Eratosthenes of Cyrene

By

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Acknowledgment

The information contained in this report is derived from the bibliography.

Introduction

The report is organized into two parts. **Part I** describes Eratosthenes biography and accomplishments during his entire career.

Eratosthenes of Cyrene (c. 276 BC – c. 195/194 BC) was a Greek mathematician, geographer, poet, astronomer, and music theorist. He was born Cyrene, North Africa (now Shahat, Libya and died in Alexandria, Egypt. He was a man of learning, becoming the chief librarian at the Library of Alexandria. He invented the discipline of geography, including the terminology used today.

Eratosthenes was born in Cyrene which is now in Libya in North Africa. His teachers included the scholar Lysanias of Cyrene and the philosopher Ariston of Chios who had studied under Zeno, the founder of the Stoic school of philosophy. Eratosthenes also studied under the poet and scholar Callimachus who had also been born in Cyrene. Eratosthenes then spent some years studying in Athens. He is best known for being the first person to calculate the circumference of the Earth, which he did by applying a measuring system using stadia, a standard unit of measure during that time period. His calculation was remarkably accurate. He was also the first to calculate the tilt of the Earth's axis (again with remarkable accuracy). Additionally, he may have accurately calculated the distance from the Earth to the Sun and invented the leap day.

He created the first map of the world, incorporating parallels and meridians based on the available geographic knowledge of his era. Eratosthenes was the founder of scientific chronology; he endeavored to revise the dates of the chief literary and political events from the conquest of Troy. In number theory, he introduced the sieve of Eratosthenes, an efficient method of identifying prime numbers.

Eratosthenes was a figure of influence in many fields. According to an entry in the Suda (a 10th-century reference), his critics scorned him, calling him *Beta* (the second letter of the Greek alphabet) because he always came in second in all his endeavors.[Nonetheless, his devotees nicknamed him *Pentathlos* after the Olympians who were well rounded competitors, for he had proven himself to be knowledgeable in every area of learning. Eratosthenes yearned to understand the complexities of the entire world.

Background of Cyrene

Eratosthenes (son of Aglaos) was born in 276 BC in Cyrene, Libya. Cyrene had been founded by the Greeks centuries earlier and became the capital of Pentapolis (North Africa), a country of five cities: Cyrene, Arsinoe, Berenice, Ptolemias, and Apollonia, Cyrenaica. In 332 BC, Alexander the Great conquered Cyrene, and following his death in 323 BC, its rule was given to one of his generals, Ptolemy I Soter, the founder of the Ptolomaic Kingdom. Under Ptolemaic rule the economy prospered, based largely on the export of horses and silphium, a plant used for rich seasoning and medicine. Cyrene became a place of cultivation, where knowledge blossomed.

The Library of Alexandrian

The library at Alexandria was planned by Ptolemy I Soter and the project came to fruition under his son Ptolemy II Philadelphus. The library was based on copies of the works in the library of Aristotle. Ptolemy II Philadelphus appointed one of Eratosthenes' teachers, Callimachus as the second librarian. In 245 BC, when Ptolemy III Euergetes succeeded his father, and he persuaded Eratosthenes to go to Alexandria as the tutor of his son Philopator. In 240 BC, on the death of Callimachus, Eratosthenes became the third librarian at Alexandria, in the library in a temple of the Muses called the Mouseion. The library is to have contained hundreds of thousands of papyrus and vellum scrolls.

Recognized for His Knowledge

Despite being a leading all-round scholar, Eratosthenes was considered to fall short of the highest rank. *Eratosthenes was recognized by his contemporaries as a man of great distinction in all branches of knowledge, though in each subject he just fell short of the highest place. He was called Beta, and another nickname applied to him, Pentathlos, has the same implication, representing as it does an all-round athlete who was not the first runner or wrestler but took the second prize in these contests as well as others.*

The following is a summary of Eratosthenes significant achievements:

The Sieve of Eratosthenes is a way of finding prime numbers.

