Sundials: Ancestors of Our Clocks

P D Anoop

This article deals with the timekeepers of the past, the sundials. Apart from discussing the structure of a few common sundials, we point out the reasons for the variation between sundial time and the time shown by mechanical timekeepers.

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1. Introduction

The earliest of the sundials dates back to 5000 BC. But it is reasonable to assume that our ancestors used 'something like a sundial' for timekeeping even before. Cavemen, who noticed the way in which the shadows of tall trees varied with the daily movement of the Sun, would have been tempted to use it as a time keeper. Later, for convenience and portability, they would have used poles or sticks for the same purpose.

By 1500 BC, with the newly-gained knowledge and understanding in mathematics and astronomy, the Greeks, the Egyptians and the Babylonians constructed sundials of greater accuracy. A crucial step in the development of sundials was made by the Arabs, who obtained the astronomical and mathematical knowledge from the Greeks. Instead of the vertical and horizontal 'gnomons' in the earlier sundials, they constructed gnomons aligned parallel to the Earth's axis of rotation. This system enabled the use of hours of equal length throughout the year. In spite of the arrival of mechanical clocks of greater accuracy, the sundials retained their status as a time keeper up to the 18th century.

A modern sundial essentially consists of a dial surface on which the hour lines are marked, and a stick or an object with a sharp edge called gnomon. The shadow of the gnomon on the dial surface tells the time. Most often the gnomon will be fixed and it will be arranged parallel to the Earth's axis of rotation. If the instrument is located in the northern hemisphere, the upper end of the gnomon will be directed towards the north celestial pole.

Keywords
Sundial, celestial sphere, equation of time, time zones, daylight saving time.

Although there are exceptions, most of the sundials are designed to be used at one location only.

2. Some Essential Concepts

In order to understand the working of a sundial, it is necessary to have knowledge about some of the basic concepts and terminologies in astronomy.

***Terrestrial Coordinate System*:** In order to pinpoint the location of an object on the Earth's surface, a terrestrial coordinate system is necessary. The two coordinates constituting the terrestrial coordinate system are latitude and longitude**.** Latitude is the north–south coordinate. It is measured in degrees. The equator corresponds to 0 degree latitude and the North and South Poles correspond to +90 degree and –90 degree latitude respectively. The east–west coordinate is the longitude. Longitude is constant along a line on the surface of the Earth, connecting the North and South Poles. Such lines are known as the meridians of longitude. The zero of the longitude lies on the meridian passing through Greenwich, England. This is known as the Prime Meridian or Greenwich Meridian. It is also measured in degrees.

***Celestial Sphere*:** Although, from the time of Copernicus itself, it is known that we are living in a heliocentric universe, many a time it is convenient to pretend that it is a geocentric one. The Earth can be imagined to be at the center of a large spherical shell, on the inner surface of which all other celestial bodies are fixed. This is what is known as the celestial sphere (*Figure* 1). When the equator of the Earth is extended, it intersects the celestial sphere in a circle. This circle is known as the celestial equator**.** Equivalent to the poles of the Earth, the celestial sphere has its own North Celestial Pole (NCP) and South Celestial Pole (SCP).

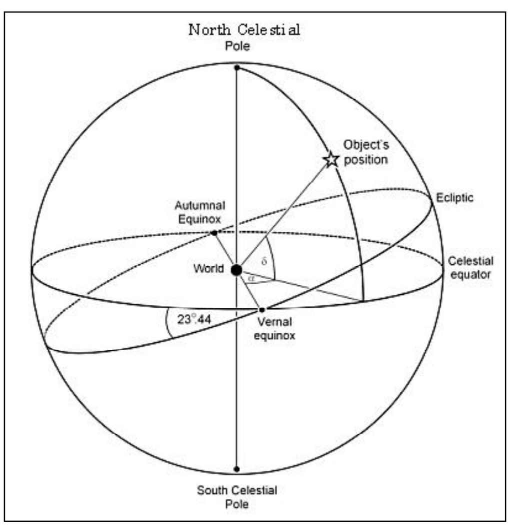

Figure 1. Celestial sphere.
Courtesy: Dr N T Jones (www.geocentricuniverse.com)

