Astronomical Instruments of India – An Overview

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Abstract:

It is very well known that India's contribution to astronomy is very valuable and its influence on the development of the subject in other parts of Asia and other continents (Ohashi, 2016). Here, we try to understand how the science was built up keeping in mind the humble tools they had for observations. Almost all the texts devote a complete chapter for the discussion on instruments. In this paper an attempt is made to extract the variants in the exact mode of observations.

1. Foundation for theories

All the texts on astronomy are profound in their mathematical and astronomical foundations. A detailed compilation of the instruments may be seen in the pioneering work of Dikshit (1981), later by Abhyankar (2008) and more exhaustively by Ohashi (1994, 2016). There are many relics hinting the exact means of observations:

(1) Large stone structures with menhir like structures aligned to solstice and equinoxes (Menon, 2016)
(2) Old temples designed to carry out the making of a calendar using both Sun and Moon's positions (Shylaja, 2016a)
(3) Metallic instruments with graduated scales. (Sarma, 2016)
(4) Navigational techniques (Shylaja, 2016b)

The instruments measure two basic quantities namely the angle and time. All the other quantities can be derived based on these measurements. Dikshit (1981) and Ohashi (1994) describe these instruments in a great detail. Table 1 lists their names and approximate era when we find records in the texts.

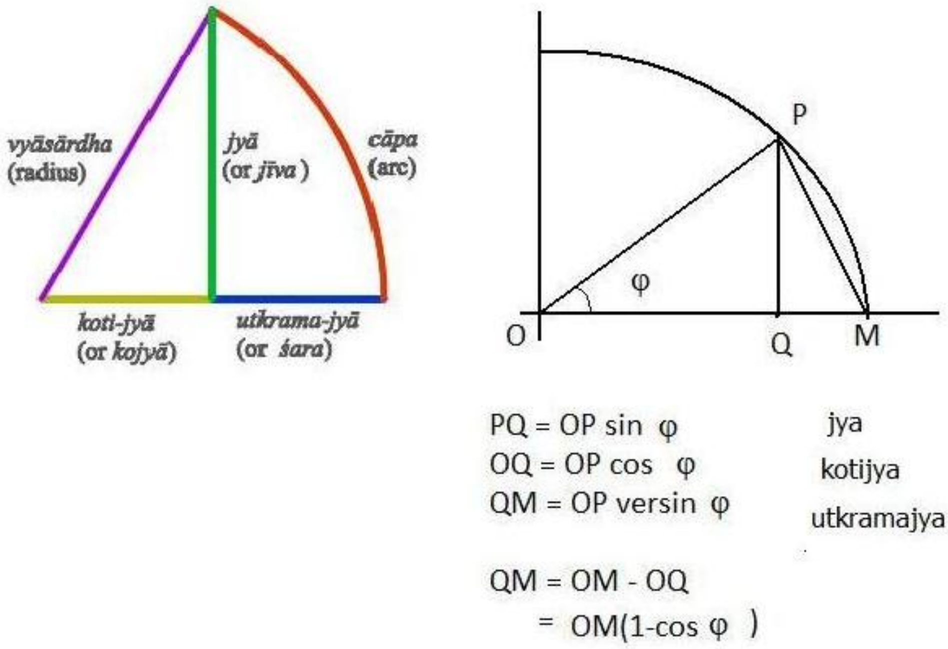
The instruments can be classified as those for measuring time, time intervals, and angles. Those using gnomons have variants which correspond to horizontal, equatorial and vertical dials. Circular dials for measuring angles which in turn are convertible to times, if needed. Sand timers and water clocks were used for measuring time intervals. A globe as an exact replica of the celestial sphere with graduated circles for the various quantities and for the orbits of planets and sun and the moon. Astrolabes were introduced by about 13th century (Ohashi, 1997) and used extensively thereafter.

