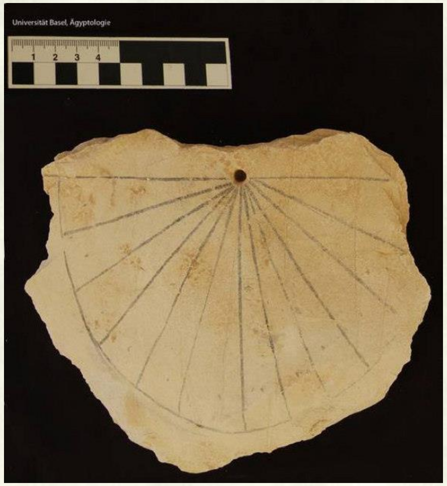
Astronomy in
Timekeeping and Navigation

ASTR 101

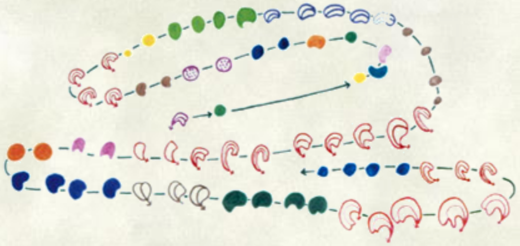
9/21/2018

Timekeeping

Stonehenge



an Egyptian sundial
(13th century. BC)

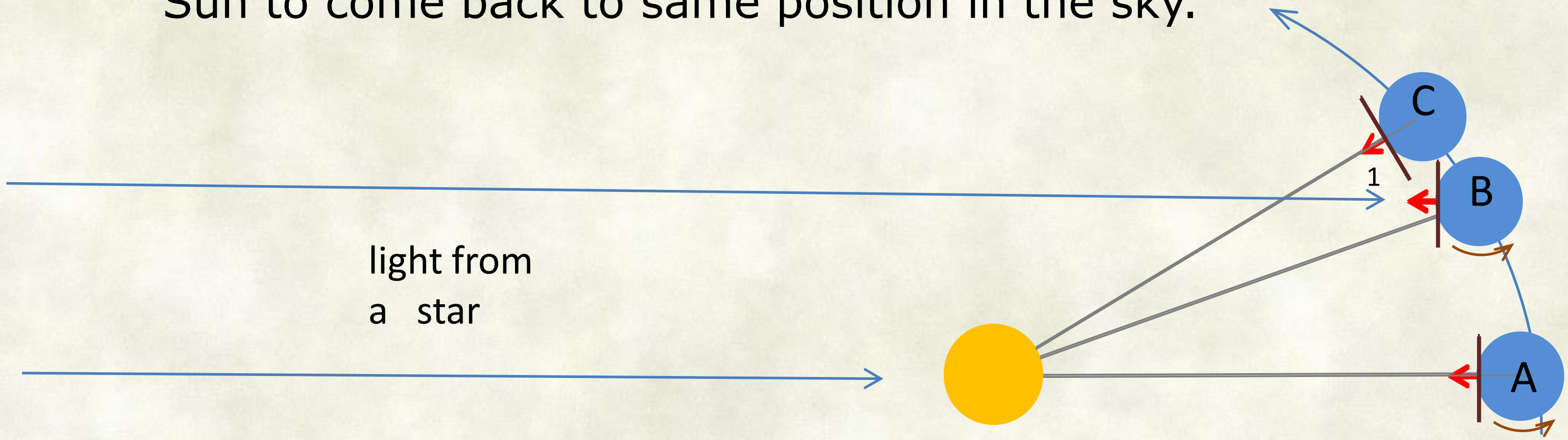


The Blanchard Bone, depicting a series of moon phases (France. 25,000 - 32,000 BCE)

- Timekeeping was one of the earliest uses of astronomy:
  - Apparent movement of the Sun and stars through the sky, changing phases of the Moon, seasons have been used to record the passage of time since pre historic times:
    - **Day:** based on the daily movement of the Sun.
    - **Month:** initially based on the 29 day lunar phase cycle
    - **Week (7-day):** one day for each of the seven special objects in the sky- the Sun, the Moon, and five planets known in the antiquity.
    - **Year:** Annual movement of the Sun and stars through the sky, cycle of seasons.