The orbit of the Earth around the Sun constitutes a plane called the ecliptic plane. Analogous to the NCP and SCP, there are north and south ecliptic poles on the celestial sphere, which are at right angles to the ecliptic plane. But, the axis of rotation of the Earth does not coincide with the axis passing through the ecliptic poles. That is, the rotation of the Earth about its own axis and its revolution around the Sun do not occur in the same plane. These two planes (the plane of the celestial equator and the ecliptic plane) make an angle of 23.5° with each other. This angle is known as the obliquity of the ecliptic. It is obvious that these planes will meet at two points on the celestial equator. These points are known as equinoxes. The point at which the Sun crosses the celestial equator when going north in spring is known as vernal equinox. The point where the Sun crosses the celestial equator when going south is called autumnal equinox.

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***Equatorial Coordinate System*:** A coordinate system is necessary for the specification of the location of a celestial object on the celestial sphere. Although many exist, the equatorial coordinate system is a particularly convenient one. In the equatorial coordinate system, the north–south coordinate (similar to the latitude of geographical coordinate system) is called declination. It is measured in degrees. The zero of the declination is on the celestial equator. It has positive values on the northern hemisphere and negative values on the southern hemisphere. The north and the south celestial poles are at +90° and –90° of declination respectively. The east–west coordinate system is called right ascension. The zero of the right ascension is at the vernal equinox. Its value increases in the counter-clockwise direction around the NCP. Most commonly, it is measured in hours, minutes and seconds.

3. Types of Sundials

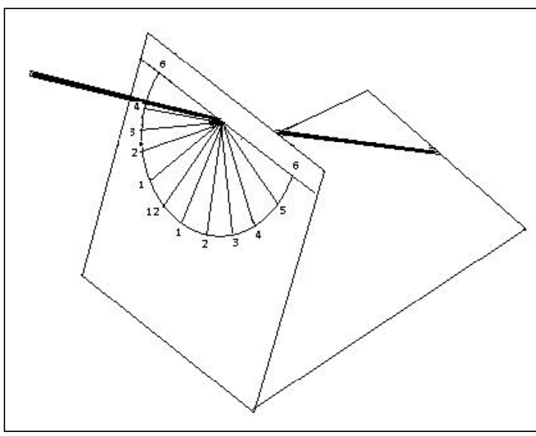
Sundials come in a large number of variety and sizes, ranging from *Samrat Yantra*[1] (King Instrument) in Jantar Mantar[2], Jaipur to pocket dials and from plane-surfaced dials to weird-shaped ones. Here we discuss only a few of the most common and easily constructible sundials.

[1] The largest man-made sundial built by Maharajah Sawai Jai Singh.

[2] See Vasant Natarajan, Standard Weights and Measures, *Resonance*, Vol.6, No.8, 2001.

***Equatorial Sundials*:** The equatorial sundial is called so, because its planar dial surface is aligned parallel to the Earth's equator. The gnomon of the equatorial sundial, which is at right angles to the dial surface, will then be parallel to the Earth's rotation axis. Also its angle with the horizontal surface will be equal to the latitude of the dial's location. Since the gnomon is parallel to the Earth's axis, the Sun's apparent motion about the Earth will give rise to a uniformly moving shadow of the gnomon on the dial surface (*Figure* 2). Since the Sun rotates 360^o in 24 hours, the hour lines on the dial surface are $360^o/24 = 15^o$ apart. The equatorial sundial has hour lines on both the faces of the dial plane. This is because of the fact that the ecliptic and the celestial equator do not lie on the same plane. During the spring and the summer seasons, the Sun is above the celestial equator; hence it will be illuminating only the surface of the dial plane facing the north. During autumn and winter, the Sun, which is below the celestial equator, will illuminate the other face of the dial plane.