Table 1. Instruments described in the Siddhantic texts (based on Ohashi, 1994)

Principle	**Name**	**Usage from**
gnomon	sanku	Sulba sutras onwards
	chaya chatra yasti	5th century onwards
	phalaka	12th Century
Circle	cakra dhanus	5th century onwards
Globe	gola kapala	
Timer	ghatika(water) ghatika (sand)	5th century onwards
astrolabe		13th century onwards

The knowledge on trigonometric functions used for conversions of coordinates is well documented. The ratio called versed sine (*utkramajya*) is unique to the Indian system and has no counterpart in the modern texts. (Figure 1)

Figure 1. The trigonometric ratio versed sine as defined in the texts



The usefulness of this ratio was exploited by navigators for determining their location on the sea and time. (Shylaja, 2015a)

2. Description of the observational techniques

The gnomon is the simplest and earliest. Shadow is a very good indication of time measure. A standard length of 12” is described in all texts. The stick may be kept vertical or parallel to the rotation axis. It is referred to as *sanku*. As can be clearly understood these refer to horizontal and equatorial sundials. This was used for fixing the cardinal points.

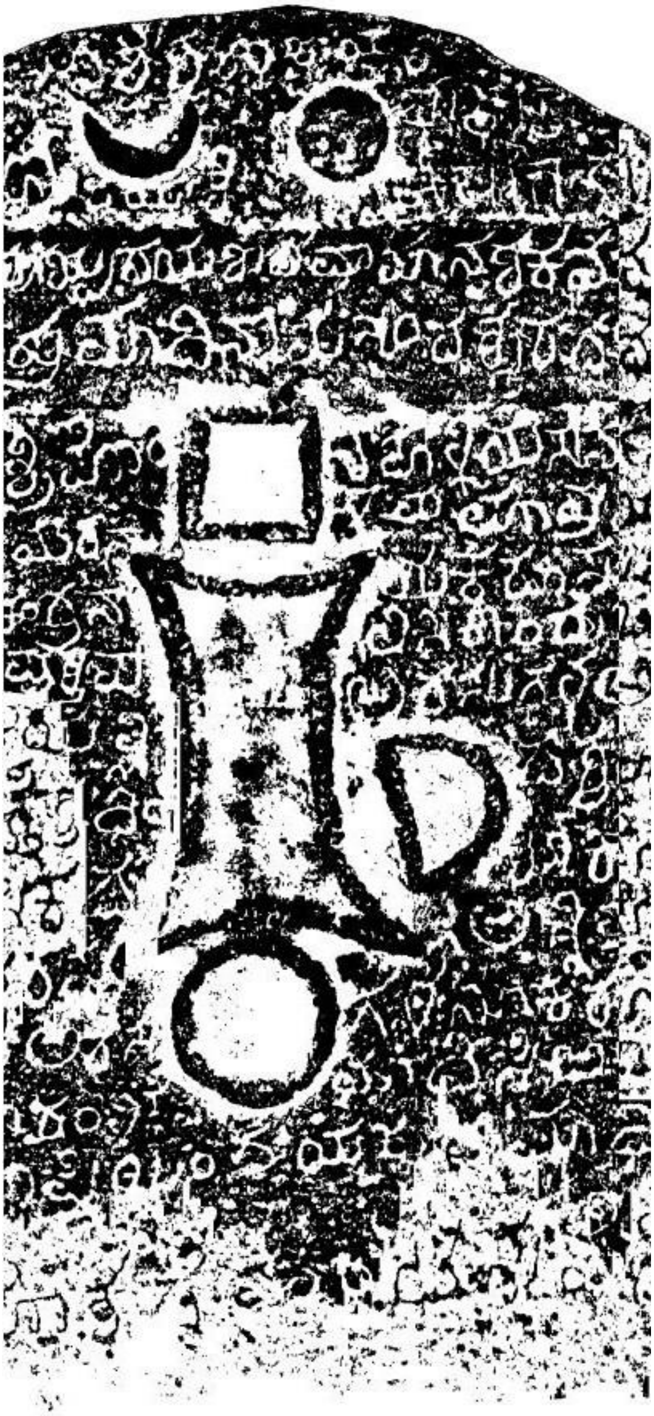
Practical observations reveal that taller the gnomon better is the accuracy; however the shadow tip of the gnomon will become diffuse resulting in error. This has been discussed in the context of the measurements from Jai Singh’s observatories. (Sharma, 1995) An attempt had been to compromise on the height of the gnomon itself. All the texts refer to the 12” gnomon while the *Sulba Sutras* hint at a 96” measure. (Shylaja, 2014a). The sticks generally have a pointed tip. Aryabhata and later many others have improved the tip specifying that a sharp needle / pointed marker to be fixed above the cylindrical base of the stick.(Ohashi, 1994)