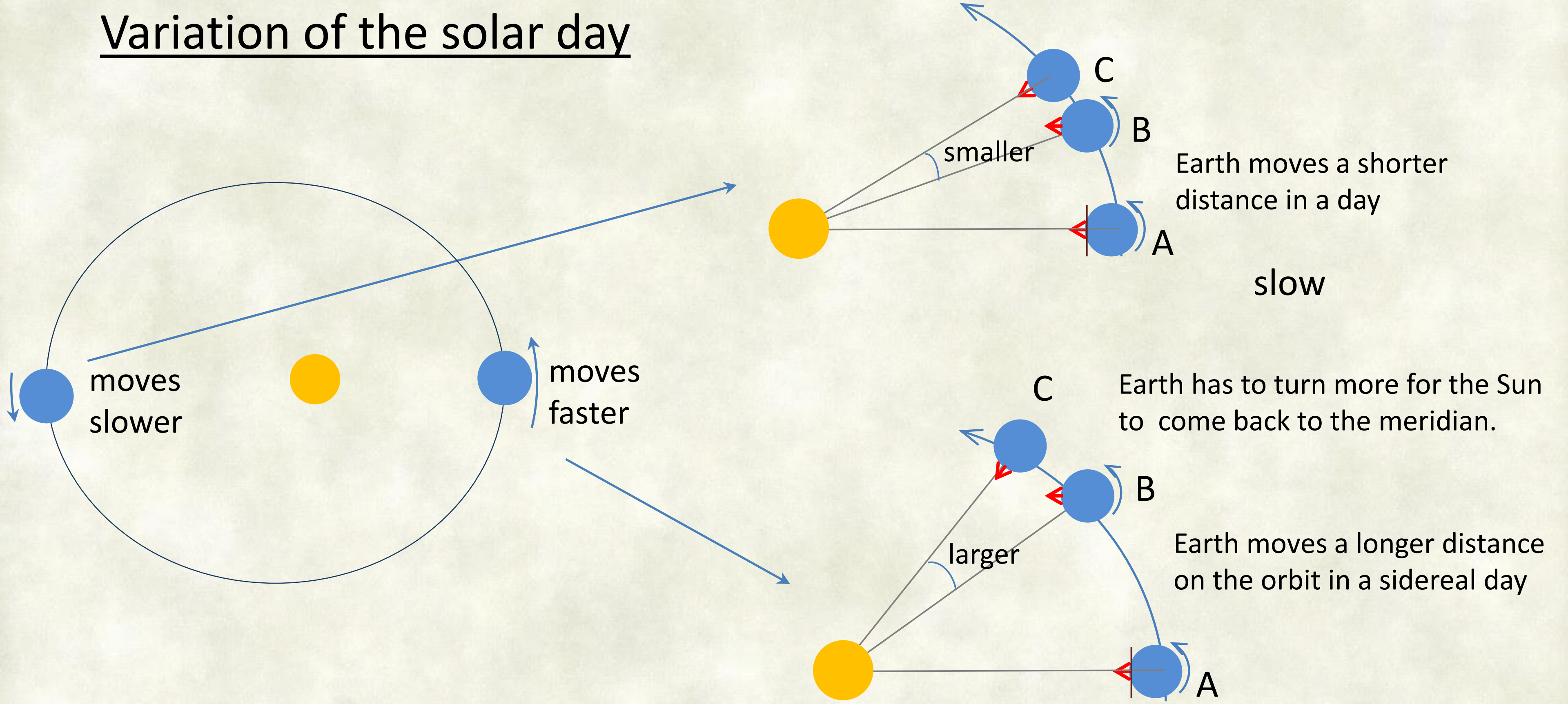
Solar and Sidereal day

- The Earth completes one rotation in 23 hours, 56 minutes, 4 seconds.
  - This duration is known as a **Sidereal day**, it is the time it takes for a star to come back to the same place in the sky (ie. rotation w.r.t. stars)
  - But due to the motion of the Earth around the Sun, it takes longer for the Sun to come back to same position in the sky.



- At time A the Sun and a star are at the zenith (or meridian)
- At time B star is again at the zenith. So earth has completed one sidereal day.
  - 23 hours, 56 minutes, 4 seconds
- But since earth has moved on the orbit during that time, at B Sun is still not at the zenith. Earth has to turn a little more. It occurs later, at C.
- Time interval from A to C is a solar day (usual day)
  - time it takes for the Earth to complete a rotation with respect to the Sun
  - time between noon to noon, sunrise to sunrise, …etc