***Horizontal Sundials*:** As the name implies, in the case of a horizontal sundial, the dial surface is kept in the horizontal direction (*Figure* 3). The style (edge of the gnomon whose shadow tells the time) is at an angle equal to the local latitude with respect to the dial surface. Hence the motion of the shadow of the style on the dial surface is not uniform. Consequently, the hour lines marked on the dial surface are also not equidistant. They can be accurately marked by the application of trignometry. It can be



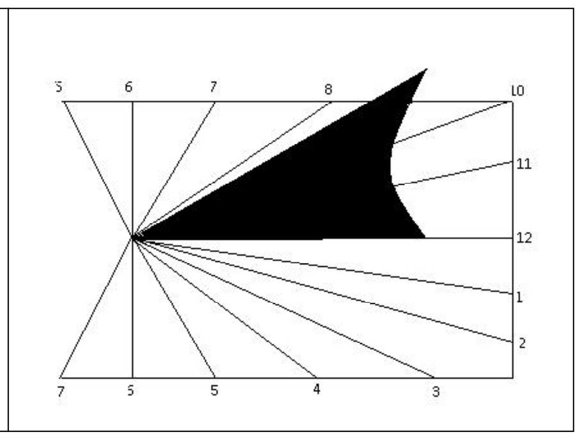


Figure 2 (left). Equatorial sundial.
Figure 3 (right). Horizontal sundial.

easily shown that, in the case of a horizontal sundial at geographical latitude Φ, the hour lines are spaced according to

$$\tan \theta = \sin \Phi \ \tan (15^{o} \times t),$$

where θ is the angle between the given hour line and the noon hour line and t is the number of hours before or after noon.

Figure 4. Veritcal sundial at Treloars College, Hampshire, England.
Courtesy: www.sundials.co.uk

***Vertical Sundials*:** Vertical sundials are common on the walls of old houses and churches, because a vertical dial plane is most suited to such surfaces. The gnomon of the sundial is aligned with the axis of rotation of the Earth (*Figure* 4). As in the case of a horizontal sundial, the hour lines on the dial surface are not equally spaced. The hour lines on the vertical sundials are drawn according to

$$\tan \theta = \cos \Phi \ \tan (15^{o} \times t),$$

where Φ, θ and t have the same meaning as in the case of a horizontal sundial.

4. Solar Time and Mean Time

The time shown by a sundial is called solar time (or true time). Anyone who has observed a sundial would have noticed that the time indicated by it does not agree with the time shown by the mechanical watch. Two questions immediately come to our mind: Why is it so? How can we relate the solar time with the time shown by our watch (called mean time)? There are three reasons for the difference between solar time and local time.

4.1 *Equation of Time*

It should be kept in mind that the working of mechanical watches is based on the concept of an imaginary, 'well-behaved' sun called the 'mean sun'. From the Earth, it will be observed to be moving at a constant speed along the celestial equator (i.e., in a circular path). If the 'mean sun' were the actual sun, then the obliquity of the ecliptic and the ellipticity of the Earth's orbit around the Sun would have been nil. This would have made the

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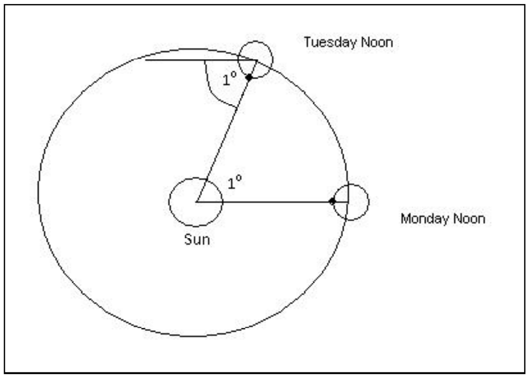

Figure 5.

calculation of local time from the solar time much easier because, it is the obliquity of the ecliptic and the ellipticity of the orbit that result in the equation of time. But, in reality, we are revolving around the 'true sun' in an elliptical orbit and the obliquity of the ecliptic has a non-zero value.