The instrument with a 12” gnomon at best can give an accuracy of about half degree in the angular measurements. It is very interesting to note that subtle differences were observed and even a mode of correction has been discussed at length. Ohashi (1994) was the first to decode the meaning of a verse in *Manasara*. It pertains to the correction to be applied for the small change within the duration from rise to set. The declination of the sun changes continuously. Thus from the time of sunrise to sunset there is a substantial difference resulting in a small change in the azimuth and time of sunset. (This can influence the fixing of the N- S line as well as the azimuth of the rise/set points.) This correction called *apachaya*, varies from season to season and is described in the verse.

We notice an attempt to fit a geometric curve to the movement of the shadow on a horizontal plane in the *Sulba Sutras* by approximating it to a semicircle (today we know that this is not correct). The scheme of the construction of the *Vedis* for performing ceremonial rites utilises this idea. The saddle shapes of the boundaries of the sacrificial fire place roughly follow the pattern of the shadow movement. The texts describe only the dimensions and an exact pictorial representation has been found in a copper plate inscription dated 1654AD (Figure 2). The position of *dakshnagni* marked the winter solstice, and the adjustment for placing it either because of the migration towards Southern regions or the small change the obliquity of the ecliptic is reflected in the different procedures adopted in the different texts. (Shylaja, 2013).

Figure 2. The saddle shaped boundaries of the vedis as found in a copper plate inscription of the 17th century

SACRIFICIAL INSCRIPTION FROM SONDA



Scale : One-Third

In the instruments described as *Chayayantra*, (shadow instrument) which are basically horizontal dials, an attempt appears to have been made for deriving a geometrical equation for the shadow path. The earliest description in

Aryabhatiyam approximates it to a circle. The figure was improvised by Lalla. The thirteenth century text of Sripathi derives it clearly as a projection of a circle parallel to the celestial equator. Ohashi (1994) describes all the above attempts in great detail; for the procedure given by Sripathi he expresses doubt on the technique itself since the height of the gnomon is not fixed but appears to vary for different times. (However, the idea that a gnomon of varying length may not be true since it is not specified.) It is clearly stated that the two measures (altitude and azimuth) define the shadow length and orientation (Sripada Bhat, 2013). Therefore the horizontal dial perhaps had a series of such curves, for enabling practical observations.

It is interesting to note that the eclipse timings were also expressed in terms of the 12” shadow length. Although the texts have not written this down explicitly, a clue comes from the work of Ragoonathacharry who wrote a monograph to convey the importance of the observations of the transit of Venus of 1874 (Shylaja, 2012a). He lists the timings of an eclipse of that year and the transit for different places in South India in terms of the shadow length. The units are *angulas* (inches) and *vyamgulas* (fraction of an inch). While projecting these numbers the correction for latitude and longitude are taken care of. Table 2 lists a sample from the text of Raghoonathachary.

Table 2 The timings of the eclipse described in terms of the gnomon shadow.

The timings of the eclipse of April 6,1875 expressed as length of shadow of 12" gnomon										
Place	First contact		shadow length at FC		Last Contact		shadow length at LC		Magnitude of eclipse	
	h	m	am	vyam	h	m	am	vyam	percentage	
Tiruvanatapura	10	31	5	6	1	9	3	30	64	
Kallikote	10	33	5	0	1	3	3	24	54	
Mangaluru	10	34	5	0	0	58	3	16	49	
Bengaluru	10	47	4	18	1	17	4	12	55	
Ballari	10	49	4	24	1	14	4	18	49	

The shadow devices were used for measuring the time elapsed since sunrise (or time to sunset) by placing a graduated disc perpendicular to the rotation axis. The concept of the diurnal motion parallel to equator and sun tracing equal angles in equal intervals of time is utilised here.

