yantra pair at Delhi

The two complementary units of a Rama yantra may be viewed as if obtained by dividing an intact cylindrical structure into radial and vertical sectors. The units are such that if put together, they would form a complete cylinder with an open roof. The procedure for measuring the coordinates at night with a Rama yantra is similar to the one employed for the Jaya Prakasa. The observer works within the empty spaces between the radial sectors



Detail of the gnomon surface at the Delhi Ram Yantra. Weathering has eroded and stained the engraved angular markings.

or between the walls of the instrument. Sighting from a vacant place, he obtains the object in the sky, the top edge of the pillar, and the vantage point in one line. The vantage point, after appropriate interpolation gives the desired coordinates. If the vantage point lies within the empty spaces of the walls, well above the floor, the observer may have to sit on a plank inserted between the walls. The walls have slots built specifically for holding such planks. Because there are no graduations between the empty spaces, arc lengths of wood or metal to fit between the walls are necessary for a reading.



The gnomon (central pillar) of the Ram Yantra at the Delhi observatory, as seen through one of the arched openings in the outer wall. For night observations an observer can move easily between the wedge shaped sectors, which are supported at chest height by masonry arches and posts.

Jantar Mantar on the Web

VR Panoramas, 3D Models, Animations, Time Lapse Studies, Interactive Media, and Outreach

One of the objectives of the multimedia web site www.jantarmantar.org is the creation of a virtual museum to present and interpret Jai Singh's observatories. At the time of writing, the web site presents an interactive tour of the jaipur observatory, employing navigable, immersive, VR panoramas, images derived from 3D models, animations illustrating the passage of the sun overhead during the course of a day,



One of the VR panoramas as it appears in a web browser. The user can pan and zoom through a fully spherical 360°.



Screen view of the *Jaipur World* from Cornell University's SciCentr

and time lapse studies illustrating the movement of the shadow of the sun on the scales of several instruments from the observatories. A collaborative project with *SciCentr*, an outreach program of Cornell University's Theory Center, is creating an interactive 3D world in the *ActiveWorlds Educational Development Universe*. This project enables science students from participating middle schools and high schools to interact with a computer based scale model of the Samrat Yantra at Jaipur, walking around it, climbing it's stairs, and observing the methods of establishing local time from a simulation of the movement of the sun's shadow across its scales.

The observatories themselves are sometimes used for making observations, but mostly serve as tourist attractions, as historic monuments and curiosities. Local guides, many of them sanctioned by the Archaeological Survey of India, which has authority over the observatories, present visitors with a mixture of truth and fiction as they explain the history and workings of the instruments.

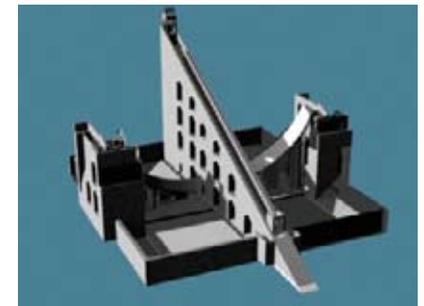
In contrast, Dr. Nandivada Rathnasree, director of the Nehru Planetarium, uses the instruments of the Delhi observatory as a real world classroom to demonstrate principles of basic astronomy to students. A group under her direction used the instruments at Delhi to chart the path of the planet Venus during its 2004 transit.



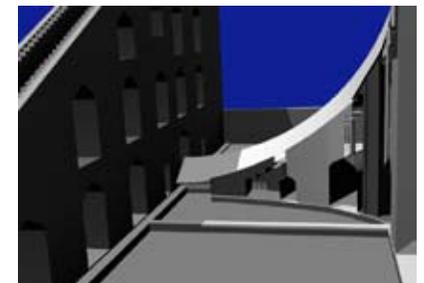
Above, an "unwrapped" rendering of a 360° spherical panorama taken from the top of the east quadrant of the Samrat Yantra at the jaipur observatory, and *above left*, an undistorted wide-angle view from the same location. *More about panoramas on the next page.*



Students and astronomy enthusiasts under the guidance of Dr. Nandivada Rathnasree, (*in blue, lower right*), use makeshift crosswires to make solar observations at the Delhi Jai Prakash.



Rendering from a computer based 3D model of the Samrat Yantra



Still frame from an animation illustrating the movement of the sun's shadow along the quadrant of the Samrat Yantra

More about Panoramas

In 2001 I began to use panoramic photography to interpret the architecture of the Jantar Mantar observatories. Advances in technology enabled photographers to capture multiple image panoramas and assemble the images digitally. Free viewing software made the panoramic images accessible to anyone with a computer. There are two types of panoramic rendering commonly in use: cylindrical and spherical.

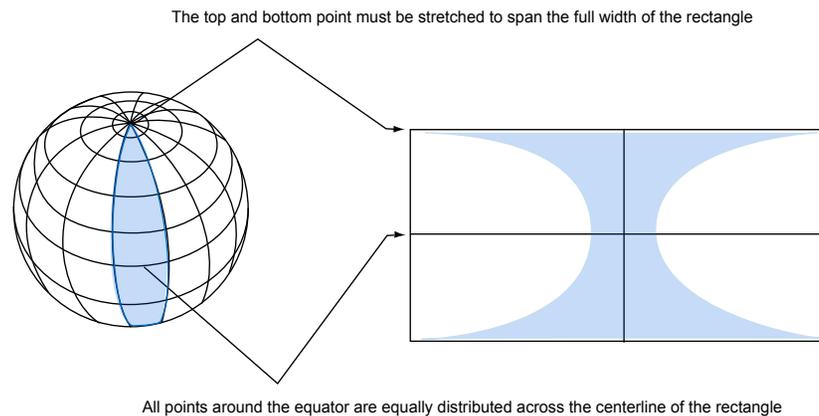
In the cylindrical panorama, a series of overlapping photographs is taken while rotating the camera 360° along the line of the horizon. The panorama's vertical angle of view is limited by the angular coverage of the lens.

The spherical panorama comprises a series of overlapping photographs that capture all areas of a scene, including directly overhead and directly beneath the camera. This is usually done with a digital camera, in multiple rows, with the camera pointed along the horizon for one row, angled upwards for a second row, and angled downward for the third row.

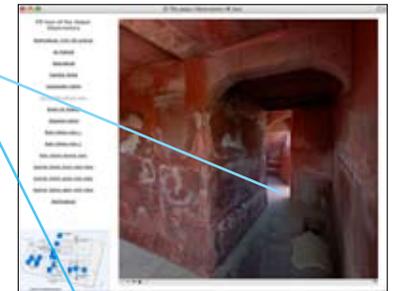
After the photographs are taken, they are transferred to a computer and loaded into a program that assembles the photographs into a composite simulating the original 360 degree scene. Called "stitching" software, these programs find the common elements in adjacent photographs and use them to seamlessly recreate the original view as though it were fitted to the inside of a sphere—with the viewer at the center. The stitching software evaluates the colors and brightnesses of adjacent photographs and creates a smooth blend between them. From this "stitched" image it is possible to generate many kinds of images, from immersive QuickTime VR movies to planar renderings (like conventional photographs) to spherical renderings like the example above.



Spherical rendering from a 360° panorama of the Jai Prakash at the Jaipur observatory. The area along the horizontal centerline corresponds to the "equator" or maximum circumference of the spherical image, and thus is the least stretched. Areas at top and bottom show the maximum stretch and distortion. At the very bottom, what appears to be a ribbon, is actually a circular map rose with copyright information. See the photograph, *lower right*.



Rendering a spherical image to a 1:2 rectangle



As seen in a browser window, the image appears as a conventional camera would render it.