A solar day is defined as the time interval between two successive passages of the Sun across the local meridian. The length of the solar day varies between 23h 59m 30s and 24h 0m 30s in a year. Also, since the Earth completes one revolution around the Sun in 365 days, in one day (~ 24hrs), it covers an angular distance of approximately 1^o around the Sun. Invoking the idea of mean sun, (for which solar days are of equal length 24h 0m 0s) and the true sun, it can be seen from *Figure* 5 that a solar day for the mean sun means approximately 361^o rotation of the Earth.

***Effect of Obliquity of the Ecliptic*:** In this section we deal only with the 'tilt contribution' to the deviation in time. That is, here we assume that the Earth follows a circular orbit around the Sun.

It is known that the obliquity of the ecliptic has a value of 23.5^o. Actually, our time measurements are based on the rotation of the Earth around the polar axis (which is at right angles to the plane of the equator). Hence it is obvious that the obliquity of the ecliptic will cause a deviation in the time measured by a sundial from the mean time.

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It can be seen that the mean sun moving along the celestial equator will have a uniform eastward motion against the background of stars. But the true sun moving along the ecliptic will have components of velocity in the northward or southward direction in addition to the eastward velocity component. Thus the eastward motion will be the greatest, when the Sun is at the solstices and it will be the least at the equinoxes (*Figure* 6). Between these two, the velocity will have a uniform variation.

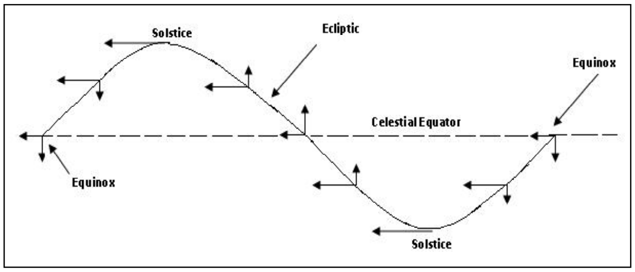

Figure 6. Variation in the velocity components of the Sun along the ecliptic.

This results in the true sun deviating from the mean sun by approximately 9 min.

Effect of the Ellipticity of Orbit**:** In this section, we consider the effect of the ellipticity of the Earth's orbit alone. That is, for the time being, obliquity of the ecliptic is assumed to be zero.

Instead of considering a stationary earth, about which the mean sun and the true sun are revolving, it is convenient to think from the perspective of a stationary sun, about which two earths, the 'mean earth' and the 'true earth' are moving. Just as in the case of the mean sun and the true sun, the mean and the true earths follow a circular and an elliptical path respectively about the stationary sun. Imagining both as starting their motion from the same point at time $t = 0$, after a time period of 24 hrs both would have rotated 361° about their own axes. During this period, the mean earth moving in a circular orbit around the Sun would have revolved 1degree. But it is known from Kepler's[3] laws of planetary motion that the velocity of revolution of the true earth around the Sun, is not uniform thanks to its elliptical path of motion. (Velocity of revolution will be the greatest, when the Earth is closest to the Sun and the least, when it is farthest). Due to this difference in its speed of revolution, it would revolve more than 1° or less, depending on its position in the orbit. This results in a difference in the time measured on the true earth from that on the mean earth and this will get accumulated over a year. It results in a deviation of approximately 8 min between the time shown by the sundials and mechanical watches.

[3] See Johannes Kepler, *Resonance*, Vol.14, No.12, 2009.

The contribution of these two effects is not in phase. The sum of these two is known as the equation of time (*Figure* 7). It gives the