Aryabhata describes a ‘*Chatra Yantra’* similar to an umbrella which looks like an equatorial sundial. This handy device is easy to prepare; we prepared it with a rod pierced through the center of a circular protractor. The length of the rod can be adjusted to make it an equatorial dial for the desired latitude. By adjusting it to the required altitude Arybhata explains how the azimuth also can be computed. This has to be rotated to match with the azimuth and a conversion table or calculation is needed for getting the time. (Ohashi,1994)

A general trend in all the instruments is towards achieving accuracy based on theoretical calculations. In the case of the horizontal dial, the correction to be applied through the year also is tabulated and named *apachaya*, as mentioned earlier.

A simple tube like stick is called *yasti yantra* and is used for extensive applications. The application to measure the altitude and azimuth of the Sun is quite straight forward. The same stick is also used to measure the time by projecting the shadow on to a graduated circle held horizontally.

More emphasis is given by later authors on solving difficult problems. For example Bhaskara II describes a method of getting the latitude of the place and declination of the Sun using three different readings of the shadow at different times of the day. This appears to be more of a theoretical exercise than of practical use. However it gives a clear indication that the observations were carried out through the day and such exercises / calculations were needed for the cloudy days. The problem (of determining declination and / or latitude) becomes meaningful in the absence of the noon transit observation.

An indirect reference to the fact that observations were made routinely is mentioned in the travelogue of the Chinese traveller Huan Tsang (Xuanxang) in the early part of 7th century AD.

In South India there were institutions called *ghatikalayas*, the earliest dating to about 932AD as per the records on stone inscriptions. (Jyostna, 1981). The inscriptions give details of the grants given to these institutions giving details on the number of students, teachers, administrators and other technical staff. Among them we find the name of an employee called *kapina ghatiyara* and *ghatika prahari* which literally mean a watchman and one who strikes at every hour respectively. However looking at the wages that were offered to them (equal to that of the teachers), these were highly respected positions. It may be inferred that they were time keepers – astronomers of high reputations.

For observing the planets and stars the same principle of measuring the altitude is used. However, instead of the shadow marking, direct viewing is achieved by replacing the stick with a hallow tube. This is termed *nalika yantra*. A modification of this is to view the reflection of the object from a plane like surface of water.

The angular separation between two celestial bodies is measured with the help of two pointers. The word *salaka yantra* is used when the pointers are needles. When the pointers two sticks held in the shape of V the instrument is called *sakata yantra*. Varahamihira used this on a graduated circular disk to get the longitude of the moon and for the determination of *thithi* (the phase of the moon).