- Measurement of the Sun-Earth distance now called the astronomical unit (804,000,000 stadia, one stadion varies from 157 to 209 meter)
- Measurement of the distance to the Moon (780,000 stadia)
- Measurement of the inclination of the ecliptic with an angle error of 7'
- Compilation of a star catalogue containing 675 stars, which was not preserved
- A map of the Nile's route as far as Khartoum and a map of the entire known world from the British Isles to Ceylon, and from the Caspian Sea to Ethiopia

Platonicus

One of the important works of Eratosthenes was *Platonicus* which dealt with the mathematics which underlie Plato's philosophy. This work was heavily used by Theon of Smyrna when he wrote *Expositio Rerum Mathematicarum* and, although *Platonicus* is now lost, Theon of Smyrna tells us that Eratosthenes' work studied the basic definitions of geometry and arithmetic, as well as covering such topics as music.

Forged Letter

One rather surprising source of information concerning Eratosthenes is from a forged letter. In his commentary on Proposition 1 of Archimedes' *Sphere and cylinder* Book II, Eutocius reproduces a letter reputed to have been written by Eratosthenes to Ptolemy III Euergetes. The letter describes the history of the problem of the duplication of the cube and, in particular, it describes a mechanical device invented by Eratosthenes to find line segments x and y so that, for given segments a and b: $a : x = x : y = y : b$.

Hippocrates Doubling the Cube

By the famous result of Hippocrates it was known that solving the problem of finding two mean proportional between a number and its double was equivalent to solving the problem of duplicating the cube. Although the letter is a forgery, parts of it are taken from Eratosthenes' own writing. In particular, he described there the history of the problem of duplicating the cube. The letter, which occupies an important place in the history of mathematics. An original Arabic text of this letter was once kept in the library of the St Joseph University in Beirut.

When the Delians proclaimed through the oracle that, in order to get rid of a plague, they should construct an altar double that of the existing one, their craftsmen fell into great perplexity in their efforts to discover how a solid could be made the double of a similar solid. The Delians went to ask Plato about it, and he replied that: "the oracle meant, not that the god wanted an altar of double the size, but that he wished, in setting them the task, to shame the Greeks for their neglect of mathematics and their contempt of geometry."

Eratosthenes was very proud of his solution for Doubling the Cube. His motivation was that he wanted to produce catapults. Eratosthenes constructed a mechanical line drawing device to calculate the cube, called the mesolabio. He dedicated his solution to King Ptolemy, presenting a model in bronze with it a letter and an epigram. Archimedes was Eratosthenes' friend and he, too, worked on the war instrument with mathematics. Archimedes dedicated his book *The Method* to Eratosthenes, knowing his love for learning and mathematics.

Alexandria Epigram

He dedicated his solution to King Ptolemy, presenting a model in bronze with it a letter and an epigram. Eratosthenes erected a column at Alexandria with an epigram inscribed on it relating to his own mechanical solution to the problem of doubling the cube:

The gift of Eratosthenes of Cyrene

"If, good friend, thou mindset to obtain from any small cube a cube the double of it, and duly to change any solid figure into another, this is in thy power; thou canst find the measure of a fold, a pit, or the broad basin of a hollow well, by this method, that is, if thou thus catch between two rulers two means with their extreme ends converging. Do not thou seek to do the difficult business of Archytas's cylinders, or to cut the cone in the triads of Menaechmus, or to compass such a curved form of lines as is described by the god-fearing Eudoxus. Nay thou could, on these tablets, easily find a myriad of means, beginning from a small base. Happy art thou, Ptolemy, in that, as a father the equal of his son in youthful

vigor, thou hast thyself given him all that is dear to muses and Kings, and may be in the future, O Zeus, god of heaven, also receive the scepter at thy hands. Thus may it be, and let anyone who sees this offering say: "This is the gift of Eratosthenes of Cyrene."

Achievement Disputes

Eratosthenes was described by the Suda Lexicon as a (Pentthalos) which can be translated as "All-Rounder"-a person skilled in a variety of things: He was a true polymath. He was nicknamed Beta because he was great at many things and tried to get his hands on every bit of information but never achieved the highest rank in anything. Strabo accounts Eratosthenes as a mathematician among geographers and a geographer among mathematicians.

Eusebius of Caesarea stated simply that Eratosthenes found the distance to the Sun literally "of stadia myriads 400 and 80,000", and the distance to the Moon to be 780,000 stadia. The expression for the distance to the Sun has been translated either as 4,080,000 stadia (1903 translation by E. H. Gifford), or as 804,000,000 stadia (edition of Edouard des Places, dated 1974–1991). The meaning depends on whether Eusebius meant 400 myriads plus 80,000 or "400 and 80,000" myriad. With a stadia of 185 m, 804,000,000 stadia are 149,000,000 km, approximately the distance from the Earth to the Sun.

