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The Mechanism and Application of Ancient Astronomical Time Measuring Tools

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Abstract: *By observing the change in the length of tree shadows throughout the day, people from both the East and the West sought tools to record these variations. In China, the predecessor of the sundial was the "Gui" (a vertical rod) and the "Biao" (a horizontal platform), which have been used to measure seasonal changes and determine the length of the year. The development of the sundial evolved from simple vertical scales to more complex circular designs, such as the equatorial sundial, which has a scale parallel to the equator and utilizes the Earth's rotation and orbit to provide accurate time readings. Other types of sundials, such as the horizontal and vertical sundials, also played a role in various regions of the world, reflecting regional adaptations based on latitude and usage. Advances in sundial technology include the "Yanggong" sundial from the Yuan Dynasty in Korea and the "Tower of the Winds" from ancient Greece, which combined time measurement with the determination of solar terms. These innovations not only enhanced the accuracy of timekeeping but also promoted agricultural planning and scientific research in the ancient society.*

Keywords: *Sundial, Twenty-Four Solar Terms, Time Measurement, Principles*

1. Introduction

Ancient people utilized the energy of their environment to facilitate their lives adeptly. Harnessing natural energy through tools to transform it into force for production and daily living is the essence of human progress. From harnessing waterpower for irrigation to using fossil energy to drive oil mills, humanity's application of natural laws has become increasingly sophisticated. The sundial is a excellent example of how laborers used natural forces to improve their lives. This paper explores the historical development of sundials, various types, and technological advancements, highlighting their significant contributions to practical time measurement and astronomical research.

2. Development of Sundials

Figure 1: The oldest known sundial, discovered in ancient Egypt (1500 BC)

The earliest sundials date back to ancient Egypt and Babylon around 1500 BC. From Figure 1, we can see that the earliest sundials already used a twelve-hour system. Over 6,000 years ago, ancient Egyptians used clay sundials to divide the day into twelve hours and estimate time.

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Figure 2: Stone Sundial, Han Dynasty, Excavated in Tokto City, Inner Mongolia of China.

In China, sundials initially appeared as “gui-biao” forms, which is a kind of gnomon. “Gui” refers to a vertical rod, and “biao” refers to a horizontal stone platform facing north. The platform had scales to record shadow lengths, and ancient people cleverly carved water channels on the platform to ensure its level and accuracy. By observing the changes in shadow lengths throughout the year due to the Earth's orbit, ancient people could determine the summer solstice, winter solstice, and further ascertain seasonal changes and the length of a whole year.

In China, the ealiest sundial was found over 2000 years ago, as shown in Figure 2. The astronomical mathematical text “Zhoubi Suanjing[1]” recorded: “On the summer solstice, the shadow is 16,000 li long, and on the winter solstice, it is 13,500 li long. When the sun is at noon, the shadow is measured. This is the number according to celestial principles. The Zhoubi is 8 feet long; the sundial on the summer solstice is 1 foot 6 inches.” This accurately documented the usage and some data of the gnomon (Gui-Biao). The text explains how to calculate the distance between the sun and the Earth using projection knowledge and the Pythagorean theorem.

Once the Gui-Biao is improved into a circular disk to show the angular changes throughout the day, it becomes a sundial. Ancient texts such as “Han Shu: Yi Wen Zhi: Sundial Book” and “Sui Shu: Tian Wen Zhi” have recorded methods related to sundials. Unlike the Gui-Biao, the sundial can detail the changes in time throughout the day. The sundial's shadow angle changes with the Earth's rotation, and by recording these angular changes, it can display time like a clock. In fact, sundials have continuously evolved in the East and the West, with various types such as equatorial, horizontal, vertical, polar, and meridian sundials emerging. Each type of sundial reflects its unique adaptation to local regions.

Here, I will briefly introduce several common types of sundials.