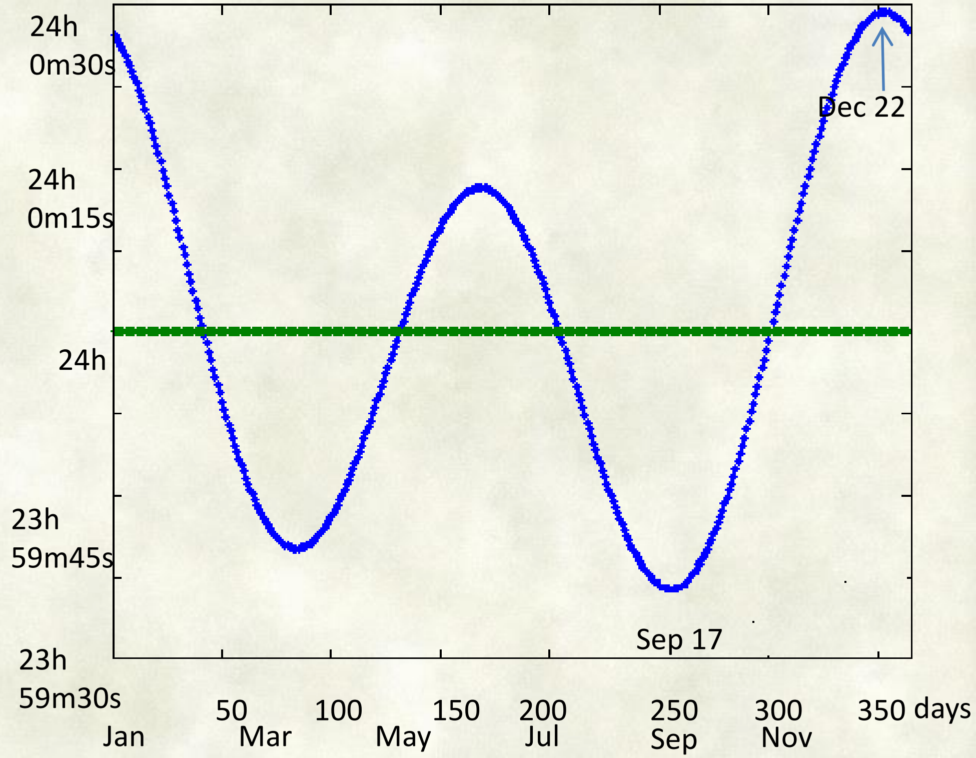
Variation of the solar day



- Since earth rotates at a constant rate, length of the sidereal day is constant.
- But the Earth's orbital speed varies,
  - Earth moves faster when closer to the Sun, slower when it is farther away.
- So the length of the solar day varies throughout the year depending on the location of the Earth on orbit.

Mean Solar Day

- Length of the Solar day changes throughout the year.
- Clocks run at a constant rate, so it is not practical to use the apparent solar day for timekeeping.



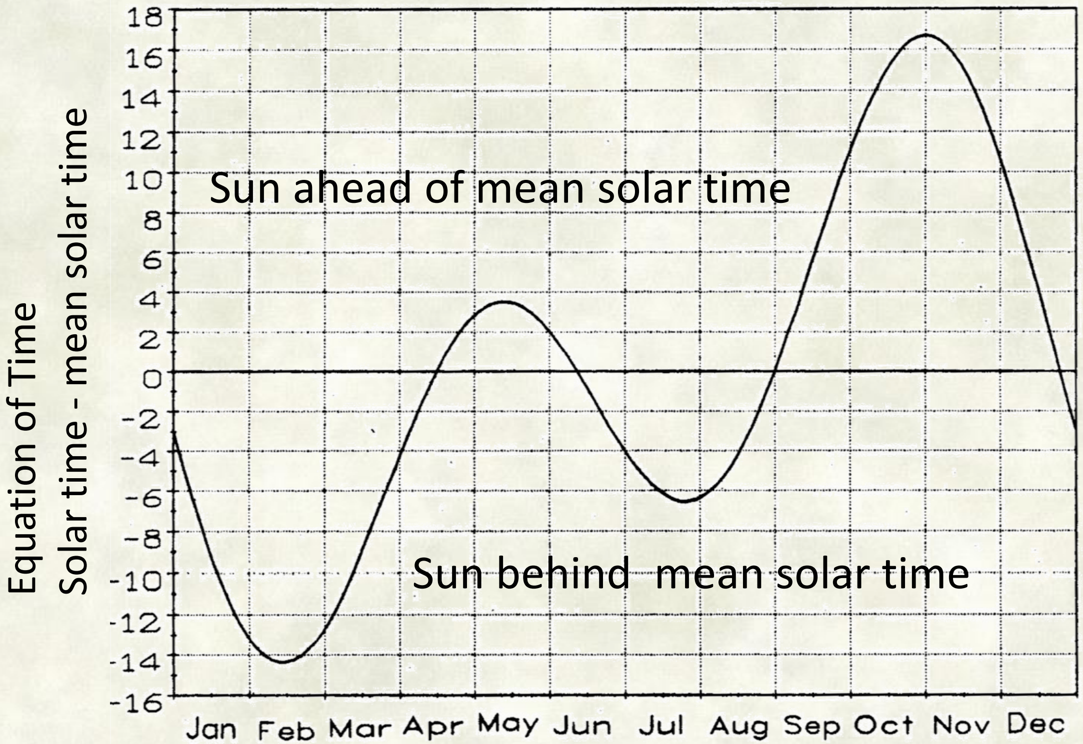
Length of the Solar day

- Solution- define a **mean solar day:**
  - take the average length of solar day over the year and use it as the standard of length of the day.