Eratosthenes also calculated the Sun's diameter. According to Macrobious, Eratosthenes made the diameter of the Sun to be about 27 times that of the Earth. The actual figure is approximately 109 times.

Calendar

During his time at the Library of Alexandria, Eratosthenes devised a calendar using his predictions about the ecliptic of the Earth. He calculated that there are 365 days in a year and that every fourth year there would be 366 days.

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Prime Numbers

Eratosthenes also worked on prime numbers. He is remembered for his prime number sieve. The 'Sieve of Eratosthenes' in a modified form, is still an important tool in number theory research. The sieve appears in the *Introduction to Arithmetic* by Nicomedes.

Measurement of the Circumference of the Earth

Another book written by Eratosthenes was “*On Means*” and, although it is now lost, it is mentioned by Pappus as one of the great books of geometry. The book was very helpful in the field of geodesy, and Eratosthenes should always be remembered for his measurements of the Earth. Figure 1 is an illustration of the method Eratosthenes used to calculate the circumference of the Earth

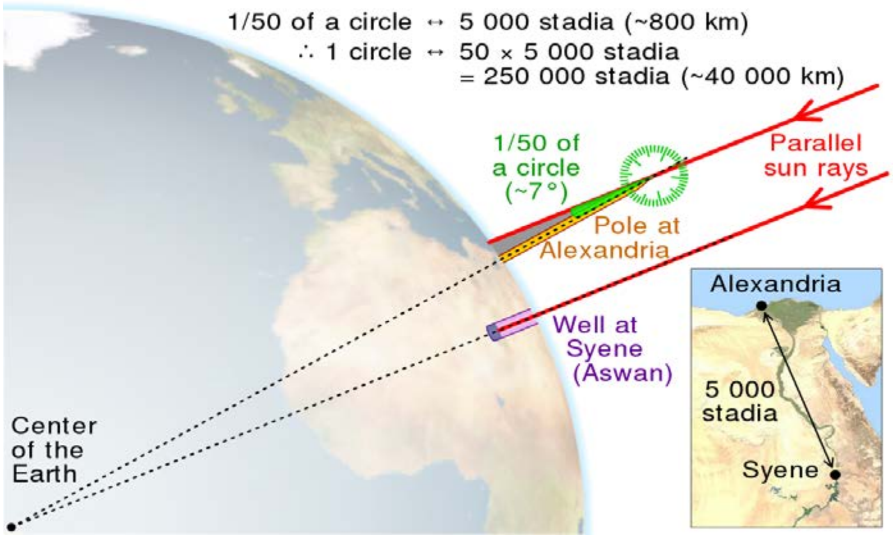

Figure 1 - Measurement of the Circumference of the Earth

Eratosthenes calculated the circumference of the Earth without leaving Egypt. Eratosthenes made a surprisingly accurate measurement of the circumference of the Earth. Details were given in his treatise "*On the Measurement of the Earth"* which is now lost. However, some details of these calculations appear in works by other authors such as Cleomedes, Theon of Smyrna and Strabo. Eratosthenes compared the noon shadow at midsummer between Syene (now Aswan on the Nile in Egypt) and Alexandria. Some say that the distance was corroborated by inquiring about the time that it took to travel from Syene to Alexandria by camel. Carl Sagan (Famous NASA) said that Eratosthenes paid a man to walk and measure the distance.

The calculation is based on the assumption that the Earth is spherical and that the Sun is so far away that its rays were essentially parallel, and then with a knowledge of the distance between Syene and Alexandria, he gave the length of the circumference of the Earth as 250,000 stadia.

How accurate this value is depends on the length of the stadium and scholars have argued over this for a long time. The article discusses the various values scholars have given for the stadium. It is certainly true that Eratosthenes obtained a good result, even a remarkable result if one takes 157.2 meters for the stadium as some have deduced from values given by Pliny. It is less good if 166.7 meters was the value used by Eratosthenes as Gulbekian suggested.