3. Types of Sundials

3.1 Horizontal Sundial (see Figure 3)

As the earliest form of sundial, it is easy to set up but requires additional time measurement tools, resulting in greater errors. Horizontal sundials are commonly seen in Europe. As Chinese sundial technology advanced, the equatorial sundial gradually replaced the horizontal sundial in China.

Figure 3: Horizontal sundial made in Europe in 1862

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3.2 Equatorial Sundial (see Figure 4)

Also known as the slanted sundial, it is the most common type of sundial. The Southern Song text "Duxing Zazhi"[2] records: "Nan Zhong once said that the method of calculating shadows is recorded... In Yuzhang, the shadow diagram is made of wood, divided into four parts, resembling a crescent moon... At the center of the diagram, a gnomon is placed pointing towards the North Pole and the South Pole. After the spring equinox, read the gnomon facing the North Pole, and after the autumn equinox, read the gnomon facing the South Pole... The side faces the equator. After the spring equinox, the sun enters the equator, and after the autumn equinox, the sun exits the equator. The two equinoxes' day and night are equal, so there is no shadow in the North and South." This passage explains how to set up and use the sundial, with the gnomon pointing towards the celestial poles, and readings are taken according to the gnomon's direction.

Equatorial sundials are common in China, such as the one in front of the Forbidden City, and Figure 4 shows the equatorial sundial in Tsinghua University.

Figure 4: Equatorial sundial made in 1920 in the lawn in front of Tsinghua University's Great Hall

3.3 Vertical Sundial (see Figure 5)

Vertical sundials are mainly used in mid to high latitudes, thus appearing primarily in Europe. They are usually embedded in walls and serve both timekeeping and decorative functions.

Figure 5: Vertical sundial built in Europe in 1726

4. Usage and Principles of Sundials

Sundials operate based on the Earth's rotation and orbit and the changing solar angles. Taking the equatorial sundial as an example, it has scales marked with twelve hours and divisions (24 hours). From the spring equinox to the autumn equinox, the sun is high, and readings are taken from the front side; from the autumn equinox to the spring equinox, the sun is low, and readings are taken from the back. Since the sun rises in the east and sets in the west, the shadow rotates clockwise from west to east. By observing the shadow's rotational angle, the current time can be read.

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When setting up an equatorial sundial, the sundial's plane should be parallel to the equator, meaning the gnomon's tilt angle should be complementary to the sundial's latitude. The gnomon must be perpendicular to the sundial's plane, with its upper end pointing towards the North Pole and the lower end pointing towards the South Pole. The scales are evenly distributed.

Table 1. The latitude of some cities and the tilt angle of the sundial

City	Latitude	Tilt Angle of Sundial = Latitude of Sundial
Beijing	39.9°	50.1°
Shanghai	31.1°	58.9°
Shenzhen	22.5°	67.5°
Equator	0°	90°
North Pole	90°	0°

Table 1 shows the latitude of some cities and the tilt angle of the sundial. The tilt angle of the sundial in a city is complementary to its latitude. Representing this with an image (figure 6):

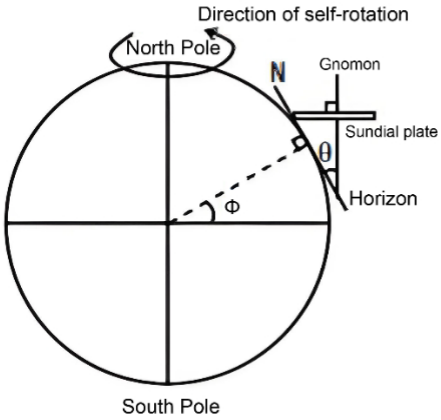

Figure 6: Figure of the setting of the equatorial sundial

This design simulates the sun's movement around the Earth (Earth's axis) to represent the sun's movement around the gnomon from east to west throughout the day. The shadow's angular velocity on the sundial is uniform, completing a full circle in 24 hours, which explains the even distribution of scales on the sundial.

