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THE KAPĀLA YANTRAS OF SAWAI JAI SINGH

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At the Jaipur observatory of Sawai Jai Singh, there is a pair of masonry instruments, Kapāla A and Kapāla B, about which only scanty and, to a certain extent, misleading information is found in literature. The object of this paper is to describe the two instruments in detail and clarify the misconceptions about them. One of the instruments, Kapāla A, is a forerunner of Jaya Prakāśa and is designed to measure the coordinates of the sun in the horizon and in the equator systems. This instrument also indicates a *lagna* or sign rising on the eastern horizon. The second instrument, Kapāla B, on the other hand, is designed to transform the horizon system of coordinates into the equator system.

Sawai Jai Singh (1688-1743) in order to update the existing planetary constants, built masonry instruments at five different sites in the country. Of his observatories, the one at Jaipur is the most elaborate and has the largest number of instruments built by him.[1] At the Jaipur observatory there is a pair of masonry instruments, Kapālīs or Kapālas, about which only scanty and, to a certain extent, misleading information are found in the literature. The object of this paper is to describe the instruments in detail and clarify the misconceptions.

At the observatory, the Kapālīs, or more appropriately the Kapālas,[2] are located on a platform, 13.96 m long, 7.88 m wide, one-half meter high, and oriented east-west. The instruments are so named because of their remote resemblance to the brain cover of a human skull. The Kapālas are concave hemispherical bowls with a diameter of 3.46 m each. Originally, and also during the restorations of 1901-02, their surfaces had been done in lime plaster, and only the rims were of marble.[3] But now both instruments have been finished in white marble. Although the two Kapālas are of the same dimensions, they differ considerably from each other in engraving and, hence, in function.

In the chronological development of the instruments of Jai Singh, the Kapālas come before his Jaya Prakāśa which, according to Jagannātha,[4] played an important role in Jai Singh's astronomical program.[5] In a map of the observatory, drawn sometimes before 1728, where the Jaya Prakāśa is nowhere to be seen, a pair of instruments resembling the Kapālas may be clearly identified in the same general location where they are today, suggesting that the Kapālas predate the Jaya Prakāśa. The Jaya Prakāśa may be looked upon. in fact, as one of the Kapālas — the Kapāla A — built into two complementary halves.

Kapāla A

On the platform where the two instruments have been built, the instrument Kapāla A is located to the west. It has been described in the *Yantraprakāraḥ*.[6] Kapāla A is designed to measure the coordinates of the sun in the horizon and the equator systems, and to indicate the local time. In addition, it also tells the ascendant,[7] and the *saṃkrānti* or entry of the sun into a sign.[8] The coordinates, local time, ascendants, and *saṃkrāntis*, are all determined by observing the shadow of a cross wire stretched between the cardinal points marked on the rim. In recent times, the cross wires have been replaced by a small circular plate with a hole in the middle which casts an elliptical image of the sun on the surface below. The center of the image serves the same purpose as the shadow of a cross wire. As the instrument has been designed to work with the shadow of a cross wire cast by the sun, it may not be used at nighttime.

The instrument has two sets of coordinate system inscribed on its surface, namely, the altitude-azimuth and the equatorial, enabling the observer to record his data in the system of his choice.

The Altitude-Azimuth Or The Horizon System Of Coordinates

For the altitude-azimuth or horizon system, the lowest point on the instrument surface represents the zenith. With the zenith point as center, parallels of altitude, or more appropriately, the zenith distance circles, have been drawn up to the very rim of the instrument which then becomes the local horizon. These circles are 6 deg apart. The horizon circle on the rim is divided into degrees and minutes, such that its small divisions measure 10′ of arc. Radiating in all directions from the zenith point on the instrument surface, there are 20 azimuth lines drawn up to the horizon or rim. For some reason, these lines have not been spaced evenly and are anywhere from 3;40 to 45;23 apart. The parallels of altitude circles and the equal azimuth lines have not been divided into degrees or minutes.