Several of the papers referenced, for example, discuss the accuracy of Eratosthenes' result. The paper is particularly interesting. In it Rawlins argues convincingly that the only measurement which Eratosthenes made himself in his calculations was the zenith distance on the summer solstice at Alexandria, and that he obtained the value of 7°12'. Rawlins argues that this is in error by 16' while other data which Eratosthenes used, from unknown sources, was considerably more accurate.

Eratosthenes made several important contributions to mathematics and science and was a friend of Archimedes. Around 255 BC, he invented the armillary sphere. In *On the Circular*

Motions of the Celestial Bodies, Cleomedes credited him with having calculated the Earth's circumference around 240 BC, using knowledge of the angle of elevation of the Sun at noon on the summer solstice in Alexandria and on Elephantine Island near Syene (modern Aswan, Egypt).

Measurement of the Sun

Eratosthenes also measured the distance to the sun as 804,000,000 stadia and the distance to the Moon as 780,000 stadia. He computed these distances using data obtained during lunar eclipses. Ptolemy tells us that Eratosthenes measured the tilt of the Earth's axis with great accuracy obtaining the value of $^{11}/_{83}$ of 180°, namely 23° 51' 15".

The value $^{11}/_{83}$ has fascinated historians of mathematics, for example several papers were written just to examine the source of this value. Perhaps the most commonly held view is that the value $^{11}/_{83}$ is due to Ptolemy and not to Eratosthenes. Heath argues that Eratosthenes used 24° and that $^{11}/_{83}$ of 180° was a refinement due to Ptolemy. Taisbak agrees with attributing $^{11}/_{83}$ to Ptolemy although he believes that Eratosthenes used the value $^{2}/_{15}$ of 180°. However Rawlins believes that a continued fraction method was used to calculate the value $^{11}/_{83}$ while Fowler proposed that the an-thyphairesis (or Euclidean algorithm) method was used at that time.

Contributions to Science

Eratosthenes made many other major contributions to the progress of science. He worked out a calendar that included leap years, and he laid the foundations of a systematic chronograph of the world when he tried to give the dates of literary and political events from the time of the siege of Troy. He is also said to have compiled a star catalogue containing 675 stars.

Father of Geography

Eratosthenes made major contributions to geography. Eratosthenes is noted for devising a map system based on latitude and longitude lines and computing the size of the Earth. Figure 2 illustrates a 19th century reconstruction designed by Eratosthenes in 194 BC.

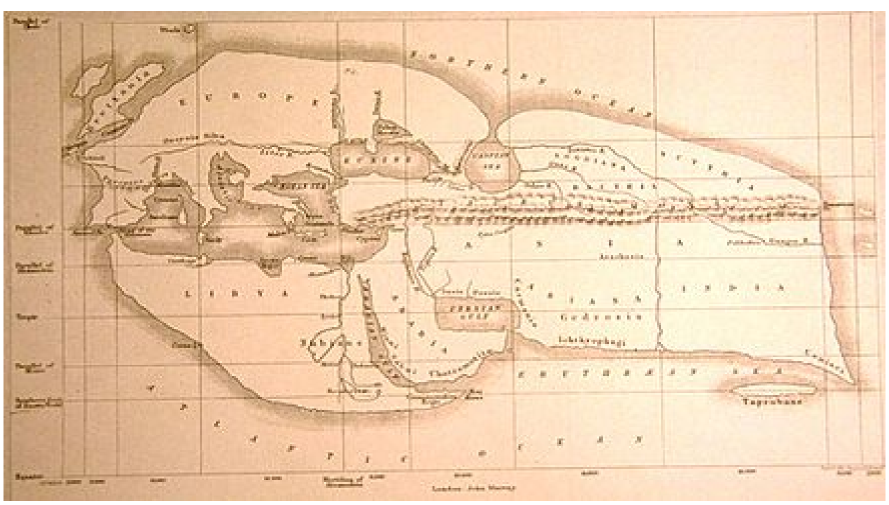

Figure 2 - 19th-Century Reconstruction of Eratosthenes' Map of the Known World (194 BC)

Eratosthenes continued with his knowledge about the Earth. Using his discoveries and knowledge of its size and shape, he began to sketch it. In the Library of Alexandria, he had access to various travel books, which contained various items of information and representations of the world that needed to be pieced together in some organized format. In his three-volume work *Geography* (Greek: *Geographika*), he described and mapped his entire known world, even dividing the Earth into five climate zones: two freezing zones around the poles, two temperate zones, and a zone encompassing the equator and the tropics. He had invented geography. He created terminology that is still used today. He placed grids of overlapping lines over the surface of the Earth. He used parallels and meridians to link together every place in the world. It was now possible to estimate one's distance from remote locations with this network over the surface of the Earth. In the *Geography* the names of over 400 cities and their locations were shown: this had never been achieved before.