In ancient China, the 12-hour system was used, so traditional sundials often divided the dial into “Zi, Chou, Yin, Mao, Chen, Si, Wu, Wei, Shen, You, Xu, Hai” and further subdivided each hour for precise timekeeping.

At the same time, the equatorial sundial reflects the “round sky and square earth” concept. “Zhoubi Suanjing[1]” records: “The square belongs to the earth, and the circle belongs to the sky. The sky is round, the earth is square, and everything has its round and square nature. The sky moves in a circular motion, and its number is odd; the earth remains still and is square, and its number is even.” In the use of the equatorial sundial, the dial surface is treated as the ground, and the sun's movement within the spherical space formed by the gnomon represents the sky or even the universe. The equatorial sundial embodies the application and interpretation of the “round sky and square earth” concept[3].

In the West, the horizontal sundial is prevalent.

Although the horizontal sundial only requires the dial surface to be parallel to the ground, if the gnomon remains perpendicular to the dial surface, the shadow, like a human's, changes in length and direction throughout the day, making it difficult to predict. To avoid inaccurate readings, people made the gnomon parallel to the Earth's axis, achieving a similar principle to the equatorial sundial by simulating the Earth's movement around the sun. The horizontal sundial requires specific calculations and design for scale distribution (figure 7):

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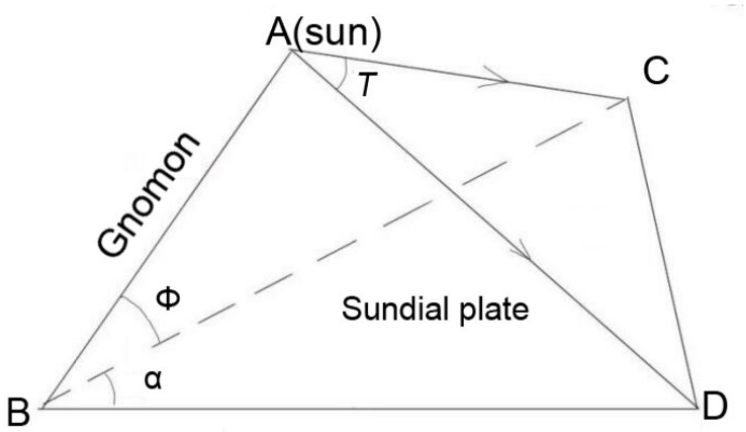

Figure 7: Diagram of a horizontal sundial

In the design of a horizontal sundial, the gnomon (AB) and the dial face (BCD) are oriented such that the angle between the gnomon and the dial face corresponds to the local latitude. This design represents the angle of solar incidence at noon. Regardless of the sun's height, the length of the shadow (BD) changes, so we observe the sun from point A. As a result, the plane ABC is perpendicular to plane ACD. Since plane ABC is perpendicular to plane BDC, line CD is vertical to plane ABC, and line BC is perpendicular to line CD. The formula derived from this design is:

$$tan\alpha = sinT + tan\phi$$

Where:

- $\alpha =$ **Shadow Angle** is the angle of shadow change.
- $T =$ **Solar Hour Angle** is the angle distance from the celestial meridian of the observer to the solar hour circle. For example, if noon is defined as 0°, the solar hour angle increases by 15° per hour. Note: Morning hour angles are negative, and afternoon hour angles are positive.
- $\phi =$ **Latitude** is the latitude of the location.

We can transfer the equation to get that:

$$\alpha = \tan^{-1}(sinT + \tan\phi)$$

This formula allows for the calculation of the divisions on a horizontal sundial. However, the horizontal sundial has limitations as it is designed for specific latitudes and cannot be easily adjusted for different locations[4].

5. Sundials and the Twenty-Four Solar Terms

In ancient China, sundials were used to observe seasonal changes. The "Zhoubi Suanjing[1]" records: "On the winter solstice, the shadow is three feet five inches long; on the summer solstice, the shadow is one foot six inches long. The shadow is longest on the winter solstice and shortest on the summer solstice." This indicates that ancient Chinese scholars noted the variation in shadow lengths throughout the year. The sundial's ability to track these changes helped determine the solar terms and the length of the year.