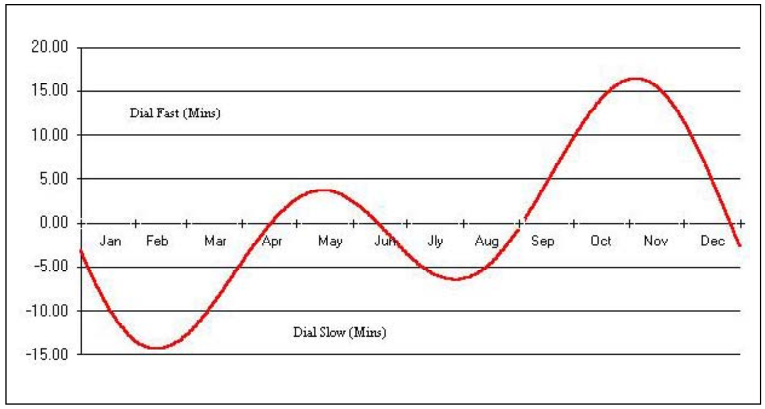

Figure 7. Equation of time.
Courtesy:www.sundials.co.uk

amount by which the true sun is fast or slow when compared to the mean sun. That is

$$\text{EOT} = \text{Solar time} - \text{Mean time}$$

4.2 *Correction for Time Zones*

There was a time, when the local time measured in two adjacent cities varied much. But, as the speed of communication and travel increased dramatically, it was felt necessary to standardize local time worldwide in some convenient manner. Such a standardization was accomplished by dividing the Earth's surface into 24 time zones centered on the Prime Meridian, each having an angular width of 15º. Within each zone, every location has the same standard time. The 'zero' of the time zones passes through Greenwich, England (the Prime Meridian). The first zone on the east and that on the west of the prime meridian differ in time by +1hr and –1hr respectively from the Prime Meridian time. Similarly there will be corrections of ±2hr, ±3hr, etc., for the next consecutive zones on the east and the west. The number of hours including sign should be added to the 'Greenwich Mean Time' (GMT) to get the time corresponding to each zone. In fact, only for those who are located exactly on a standard meridian, local mean time will be the same as the zonal time. The difference between zonal time and local mean time will increase by 4 min for every degree one is away from the standard meridian.

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4.3 *Correction due to Daylight Saving Time (DST).*

The daylight saving time was proposed by William Willet in 1907. Essentially, it is to set the local time 1hr later on the clock than the standard time during summer. It was actually proposed to save the daylight into the afternoon, so as to limit the usage of electric power. Many countries in Europe and the United States use it. Sundials used in such locations should be corrected to suit it.

It should be kept in mind that, even after applying all these corrections, the time computed using a sundial shows a minimum error of 1 minute.

4.4 *Relation between Local (Mean) Time and Solar (True) Time.*

Thus the local mean time can be obtained by taking into account the above 3 factors (Sections 4.1, 4.2, 4.3).

Mean time = True time – EOT + time zone correction + DST correction

It should be kept in mind that, even after applying all these corrections, the time computed using a sundial shows a minimum error of 1 minute. This error is a consequence of the fact that the Sun, as seen from the Earth is not a point object. Rather it is seen as a disc of angular width of $(1/2)^o$. When observed from the Earth, the Sun covers 360^o around the Earth in 24 hours. So, in order to cover $(1/2)^o$, the time taken is 2 minutes. Hence a minimum error of ±1minute will be there, whenever time is measured on the basis of the solar motion. Because of this inaccuracy, which is unacceptable in the modern world, sundials are not used for timekeeping anymore. Although, many sundials are constructed at different parts of the world even today, they primarily have the status of artifacts. Naturally a question arises. Why then should we learn about these inaccurate antiques? The reasons are many.The theory of sundials will be an excellent starting point for anyone with a passion for astronomy. Also, sundials are not just 'useless antiques', rather, they are an elegant combination of science and art. It may be that now they are out of date, but one should remember that they once had a golden era. Our ancestors relied on them for time keeping. And our mechanical watches are just a continuation of their legacy.

Suggested Reading

[1] Denis Savoie, ***Sundials: Design, Construction and Use***, Springer in association with Praxis Publishing, Chichester, UK. 2009.

[2] Mark R Chartrand III, ***Amateur Astronomy – Pocket Skyguide***, Newnes Books, Middlesex, England, 1984.

[3] ***http://www.sundials.co.uk/***

[4] Nick Strobel, ***Astronomy without a Telescope, http://www.astronomynotes.com/***

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