Unfortunately, his *Geography* has been lost to history, but fragments of the work can be pieced together from other great historians like Pliny, Polybius, Strabo, and Marcianus. In 200 BC, Eratosthenes is thought to have coined or to have adopted the word geography, the descriptive study of the Earth.

First Book of Geography

The first book was an introduction and gave a review of his predecessors, recognizing their contributions that he compiled in the library. In this book, Eratosthenes denounced Homer as not providing any insight into what he now described as geography. His disapproval of Homer's topography angered many who believed the world depicted in the Odyssey to be legitimate. He also commented on the ideas of the nature and origin of the Earth. He had thought of Earth as an immovable globe; while on its surface was a place that was changing. He had hypothesized that at one time the Mediterranean was a vast lake that covered the countries that surrounded it and had only become connected to the ocean to the west when a passage had opened up sometime in its history.

Second Book of Geography

In the second book is his discovery about the circumference of the Earth. This is where, according to Pliny, "The Geography world was grasped." Eratosthenes described his famous story of the well in Syene, described above. This book would now be considered a text on mathematical geography.

Third Book of Geography

His third book of the *Geography* contained political geography. He cited countries and used parallel lines to divide the map into sections, to give accurate descriptions of the realms. This was a breakthrough, and can be considered the beginning of geography.

Invention of Armillary Sphere

In 255 BC, he invented the armillary sphere (an astronomical instrument for determining celestial positions), which was widely used until the invention of the orrery (planetarium) in the 18th century. He sketched, quite accurately, the route of the Nile to Khartoum, showing the two Ethiopian tributaries. He also suggested that lakes were the source of the river.

A study of the Nile had been made by many scholars before Eratosthenes and they had attempted to explain the rather strange behavior of the river, but most like Thales were quite wrong in their explanations. Eratosthenes was the first to give what is essentially the correct answer when he suggested that heavy rains sometimes fell in regions near the source of the river and that these would explain the flooding lower down the river.

Yemen Population

Another contribution that Eratosthenes made to geography was his description of the region "Eudaimon Arabia", now the Yemen, as inhabited by four different races. The situation was somewhat more complicated than that proposed by Eratosthenes, but today the names for the races proposed by Eratosthenes, namely Minaeans, Sabaeans, Qatabanians, and Hadramites, are still used.

Poem Hermes

Eratosthenes writings include the poem *Hermes*, inspired by astronomy, as well as literary works on the theatre and on ethics which was a favorite topic of the Greeks.

Eratosthenes Criticized Aristotle

Eratosthenes believed there was good and bad in every nation and criticized Aristotle for arguing that humanity was divided into Greeks and barbarians, and that the Greeks should keep themselves racially pure.

Death

In 195 BC, as he aged he contracted ophthalmia, becoming blind. Losing the ability to read and to observe nature plagued and depressed him, leading him to voluntarily starve himself to death. He died in 194 BC at the age of 82 in his beloved Alexandria. Eratosthenes is said to have became blind in old age, and it has been claimed that he committed suicide by starvation.

Part II illustrates the conduct of the Eratosthenes' experiments and the different methods used to calculate the sunrise and sunset.

Definitions

Tropic of Cancer is one of five major circles of latitude that mark maps of the Earth. The Tropic of Cancer currently latitude is 23° 26′ 22″ north of the Equator.

Local noon is when the sun is the highest in the sky and can be quite different from 12:00 noon on the clock.

Solstice is an astronomical event that happens twice each year, when the tilt of the Earth's axis is most inclined toward or away from the Sun. In the northern hemisphere, the maximum inclination toward the sun is around 21 June (the summer solstice) and with the maximum inclination away around 21 December (the winter solstice). For the southern hemisphere winter and summer solstices are exchanged.