- 1/24th of the mean solar day 1 hour.
- Longest solar day: December ~22 24h 30s ; 30s longer
- Shortest solar day : September 17 23h 59m 39s ; 21s shorter

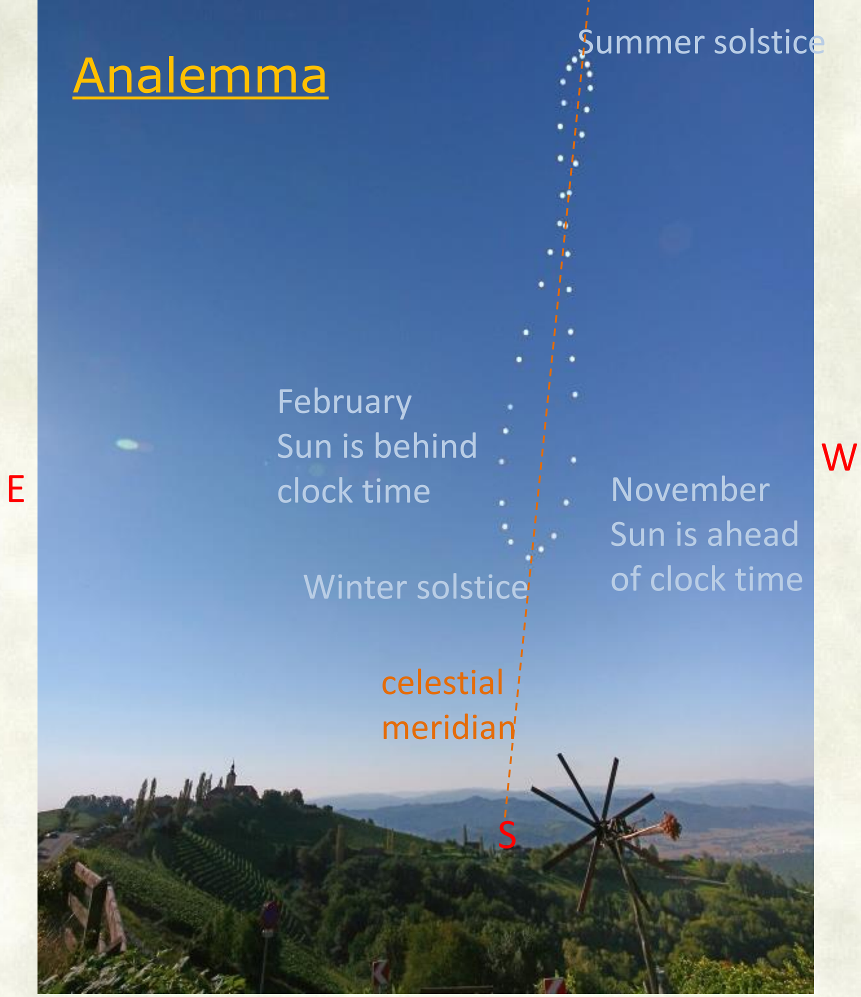
- Although this difference is small (at most 39s) it accumulates.

Equation of Time



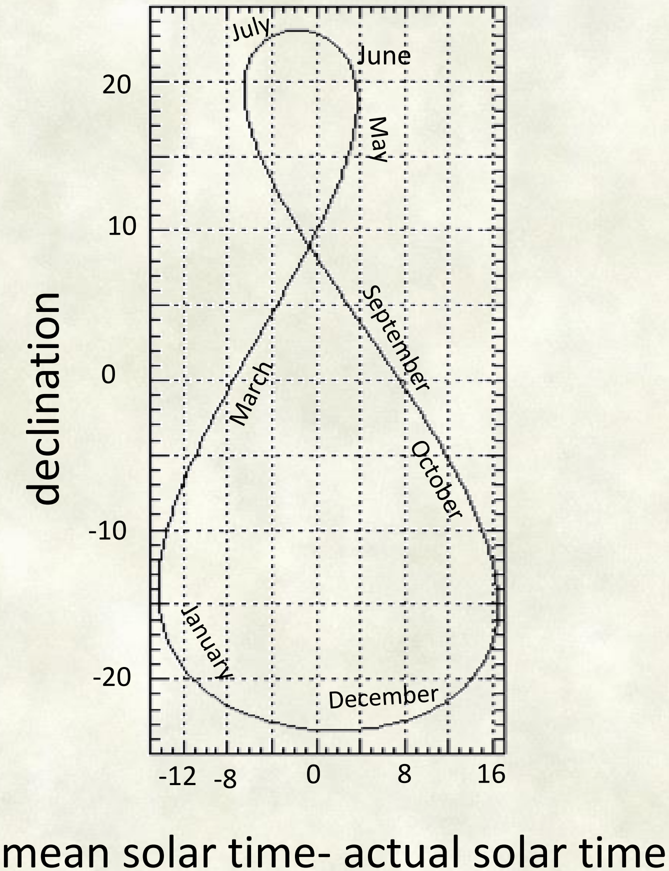
- Although this difference is small (at most 39s), it accumulates, could be up to 17 minutes off
- The difference between actual solar time and the mean solar time is called the Equation of time