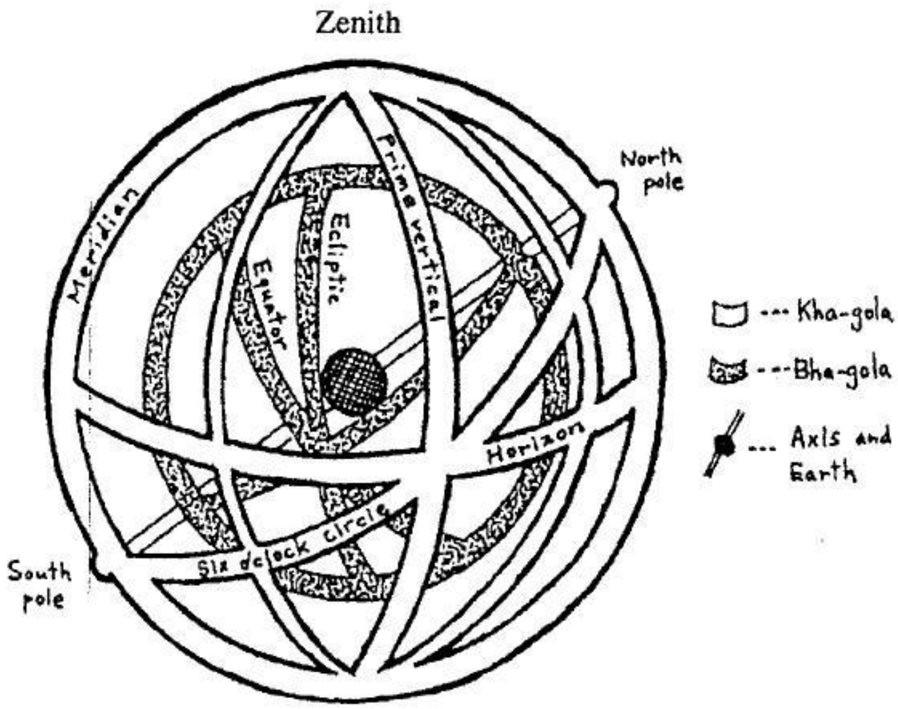
Brahmagupta and Bhaskara II describe the use of the *yantra* for terrestrial survey, for example getting the height of a tall structure like a tree or the width of river. Bhaskara II uses two sticks (one of adjustable length) to get both the quantities, the height of a tree and its distance. He uses the method of simultaneous equations by making two observations – one standing and the other in the posture of sitting.

Some instruments are simple circular dials, usually held in the plane of equator. *Chakra yantra* uses a complete circle while *Dhanur yantra* uses only a semicircle. Two intersecting circles are used in *Kartari yantra* – one circle in the plane of equator and the other in the plane of meridian. It is interesting to note that the *cakra yantra* is the forerunner of today's equatorial mountings of telescopes which utilises a motor to tracks the star by moving parallel to the equator. (Shylaja, 2011)

The variants of these are termed *nadivalaya*, *kapala yantra* and *turya gola yantra.* The best results were achieved by Maharaja Sawai Jai Singh in the huge masonry constructions of *Rama yantra* and *Jaiprakash yantra*. (Sharma, 1995)

The most important task of the astronomer was to mark the position of the celestial body and monitor its movements. This was achieved with a physical model called the *gola yantra* or *gola bandha*. The spherical model has the earth at the center. Three great circles that encompassed it are the prime vertical (*sama mandala*) meridian (*yamyottara)* and the horizon (*kshitija*). The celestial equator tilted at an angle equal to the latitude of the place was *visuva mandala*. The six o clock circle inclined to horizon is called *unmandala*. The other circles include ecliptic (*apa mandala*) and the circle passing through the pole of ecliptic (*drk kshapa mandala*). There are 6 circles (*vi-mandalas*) for the moon and five planets. Altogether it looks like a maze of 51 movable circles. (A photograph may be seen in Sarma, 2016)

Figure 3. The golayantra (reproduced from Ohashi, 1994)



This complicated sphere was used in the day time to fix the *lagna* (the ascendant) and the time of the day by inserting a stick through the center and the point on the ecliptic which corresponds to the position of the Sun. For the planets, the altitude and azimuth were measured using other instruments and the movable circles for the corresponding planets were adjusted on this globe to read out the coordinates on the graduated circles.

There were instruments to measure time intervals. The amount of water to run through a specified size of the hole was called *ghati*. Likewise, there were devices to set the flow of sand used at later times. The size of the hole was specified. Quite interestingly, some verses were phrased in a specific grammatical meters so that the time needed for the recitation itself was a measure of time. (Ohashi, 1994)

It is interesting to note how the time in the night was measured; for a trained eye the celestial sphere itself suffices. (The author had the privilege of learning this technique directly from the starry sky while carrying out observations at VBO during 80's when sophisticated time measuring devices were not yet in use.) Still the accurate determinations were achieved with the circumpolar constellations of Ursa Major and Ursa Minor (for higher latitudes). Padmanabha describes an instrument called *dhruvabhrama yantra* (Sarma, 2016) and a more or less similar one was devised for the use of amateur astronomers by the author (Shylaja, 2011).