Equatorial Coordinates

For the equator system of coordinates, a point on the meridian, 27 deg below the south point of the rim, represents the North Celestial Pole. A great circle, 90 deg further down the meridian circle is the equator labeled as the "*Meṣa-Tulā Horā Vṛttam*" or Aries-Libra diurnal circle. On either side of the equator are altogether six diurnal circles, corresponding to the declination of the first point of the signs of the zodiac. An additional diurnal circle indicates the path of the pole of the ecliptic during a 24 hour day, and it is drawn at a distance of 23½ deg around the pole. These curves have been labeled in Devanāgari, such as "*Mithuna Siṃha Horā Vṛttam.*" Next, arcs representing the hour circles, spaced at 6 deg intervals, amanate from the pole in all directions. The 6-degree interval between two adjacent hour circles may have been chosen because the sun takes exactly one *ghaṭikā* or one Hindu unit of time to travel a 6-deg distance. Here again there are no subdivisions of any kind.

As there are no subdivisions on the arcs, and as it is inadvisable to step down on to the marble surface of the instrument for better reading, it is cumbersome to take a reading with precision. Besides, the precision of a reading itself depends on the coordinate measured. For instance, both the zenith distance, and the declination may be measured, with some interpolation, with a precision of ± 5 arc minutes, or better. However, for the azimuth and the hour angle both, the accuracies vary and, in fact, depend upon the zenith distance and the declination of object respectively. For large zenith distances, such as for an object near the horizon, the accuracies in the readings of the azimuth are of the order of ± 3′ of arc.[9] However, for small zenith distances, where the parallels of altitude shrink in cricumference, an error of several degrees may easily be incurred. In fact, when the sun is near zenith, around noon during the summer months, the azimuth readings become practically meaningless. Similarly near the north celestial pole, where the hour circles converge, and the diurnal circles progressively shrink in size, the readings may be highly imprecise. The readings are most sensitive at the equator, however, where the separation between the hour angle divisions is the greatest. There the uncertainties are of the order of ± 3 arc minutes.

For determining the ascendant, the instrument has a set of 12 curves inscribed on its surface and labeled in Devanāgari according to the ascendant they indicate. On a clear day, the shadow of the cross wire falling on one of the curves indicates the sign emerging at the horizon at that very moment. However, the signs indicated by this method are according to the *sāyana* system, in which the first point of the Aries is always at the vernal equinox. Having read a *sāyana* sign off the instrument, its *nirayaṇa* counterpart may be obtained by applying a correction for the precession of the equinoxes.[10]

Theoretically, the curves indicating the rising signs, or ascendant, are the loci of the sun's image on the instrument surface as a sign rises on the horizon from one day to another during the course of a year. The curves may also be considered as the projection of the ecliptic on the instrument surface when a sign appears on the horizon. The loci, or projection points, on the instrument might have been calculated either with the equations of spherical trigonometry or read directly off an astrolabe made for the latitude of Jaipur. Another method of drawing these curves is to appropriately divide the diurnal circle of the pole of the ecliptic into 12 equal parts. Then with the points of division as centers, draw arcs of radius of 90°, or equal to the angular distance of the ecliptic from its pole, on the surface. These arcs then represent the path of the sun's shadow on instrument's surface. A spot check revealed that at least some of the curves have been improperly drawn on the instrument surface.

LOCAL TIME

The local time is read from the shadow of the cross wire on the instrument surface. In this respect the instrument is similar to any other hemispherical sundial, such as the Skaphe of the medieval Europe and the *Yang i* of the Chinese Imperial Observatory at Nanking (modern Bejing) in the 14th century.[11,12] The concept to using a hemisphere as a sundial for indicating local time is not new. Berosus, a Babylonian astronomer, is said to have made a hemispherical sundial, in about 300 B.C.[13] As it turns out, an instrument of this type is most accurate at equinox when the sun travels along the equator of the instrument, and where the distance between the hour circles is the widest, At equinox the time may be read with the Kapāla A with an accuracy of about ± 1/2 minute.