Equation of Time = Actual Solar time- Mean solar time



Position of the Sun at 12PM clock time,
(from Austria ,48^{o}N)

apod.nasa.gov/apod/ap120922.html

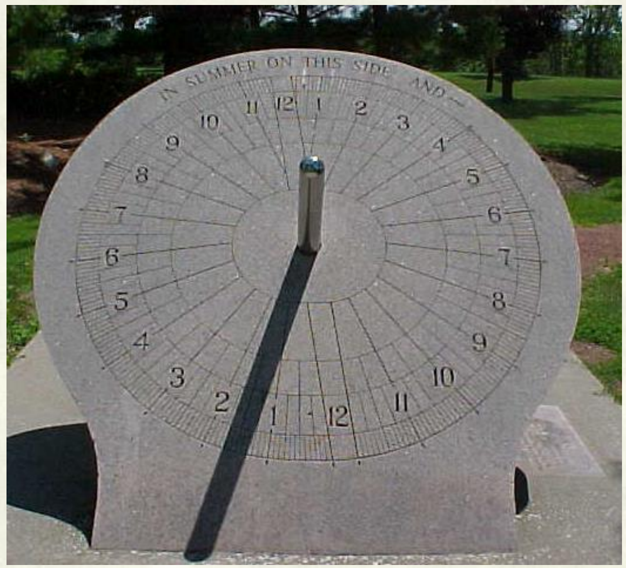


Analemma: The path traced out in the sky by the location of the Sun at a given time of the day over the course of a year.

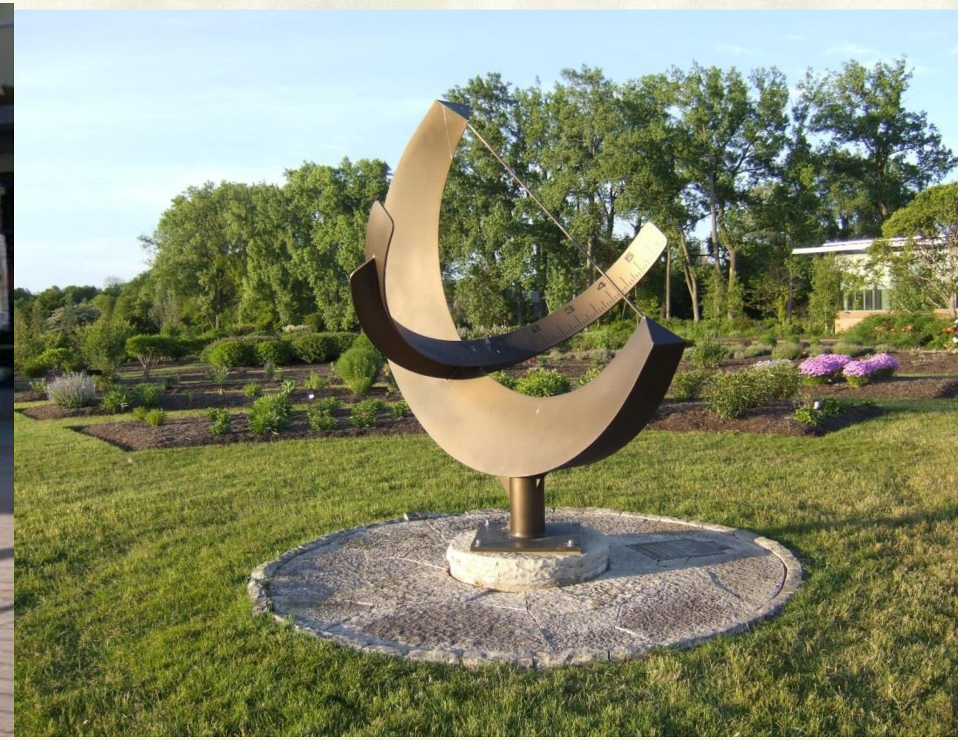
Sundials

- Sundial is probably the oldest type of clock
- It tells the apparent solar time by measuring the position of the shadow of a rod (gnomon).

Pillar (Obelisk) sundial

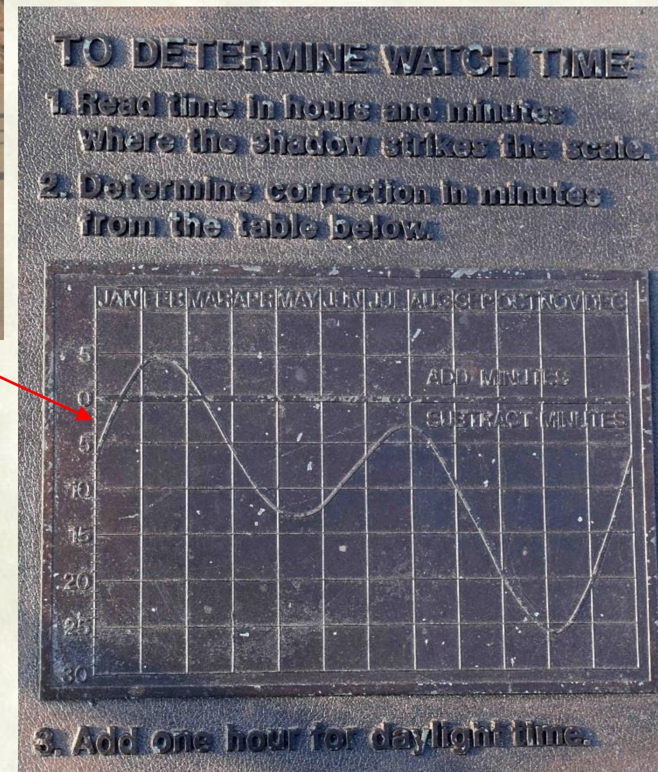


- Easiest to understand is the equatorial sundial
  - It has a gnomon placed parallel to the axis of the Earth (ie. pointing to celestial pole)
  - Its shadow on a disk placed perpendicular to it is uniformly graduated to read time.