Astrolabes may be treated as simple projections of the celestial sphere on to a plane. in about 12th century, Mahendra Suri introduced the instrument as *yantraraja*. (Pingree, 1978). Subsequently many authors have written texts describing its use. (details in Pai and Shylaja, 2016).

3. Observations:

All the texts concentrate on the observations using shadow and hence only solar measurements. Very few discuss the observations of the planets and those of stars are not covered at all.

Triprsnadhikara – finding three quantities, location, direction and position is therefore generally applicable to observations with the only the sun.

Finding north and south is considered too trivial and not discussed in great detail in later texts. They refer to the “fish” method. This requires that a circle of radius 12” to be drawn; the gnomon is the 12” stick kept vertically at the center. The points where the shadow tip touches the circle (once in the fore noon and again in the afternoon) are joined to provide the east west line. A perpendicular bisector is drawn using compasses (by drawing two arcs from the two points at distances more than half the separation). This method is not described in all texts. Most often the description starts directly with a dial with cardinal points marked. Chitrabhanu, disciple of Nilakntha Somayaji, (~15th century) deviates slightly when he provides an alternative “*yantra*” which consists of two sticks perpendicular to each other. The two sticks are double the length of shadow and that of *sanku*. (The need of the double length is not immediately clear.) After marking the points on the circle the sticks are placed along the line joining the tips of the shadow so that the cardinal points are established.

The length of the year was obtained by marking the position of the sunrise/set/ on *uttarayana* (winter solstice). Bhaskara II describes the procedure very briefly as follows.

“*On a flat ground, a circle should be drawn by a pair of compasses of desired measure, which is marked with the measurements of the Radius, and the circle should be graduated with directions and degrees. During Uttarayana, (when the sun rise is seen) towards a point which is south of cardinal point but not very far, the point of rise should be observed with a pin at the centre of the circle. Then the number of sun rises should be counted for a year. It is equal to 365. At this sunrise the point of sun rise is a little to the south of the previous point. The distance of these two points should be measured. Then on the next day, sunrise should be measured again. It is a little to the north of the previous (the last year’s mark). The distance of these two points also should be measured.*

Then from the rule of three should be applied. If the sum of these two differences is 60 ghatikas what is the amount of southern distance?”

Ohashi (1994) has commented on the incompleteness of the procedure since there is a jump in the very next verse to the result that the length of the year is *365 days, 15 ghatikas, 30 palas and 22.5 vipalas.*

Here we need to observe an important difference in the translation – the word *antara* is interpreted as distance. But the final answer is in *ghatika*, a time measure. Therefore the intended meaning is that the interval of time is to be noted. Another point of interest is the word "next day". The word "*anyasmin dine*" means another similar day. This can be the one for next year. Then the meaning is clear. One has to note the successive shift in the time interval which adds up to one day at the end of 4 years to 60 *ghatikas* correspond to 24 hours.

It should be noted that the points of sunrise are to be selected so that in successive years there is a shift to south and then back to north.

This procedure raises two important questions –
1. How was the time interval between two successive sunrises reckoned?
2. How can only two years data be extended to get the total duration of the year to the fraction of an hour?

Let us take a practical example which was done during 2012 to 2016; it was attempted with the meridian transit (not the sun rise point) with a 1m gnomon. The noon transit timings were noted down for five days around winter solstice. The daily changes in the interval for all the years were nearly the same. However on the fourth year it shifted by a day. Therefore the difference in the time can be rounded off to 24 hours. However one needs the exact time of the declination reaching the southernmost value; then one needs to measure it all through the day. This was attempted; but the accuracy achievable with the 1m gnomon cannot provide this answer.

Therefore, the fractional values were probably achieved by continuously monitoring the shadows over the several decades. Or perhaps they had really tall pillars which were used as noon markers.

Almost all the texts describe observations of the sun and even the calculations are aimed at fixing the position of the sun and time. The next object of interest is obviously the moon. For the sun and the moon even the corrections because of change in declination within a day and due to parallax are discussed in great length.