SAṂKRĀNTI

The *saṃkrānti* or entry of the sun into a sign is indicated by the shadow of the cross wire falling on one of the first-point diurnal circles described above. The indication is, of course, according to the *sāyana* system, in which the vernal equinox is always at the first point of Aries. If the *nirayaṇa* system is to be used, a correction for the precession of the equinox has to be applied to the time of the *sāyana-saṃkrānti*. The error in *saṃkrānti* may be anywhere from a few hours near the equinox to several days at the solstices.[14]

The instrument Kapāla A is a good teaching tool as it shows a number of things of interest to an astronomer, such as the relationship between the horizon and the equator system of coordinates. The instrument is also quite useful to an astronomer for casting a horoscope.

KAPĀLA B

The Kapāla B is situated to the east of its sister unit, the Kapāla A, on the same platform. Kapāla B is the only instrument at the Jaipur observatory which is not meant for observing. Instead, its object is to transform graphically the horizon system of coordinates into the equator system and vice versa. for the latitude of Jaipur. The transformation implies converting the zenith distance and azimuth of an object into its corresponding declination and hour angle respectively. For these trigonometry, which may involve lengthy calculations.[15] The Kapāla B, in theory at least, is an ingenious device as it eliminates these calculations.[16]

On the surface of the Kapāla B are inscribed arcs representing the two sets of coordinate systems, namely, the horizon and the equatorial. For the horizon system, the rim of the instrument represents the meridian and the north point of the rim the zenith (See Fig. 1). Another point, almost 27 deg to the east of this zenith on the rim, designates the north celestial pole. The north point of the "original horizon" is located at the east point of the rim. The "original horizon" lies in the vertical plane passing through the east-west points on the rim. A great circle passing through the north and