The "gui Biao" (a vertical rod) was used to measure solar terms and seasonal changes. By observing the longest and shortest shadow lengths at the solstices, ancient people could calculate the number of days between solstices and divide the year into 24 solar terms. The length of the shadow at noon during each solar term was recorded for agricultural and practical purposes. For example, the lengths of shadows at the solstices and equinoxes can be depicted as follows (figure 8):

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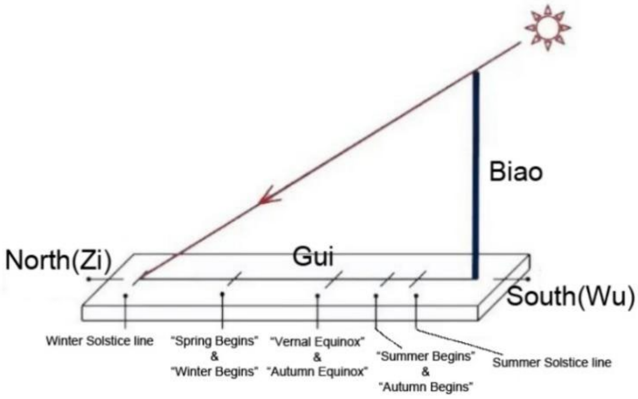

Figure 8: Ancient Chinese gnomon (Gui Biao)

If we plot the shadow lengths of the gnomon corresponding to different seasons at noon on the gnomon dial (figure 9):

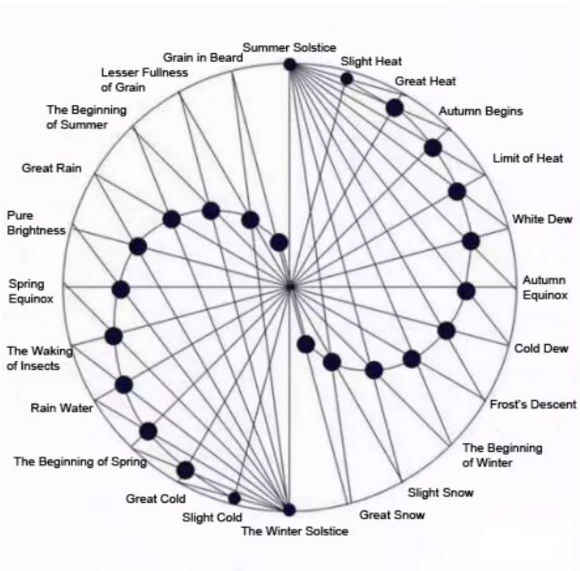

Figure 9: Shadows of a sundial at different solar terms

From the figure, we can see that the symmetry in shadow lengths during equinoxes and solstices reflects the cyclical nature of the solar terms. This observation led to the development of the 24 solar terms system, which guided agricultural practices throughout the year.

What's more, the shadow lengths for each pair of opposite solar terms, such as the summer solstice and winter solstice, or the vernal equinox and autumnal equinox, are the same but the directions are opposite, creating a pattern similar to the Taiji diagram. This may indeed be the origin of the Taiji diagram. People could record the gnomon shadows at noon during each solar term throughout the year to guide future agricultural production.

It can be observed that the use of the gnomon in ancient China not only guided people's practical production and daily life but also connects with the roots of Chinese culture. The invention of the gnomon has had an indelible impact on both the material and spiritual aspects of Chinese society.