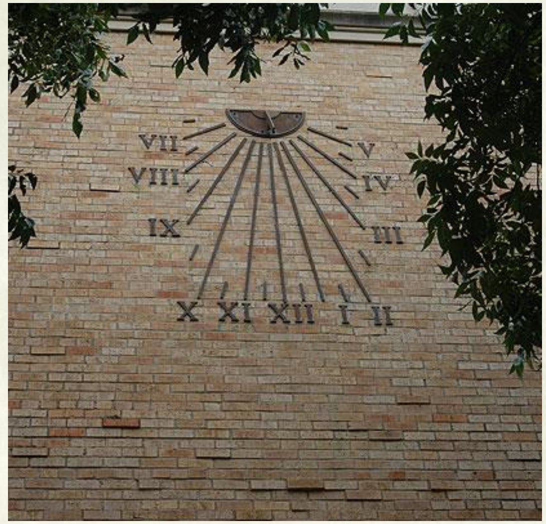


Equatorial sundial at the Chicago botanical garden

used as outdoor sculptures



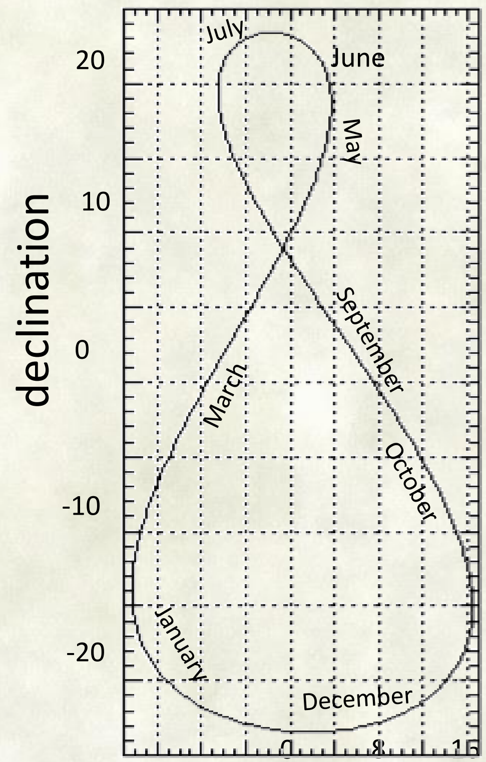
Sundial at the Adler planetarium -Chicago



- Dial of the sundial could be horizontal, vertical or at any angle. But unlike for the equatorial, graduations are not equally spaced.

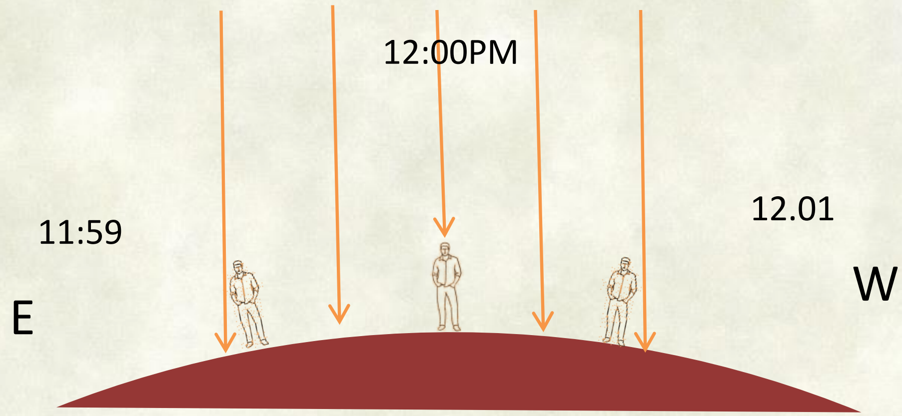
- Sundial tells the actual solar time,
- To obtain standard clock time a correction has to be applied.