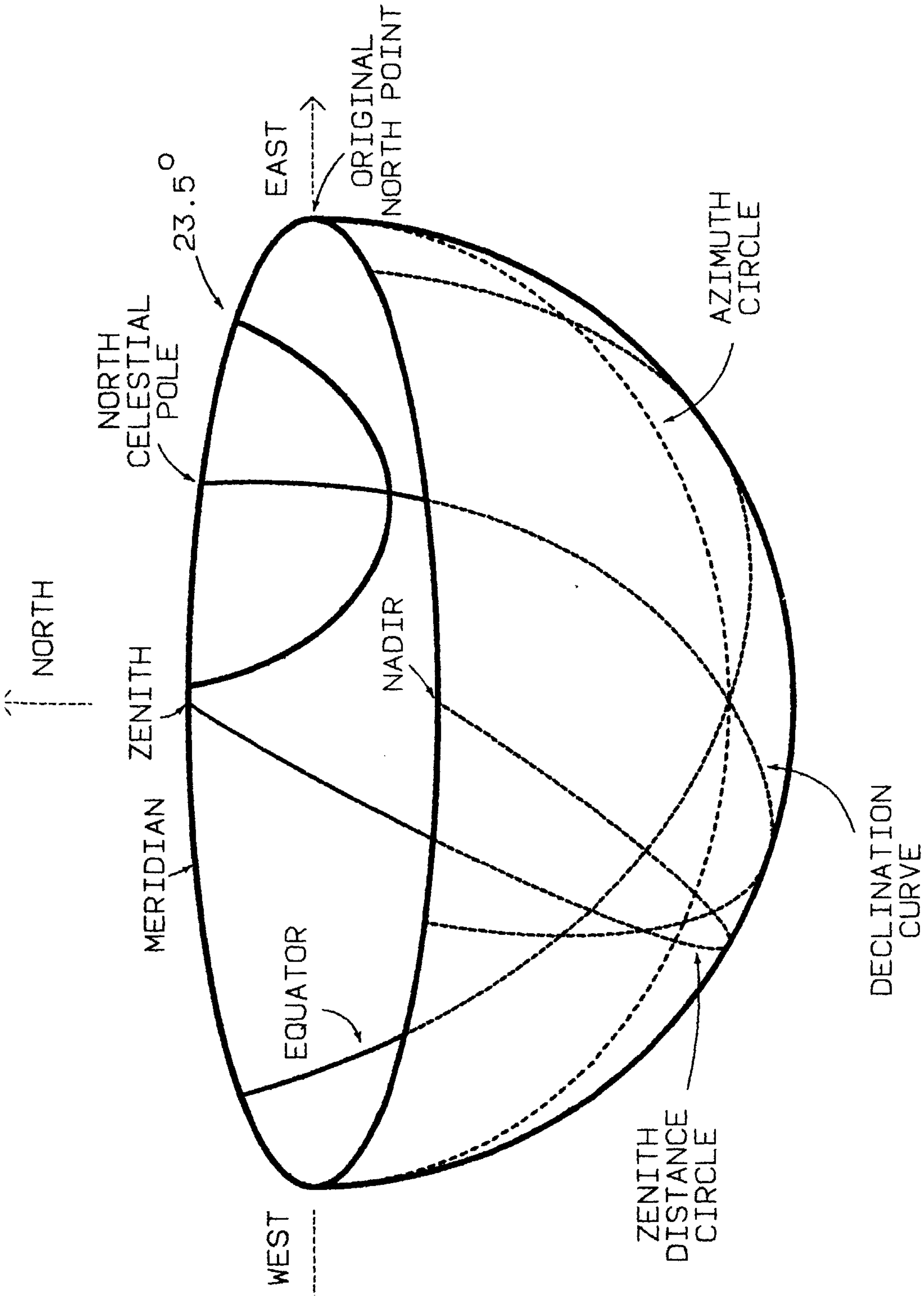

Fig. 1 The Kapāla Yantra B of the Jaipur Observatory. The drawing shows a few lines only for illustrating the principle of the instrument.

south points of the rim and the bottom-most point of the instrument, represents the prime vertical.

In order to comprehend this peculiar arrangement of the celestial points on the rim and the orientation of the great circles, such as the original horizon and the prime vertical, it is helpful to think as if the instrument surface represents the celestial sphere which has undergone two rotations as follows: First, rotate the celestial sphere along a horizontal east-west diameter until the zenith point is at the north point of the rim. Next, rotate the sphere again, this time about a north-south diameter, counterclockwise looking northward, by 90 deg. When this is done, the original meridian turns into the rim of the instrument, and the plane of the horizon becomes the vertical plane passing through the east and west points on the rim. Representing this orientation, the bowl of the instruments, may be considered as one-half of the celestial sphere to the west of the meridian plane of the place. The rim of the instrument, representing the meridian, has been divided into degrees and minutes, such that its small dicisions measure 10′ of arc, and they are labeled in Ḍevanāgari.

In literature, the instrument has been described inaccurately. For example, Garrett who was in charge of the engineering aspect of the restoration of the 1901-02, states that there are latitude and longitude lines engraved on the instrument surface and that the instrument is capable of converting declination and right ascension into these two coordinate angles.[17] In addition, he calls the rim of the instrument the solstitial colure which is also somewhat misleading.[18] In order that the rim may represent the solstitial colure, the pole of the ecliptic must be a fixed point on the rim, at a distance of 23½ degrees from the north celestial pole. The pole of the ecliptic, however, revolves on an hour circle inscribed 23½ deg below the pole on the instrument surface. Kaye, Soonawala and Singh, following Garrett's lead, commit similar errors.[19]