5.1 Advanced Sundials for Time and Solar Terms

To measure both daily time and yearly solar terms, advanced sundials were developed. In China, during the Yuan Dynasty, astronomer Guo Shoujing invented the "Yuan Dynasty Yang Yi," which utilized a spherical design to accommodate both time and solar term measurements. This design was further refined by Korean scholars, resulting in the "Yanggong Sundia[5]."　(See figure 10)

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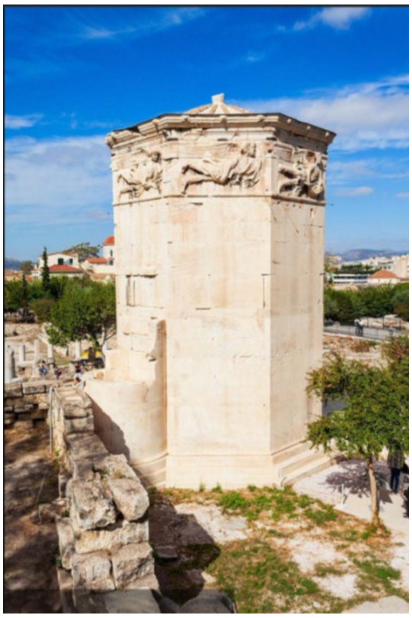
Figure 10: Korean Yanggong Sundial from around 1713

The astrolabe sundial features a gnomon parallel to the Earth's axis pointing towards the North Celestial Pole and a sundial face parallel to the ground. The difference is that the sundial face is a downward-concave hemisphere. It is marked with both timelines and solar terms lines. The horizontal lines perpendicular to the gnomon represent the length of the gnomon to measure the current solar term, while the vertical lines parallel to the gnomon are used to track the movement of the shadow throughout the day to determine the time. This ingenious design effectively utilizes the Earth's rotation and revolution, distinguishing between solar terms and time readings, making it more convenient to use and saving space[6].

5.2 Western Innovations: The Tower of the Winds

In the West, the Tower of the Winds in Greece exemplifies a sundial that combines time and solar term measurements. The Tower of the Winds features eight vertical sundials, each responsible for specific solar terms and times (See figure 11-12).

Taking the Southern sundial as an example, where the upper and lower arcs represent the summer solstice and winter solstice, respectively, and the remaining straight lines indicate the time markers. The other seven sundials reflect different solar terms and times. By combining the eight sundials, one can measure the time and solar terms for each day comprehensively. This can be compared with the upright sundial; both use the design of intersecting lines to achieve the simultaneous representation of time and scales.



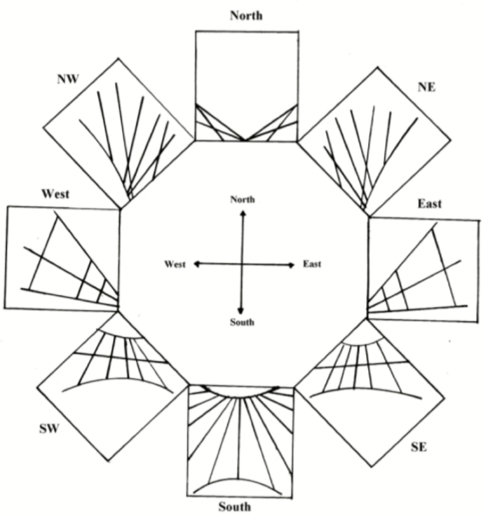


Figure 11 & 12: The Tower of the Winds and its vertical sundials

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However, compared to the upright sundial, the Wind Tower design has the drawback of requiring a large area and even necessitating the use of a tower, making it less practical. Yet, it brings an enhancement in artistic achievement, with sculptures on the tower and paintings on the sundial face, adding different meanings related to religious mythology[7].

6. Conclusion

Sundials played a crucial role in ancient timing and the determination of solar terms. They enhanced agricultural efficiency, improved societal control over time, and fostered advancements in astronomy, mathematics, and physics. The design and application of sundials reflect ancient civilizations' profound understanding of natural phenomena, laying the groundwork for modern timekeeping technologies. Through these ancient tools, people were able to align their daily lives with natural cycles, promoting societal progress and cultural development.

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