Facts of the Experiment: The summer solstice, local noon, the sunrays are just overhead (at a right angle to the ground) on the Tropic of Cancer.

Figure 3 illustrates the geodesy of Alexandria relative to Syene, the boundary of the Tropic cancer and Equator, and the angle of the sunrays reference to the equator.

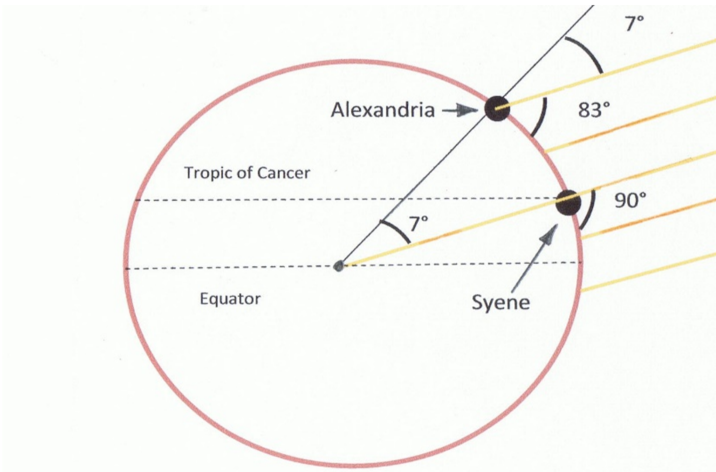

Figure 3 - Eratosthenes' Experiment

Eratosthenes knew that on the summer solstice at local noon on the Tropic Cancer, the Sun would appear at the zenith, directly overhead (sun elevation of 90°) - though Syene was in fact slightly north of the tropic. He also knew, from using a vertical stick and measuring the cast shadow, that in his hometown of Alexandria, the angle of elevation of the Sun would be 83° or 7° south of the zenith at the same time. Assuming that Alexandria was due north of Syene - Alexandria is in fact on a more westerly longitude - he concluded, using geometry of parallel lines, that the distance from Alexandria to Syene must be 7/360 of the total circumference of the Earth.

The distance between the cities was known from caravan travellings to be about 5,000 stadia. He established a final value of 700 stadia per degree, which implies a circumference of 252,000 stadia. The exact size of the stadion he used is no longer known (the common Attic stadion was about 185 m), but it is generally believed that Eratosthenes' value corresponds to between 39,690 km and 46,620 km. The circumference of the Earth around the poles is now measured at around 40,008 km. Eratosthenes result is not bad at all.

What is very interesting is that the measurement of the distance between Alexandria and Syene is based on the estimated average speed of a caravan of camels that traveled this distance. Camels traveled the distance many times to obtain an average estimate.

A Simplified Explanation of Eratosthenes' Experiment

Eratosthenes measured, at his local noon in Alexandria, the angle of elevation of the sun on the summer solstice (21 June). Eratosthenes used the local noon and no other time of the day since at local noon all relevant places and sunrays are placed on the same imaginary plane enabling the use of simple geometry for his calculations. In order to repeat Eratosthenes' experiment you will have to do the same.

Calculation of Sunrise and Sunset Methods

First, calculate your local noon because it may be quite different from 12:00 noon on the clock. There are several ways to compute its exact occurrence. You can also obtain it by yourself by using a sundial or find out when the shadow is the shortest around noon time. Another option is to retrieve the web site You can also obtain it by yourself by using a sundial or find out when the shadow is the shortest around noon time.

The following web site provides information how to calculate the sunrise and sunset: http://aa.usno.navy.mil/data/docs/RS_OneDay.php

On June 21, erect a vertical straight stick or pole of about 1 meter using a carpenter's level and measure the length of the shadow it casts at your local noon. With simple trigonometry you can obtain the angle of the elevation of the sun. You can also obtain the angle, without trigonometry, by drawing the stick and shadow proportionally and measuring it with a protractor. You can compare your results with a web based applet like this: http://www.jgiesen.de/azimuth but be careful to use it correctly (insert your correct time zone, local noon, coordinates, date and ensure that the dropdown menu points to elevation).