The Moon's sidereal period is obtained by marking the instants of conjunction. The procedure uses the word conjunction; however, for practical observations the opposition is a better choice. The instants of full moon are noted for successive months. This is explained in detail in the context of *chakra yantra* and another instrument called *salaka*.

The planets rarely find a mention. The use of a *cakra yantra* for the determination of the longitude of a planet is given by Brennard (1896) as,

"It is also used for finding the longitude of a planet; for if the instrument be inclined, and held or fixed so that any two of the stars Regulus, δ Cancri, ζ Piscium, or λ Aquarii, appear to touch the circumference, the plane of the circle will coincide with the plane of the Ecliptic, since these stars have no latitude. (Spica, whose latitude is inconsiderable, 2^0 S., and other stars near the Ecliptic, would appear also to touch the circumference.) The latitude of a planet, also, which is in general very small, has its orbit nearly in the same plane with that of the Ecliptic.

Looking, then, through a sight at the zero point of the circle, so that the planet appears opposite the axis, the position of the circle then remaining fixed, the eye is moved along the lower part of the circumference, so that any one of the above stars is seen opposite the axis, the arc between the two positions of the eye is the difference of longitude between the planet and the star; but the longitude of the star being known, that of the planet will also be known."

The measurements of coordinates of stars are not described in any text explicitly. Dikshit (1981) discusses the possible scheme based on observations

(a). by observing the conjunction of stars with planets
(b). by direct observation using a *nalika yantra*.

He further explains how procedure (a) can be erroneous because the stars coordinates would have changed. Therefore actual observation as per (b) is recommended.

The *gola yantra* was more like a table top model. The observations of the positions were transformed on to the sphere and the coordinates were read out with the help of movable graduated circles as described by Samanta Chandra Sekhara. (Naik and Satpathy, 1998)

This procedure also explains the discrepancies in the coordinates when compared to the modern methods. Since all the graduated circular dials had Ashwini as the zero, the corresponding numbers read out would have to be corrected for the epoch also. This is mentioned by Padmanabha; he says all measured values of *Dhrvaka* will have to be added with 15^0. Then the discrepancy is settled. (Pai and Shylaja, 2017)

Amongst all texts describing the construction of an astrolabe Nityananda describes that it is important to measure the maximum altitude of the stars (listed as *paramonnatamsa*); he even gives a practical example for Revathi (Aldeberan). The measurements by Malayendu gives *Dhrvaka* as 2^R (2^R = two zodiacal constellations = 30^0) 1^0 $22^{'}$ $52^{''}$, which means 61^0 $22^{'}$ $52^{''}$. He also provides *Drkshuddha* (corrected from observation) as 2^R 2^0 $36^{'}$ $13^{''}$, which means 62^0 $36^{'}$ $13^{''}$. Using this value we can calculate the declination as 15^0 12'. The declination in the table is 15^0 $22^{'}$ $7^{''}$. From Hipparcos data this declination applied to 14^{th} century which agrees within the observational errors for the date of the work.

This method of transforming actual coordinates is discussed by Abhyankar, 2008 and Chandra Hari, 2006. Transferring the observations on to a smaller globe for reading out the coordinates results in another source of error. This is especially applicable for the northernmost or the southernmost stars. The angles measured are *Dhrvaka* along the ecliptic and *vikshepa* along the hour circle. *Vikshepa* and declination are related by

$$\delta = \beta^* - \sin^{-1}\{\sin \lambda^* \sin \varepsilon\}$$

where λ^* is the longitude / *Dhrvaka*.

There are two entries corresponding to 7R and 24 *Bhaga* and 30 *amsa*, which means (7x 30 + 24 =) 234^0 and 30'. There is another entry corresponding to 8R and 2 *Bhaga* and 9 *amsa* which corresponds to (8x 30+2=) 242^0 and 9'. If there is an error in fixing the 7R or 8R, the corresponding error in declination could be enormous and identifying the star becomes a challenge. In this case the stars have been named as *Sarpa shirhsa* and *Bhujaga Shirsha*, which can lead to searching two different stars. Their *vikshepa*s are 36^0 and 37^0 respectively. We can conclude that both refer to the same star since the literal meaning of both words is 'serpent's head'.