As the restorers of 1901-02, Garrett and Bhavan, did not fully comprehend the function of the instrument, the plaques erected by them at the instrument site are misleading. The English version of the plaque says, "Representation of the half celestial sphere. Rim represents solstitial colure..." The Hindi version of the plaque, although identifying the rim as the meridian correctly, is inaccurate otherwise. It calls the instrument a representation of the eastern half of the celestial sphere, whereas, it is a representation of the western half of the celestial sphere as explained earlier.[20]

The Horizon Or Altitude-Azimuth System Of Coordinates

For the horizon system of coordinates, the zenith and nadir both are located on the rim, 180 degrees apart, along a north-south horizontal line (See Fig. 1). The zenith distance is measured from the zenith point on the rim along the great circles drawn 6 degrees apart from the zenith point to the nadir point.

A number of great circles, 6 degrees apart, inscribed from the east point to the west point of the rim represent the curves along which the azimuth is measured. The great circle between the east and west points and passing through the bottom-most point of the instrument represents the horizon or, more appropriately, the western half of the horizon. The great circle of the horizon divides the hemisphere into two equal halves.

THE EQUATORIAL SYSTEM

As pointed out earlier, on the rim, at a distance of about 27 degrees to the east of the zenith (the north point of the rim) is marked the north celestial pole. The south celestial pole is, similarly, at a distance of 27 degrees to the west of the nadir (the south point of the rim). Great circles or hour circles spaced six degrees apart are drawn from one pole to the other. Intersecting these hour circles are seven diurnal circles, with the one in the middle representing the equator which divides the hemisphere into two equal halves. The diurnal circles have been drawn on either side of the equator at distances of approximately 11;20, 23;25 and 66;30, respectively. These arcs represent the declination of the first point of the signs of the zodiac. Some of these curves have not been drawn very accurately and are off by as much as 8′ of arc from their true value.

In principle the instrument works as follows. If one wishes to convert the azimuth and zenith distance of a body into its hour angle and declination respectively, he should first plot a point on the instrument surface according to the given coordinates. Next, he should read the angular distance of this plotted point from the equator along the hour circles. The angular distance is then the declination of the body. Similarly, the angular distance from the rim or the meridian provides the hour angle. Finally, adding or subtracting from the hour angle the angular distance between the vernal equinox and the meridian when the observation was made, the right ascension is obtained.

The angular distance between any two stars may be determined by plotting two points on the instrument according to their coordinates and spanning the points with a divider. Next, placing the ends of the divider on the graduated scale on the rim, the separation is converted into degrees and minutes.

In principle, Kapāla B is quite elegant. However, it has a varying degree of accuracy. Its scales have been divided at intervals of 6 degrees only, and their largest separation is about 18.26cm. With careful interpolation, where the separation is largest, accuracies of the order of 3′ of arc may be achieved. The accuracies deteriorate if the object is close to the zenith point or near the poles where the great circles of equal azimuth and that of hour circles merge into a point respectively. In this aspect, the instrument has the same limitations as the Jaya Parakāśa or the other Kapāla. Besides, every time a conversion is to be made, the observer may have to climb down to the surface of the instrument for a better interpolation, a practice which could be detrimental to the scale markings and thus inadvisable.

ACKNOWLEDGEMENTS

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Notes And References

[1]For Jai Singh's observatories and their instruments, See Kaye, George, *Astronomical Observatories of Jai Singh*, reprint, Delhi, 1973

[2]Although the instruments are colloquially called "Kapālīs," the Sanskrit version of their name is "Kapāla," by which they will be designated henceforth.

[3]Garrett, A. ff., *The Jaipur Observatory and Its Builder*, p. 49, Allahabad, 1902. Also Bhavan, Gokul Chand, *Bhāratīya Jyotiṣa Yantrālaya Vedhapatha Pradarśakaḥ*, p. 11, Varanasi, 1911. Bhavan writes that the instrument was restored without making any alterations.