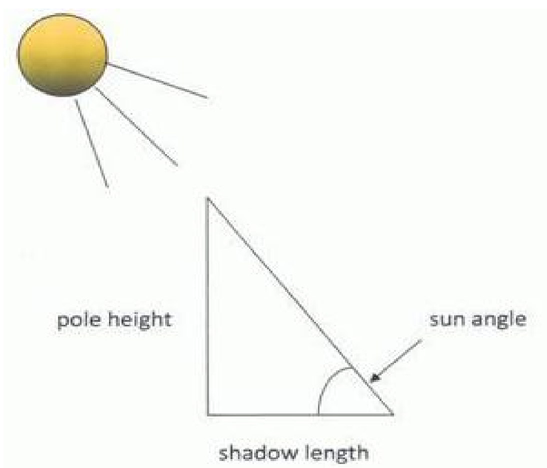

Figure 4 – Angle of Elevation of the Sun

After you get the angle of sun elevation, itis very easy to calculate the zenith angle by subtracting it from 90° like Eratosthenes did. Now you'll have to measure the distance from your location to the Tropic of Cancer latitude line - not by camel caravans of course, the Eratosthenes way. You can use a relatively large scale map, but take in account that maps tend to distort distance and the best option is to use a globe. The distance from your location to the Tropic of Cancer should be measured from north to south. In other words, the distance line has to cut the Tropic of Cancer at a right angle. There are also web-based calculators for this: https://web.archive.org/web/20150419021754/http://facstaff.gpc.edu/~pgore/ISCI/earthcircumference.html.

Now it is easy to calculate the Earth circumference by using the following formula:

$$\frac{\text{angle of the sun}}{360^0} = \frac{\text{distance to Tropic of Cancer}}{Earth\ \ circumference}$$

Likewise, you can also perform this experiment on the winter solstice that takes place around 21 December. You will have to measure your distance from the Tropic of Capricorn instead of from the Tropic of Cancer, because on this date the sun reaches its highest degree of elevation on the Tropic of Capricorn (23° 26′ 22″ south of the Equator).

It is also possible to perform this experiment on the two Equinoxes which occur on 20 March and 23 September each year when the sun is crossing the equator at the local noon on those dates and the sun rays are just overhead the equator at a right angle to the ground. Instead, to measure your distance from the Tropic of Cancer or the Tropic of Capricorn, you will have to measure it from the equator.

There is another option where you can perform this experiment on any other date of the year at local noon-time, but you should have a partner located on your longitude willing to measure sun elevation at the same time. Take into account that you will have to be a little careful treating correctly the sun angles obtained in this case.

On any given date, the sun will reach its highest position at noon-time at some latitude. From here, it is clear that if the two places involved are located on the same side of this latitude (north or south), the shadows will be cast in the same direction. The obtained angles should be subtracted from each other, whereas if the places are located on different sides of this latitude, the shadows will be cast at different directions (southward or northward), and the angles should be added.

Summary

Eratosthenes of Cyrene was a Greek mathematician, geographer, poet, astronomer, and music theorist. He was born in Cyrene, North Africa (now Shahat, Libya) and died in Alexandria, Egypt. He is best known for being the first person to calculate the circumference of the Earth, which he did by applying a measuring system using stadia, a standard unit of measure during that time-period. His calculation was remarkably accurate. He was also the first to calculate the tilt of the Earth's axis (again with remarkable accuracy). Additionally, he may have accurately calculated the distance from the Earth to the Sun and invented the leap day. He created the first map of the world, incorporating parallels and meridians based on the available geographic knowledge of his era. In number theory, he introduced the sieve of Eratosthenes, an efficient method of identifying prime numbers. Eratosthenes yearned to understand the complexities of the entire world.

In 200 BC, Eratosthenes is thought to have coined or to have adopted the word geography, the descriptive study of the Earth. Eratosthenes denounced Homer as not providing any insight into what he now described as geography. Eratosthenes had thought of Earth as an immovable globe, while on its surface was a place that was changing. In 240 BC, on the death of Callimachus, Eratosthenes became the third librarian at Alexandria, in the library in a temple of the Muses called the Mouseion. The library is to have contained hundreds of thousands of papyrus and vellum scrolls. Eratosthenes' contemporaries recognized him as a man of great distinction in all branches of knowledge. In 255 BC, he invented the armillary sphere. Eratosthenes, cording to history, also said to have compiled a star catalogue containing 675 stars.

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