- Clock time = sundial time + equation of time



Actual solar time - mean solar time (clock time)

Standard Time Zones



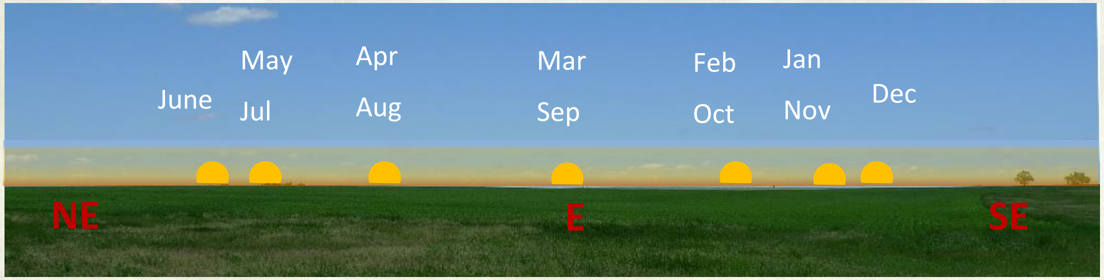
- Position of the sun in the sky changes with location (longitude).
  - When Sun is at the meridian at one location, it is in a different direction a few miles away.

E

- So local solar time changes with longitude.
  - When it's 12:00PM at Oxford,
    - At a location 23 km to east, it is 11:59AM solar time.
    - At a location 23 km to west, it is 12.01PM solar time.
- Earlier on, each town had its own local time, synchronized to local solar noon.
  - That didn't matter when travel and communication were slow.
  - But became a problem when rail transportation became available in the late 19th century.
  - Difficult to schedule or catch a train when every town and every railroad company kept a slightly different time!

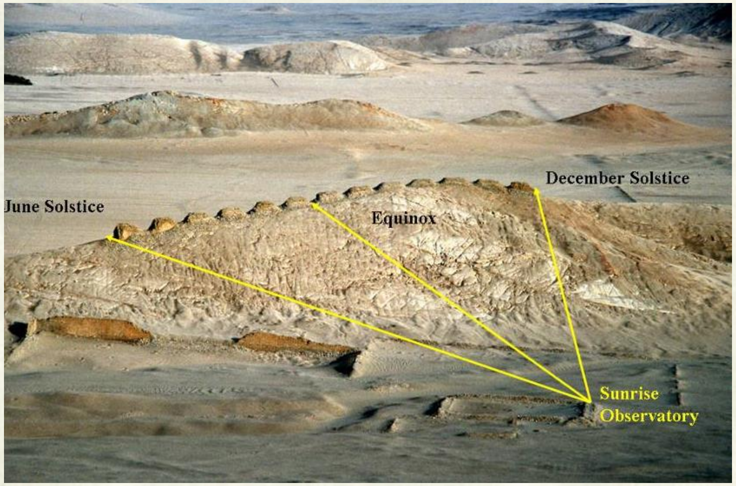
- In 1883 the US and Canadian rail companies adopted standard time zones.
  - In each zone, all clocks are set to the Local Mean Time of a standard longitude:
    - 75° west for Eastern Standard Time, 90° for Central, 105° for Mountain, and 120° for Pacific.
- Since each zone is 15° apart, each time zone differs from its neighbors by one hour.
- It became the law in 1918

The Calendar



Position of the Sun rising along the horizon changes throughout the year

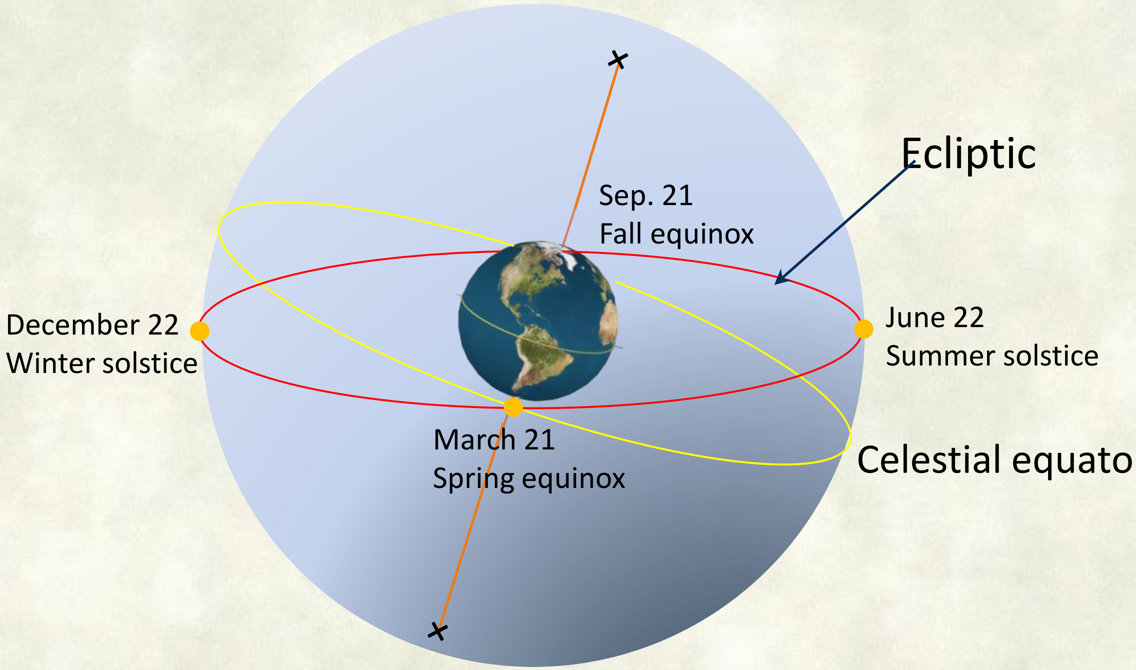
Stonehenge



Towers of Chankillo, Peru

- Seasons and the movement of the Sun and stars follow a 365 day solar year. Egyptians were the first to adopt the 365 day solar calendar.
- People used stars, solstice, to determine the length of the year.