The determination of the positions of the nodes was another challenge. The procedure naturally has to be decided by the simple tools described above. The position of the moon can be determined easily only from about the 3^{rd} before new moon. Therefore, one can monitor the declination every night, the value of its declination and latitude can be determined. Bhaskara II arrives at the position of the node corresponding to the latitude becoming zero. (Ohashi, 1994) However we found another possible procedure. The same observations can give the maximum declination of the moon. It can range from 18^0 to 29^0. If the maximum value is 29^0 (23.5+5), the nodes will have to coincide the First points of Aries and Libra. If the maximum value is 18^0, the nodes will be at the points corresponding to solstices. For the position of the nodes in between, the maximum value of declination changes to intermediate values.

This idea can be graphically represented by simple superposition of sine waves (declinations) throughout the month. The phase shift of the sine wave determines the location of the node. This idea was used as a practical tool by coining a term called *vyathipatha*. This uses the idea of measuring the longitude of the moon when the declinations are equal. The declination of the Sun is given by

Sin $\delta_s = \sin \epsilon \sin \lambda$ ------------(1)

The declination of the moon is given by a similar expression but requires the coordinates of the point of intersection of the secondary to the ecliptic passing through the moon which, in turn is decided by the location (longitude) of the node.

When the two declinations are equal, we get an expression for the longitude of the node in terms of the maximum declination. (Ramasubramanian and Sriram, 2011)

$$\mathbf{Sin\ (I)} = \sqrt{\{\sin(l)\sin(i)\}^2 + \{\cos(i)\sin(e) - \sin(i)\cos(l)\ \cos e\}^{2}} \quad \text{....(2)}$$

Here *l* is the longitude of the node. Therefore, by monitoring the moon's declination and noting down the day of equality of the declinations of the Sun and the Moon, we may determine the longitude of the node. This will decide the possibility of eclipses in the forthcoming months. We may look at a practical example to understand this principle. These may be verified by the records of *vyatipatha* on stone inscription. The same technique was used for the prediction conjunctions of the planets with the Sun and the Moon. We see some practical citations of conjunction in stone inscriptions. (Shylaja and Geetha, 2014 a and b, and 2016)

The instruments were probably inherited / and / or replicas were made without changing the dial readings. Therefore, all the texts give almost identical values of the coordinates. Only in some cases the relevant corrections are mentioned.

Since most of the texts were aimed at fixing the planetary positions (which are close to the ecliptic) the error in the declination is not noticeable.

The practical tool of observations requires sophisticated equipments. However, this seems to have been partly solved by looking at the reflection as in *Siddhanta Siromani* (Chaturvedi, 1981). The clue on the use of reflection is available in *Grahalaghava* of Ganesha Daivagna. In the chapter concerning shadow of planets he describes a practical example. (Balachandra Rao, and Uma, 2006). One needs to see the reflection of the planet aligned with the tip of the *sanku* (12" vertical shaft). Then by applying the theorem of similar triangles the altitude of the star can be measured.

The 17th century text *Karanapaddhati* lists the coordinates as double the actual values. (Venketeswara Pai et al, 2016.) The scales were probably graduated for getting an advantage of improved accuracy. However this idea is not explicitly mentioned anywhere and will be verified only when such a gadget is available.

Conclusions:

Although most of the texts describe only the theories of the instruments, hints on the actual procedures and modifications to improve the accuracy are also available. The procedures for the measurement of the length of the day, (solar and sidereal), moon's perigee and apogee and position of nodes and the coordinates of stars are deduced. The observational procedures that are concealed in the texts are extracted by applying practical methods. Some of them result in questions on how the accuracies were achieved. The short comings appear to have been compensated by theoretical computations involving more observations.

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