[4]*Samrāṭa Siddhānta* of Jagannātha Samrāṭa, ed. Sharma, Ram Swarup, pp. 1162-1163, vol. 2, Delhi, 1967. Or, *Siddhāntasamrāṭ*, ed. Muralidhar Chaturvedi, p. 38-39, Sagar, 1976.

[5]For a description of Jaya Parkāśa see Kaye, p. 37. Ref. 1.

[6]*Yantraprakāraḥ* of Jai Singh, f. 12, Sawai Man Singh II Museum, Khasmohar No.61.

[7]The instument, in fact, tells the emergence of the first point of a sign on the horizon.

[8]The Kapāla A of Jai Singh should not be confused with that of Lalla which is nothing but a sundial on a flat horizontal surface. *Śiṣyadhīvṛddhida Tantra of Lalla, with Commentary of Mallikārjuna Sūri*, part 2, tr. Bina Chatterjee, p. 285, Delhi 1981. The *Sūrya Siddhānta* also mentions a Kapāla, but that is apparently a clepsydra for measuring time. *Sūrya Siddhānta*, ch. 30, verse 21.

[9]Because of its low location, the instrument is unsuitable for observing the objects near the horizon.

[10]The correction due to the precession for March 21, 1990 is — 87 min, 36 sec. For other years after 1990, but not far from it, the average right ascension precession of — 3.07 seconds per year should be added to this value.

[11]Price, Derek J., "Precision Instruments: to 1500," in *History of Technology*, ed. Singer Charles et al, pp. 5492-596, vol. 3, Oxford, 1965.

[12]Needham, J., *Science and Civilization in China*, vol. 3, p. 369, Cambridge, 1959.

[13]The sundial of Berosus was a hemisphere of wood or stone on which was fixed a pointer such that its end was at the center of the hemisphere. The surface of the instrument was inscribed to indicate 12 hours between sunrise and sunset. According to al-Battani (Albategnius, c. AD 858-929) the dial was still in use in Muslim countries during his days. *Encyclopedia Britannica*, "Clock, Watches, and Sundials." vol. 4, p. 743, 1980.

[14]Near a solstice, the declination of the sun changes rather slowly, therefore, the determination of exact moment of the solstice is difficult with an instrument such as the Kapāla A. For example, a change of 4′ in the declination may take as much as 4 to 5 days at solstice with the Kapāla.

[15]The equations for transforming the azimuth and the zenith distance to declination and to hour angle are as follows.

$$\text{Cos } z = \text{Sin } d \text{ Sin } l + \text{Cos } d \text{ Cos } l \text{ Cos } H$$
$$\text{Sin } d = \text{Sin } l \text{ Cos } z + \text{Cos } l \text{ Sin } z \text{ Cos } A$$

where d = declination
z = zenith distance
l = latitude of the place
H = hour angle measured from the observer's meridian
A = Azimuth

[16]Tycho Brahe also constructed a device for graphically transforming coordinates. His device was a sphere of wood covered with brass, about 5 ft in diameter. Later, he used the sphere to depict the stars whose coordinates he measured. See Thoren, Victor E., "New Light on Tycho's Instruments," *J. Hist. Ast.* vol. iv, pp. 25-45, 1973.

[17]Garrett, pp. 48-49. Ref. 1.

[18]The solstitial colure is a great circle on the celestial sphere passing through its poles, the poles of the ecliptic and the solstitial points.

[19]Kaye, pp. 52-53, Ref. 1. Soonawala M. F., *Maharaja Sawai Jai Singh II of Jaipur and His Observatories*. p. 37, Jaipur, 1952. Singh, Prahalad, *Stone Observatories in India*, p. 164, Varanasi. Kaye, confusing the Kapāla B with its counterpart A, makes another mistake in stating that Kapāla B indicates the rising signs.

[20]Bhavan repeats the mistake of the Hindi plaque in his book as well. Bhavan, p. 11, Ref. 3.