The solar year
(Tropical year)



- Length of the solar year (Tropical year) is defined as the time that the Sun takes to return to the same position in the cycle of seasons.
  - i.e. the time from vernal equinox to next vernal equinox, or from Summer solstice to summer solstice.
  - It is about 365 days, 5 hours, 48 minutes and 46 seconds
- So the 365 day year is about ¼ day shorter than one solar year.
  - lags ¼ day per year against the Sun, which will keep adding up drifting calendar days considerably against the Sun and the seasons over centuries.

A reconstructed ancient Roman calendar " *Fasti Antiates*"

from: penelope.uchicago.edu/~grout/encyclopaedia_romana/calendar/antiates.html

- Julius Caesar introduced an official calendar for the Roman empire.
  - By the time of Julius Caesar, the old lunar calendar of the Roman Republic (maintained by priests) were completely out of alignment with the seasons.
- Greek astronomer Sosigenes suggested a modified version of the 365-day Egyptian solar calendar:
  - an extra day every fourth year (leap year) to account for the actual 365 ¼ day solar year.
- The Julian calendar went into effect in 45 BCE.
- Julian calendar was very successful for many centuries, but later on a flaw began to appear.
  - the solar year (365d, 5h, 48m, 46s) is shorter than 365 ¼ days by 11 minutes 14 seconds, which had been adding up (one day in 130 years).
- Over the span of a millennia it added up to be significant. Calendar was again out of sync with the equinoxes and solstices and seasons.

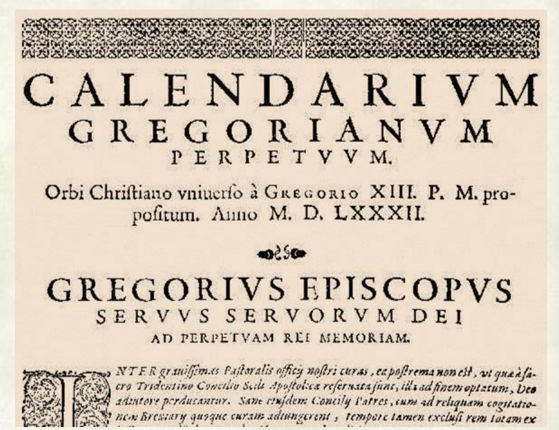
Gregorian Calendar

- By 16th century it was a 11 day discrepancy. Spring equinox was no longer on March 21st but occurred 11 days earlier. (calender was 10 days behind)
  - It became a problem for the church, since day of the Easter was taken as the first Sunday following the full moon after the spring equinox.
- Few Popes took initiatives to reform the calendar, but was unable to do so.
- Finally Pope Gregory XIII appointed the Jesuit astronomer, Christopher Clavius to find a solution.
- Clavius noticed that there had been 3 leap days more than needed every 400 years. (one per 130 years), so to fix the problem some leap years had to be skipped.

- He came up with a clever proposal:
  - century years (those ending in '00') should only be leap years if divisible by 400. This eliminates three leap years in every four centuries.
    - For example, the years 1700, 1800, and 1900 are not leap years, but the year 2000 is.

Pope Gregory XIII

Christopher Clavius



CALENDARIVM
GREGORIANVM
PERPETVVM.

Orbi Christiano vniuerso à GREGORIO XIII. P. M. propositum. Anno M. D. LXXXII.

GREGORIVS EPISCOPVS
SERVVS SERVORVM DEI
AD PERPETVAM REI MEMORIAM.

NTER grauissimas Pastoralis officij nostri curas, ea postrema non est, vt quæ à sacro Tridentino Concilio Sedi Apostolicæ reseruata sunt, illa ad finem optatum, Deo adiutore perducantur. Sane eiusdem Concilij Patres, cum ad reliquam cogitationem Breuiarij quoque curam adiungerent, tempore tamen exclusi rem totam ex

First page of the papal decree , by which Pope Gregory XIII introduced the Gregorian calendar

"Give us our eleven days"

- Pope Gregory put the proposal into immediate effect
  - He announced that the day after October 4 in 1582 will be October 15 - thus fixing the lag in 11 days.

- Because of religious differences (Catholic versus Protestants)adoption of the Gregorian calendar outside the papal states was not immediate.
  - Great Britain, Ireland and the American colonies in 1752, Soviet Russia in 1918, Greece 1924.

- Many people objected to the loss of 11 days by adopting the Gregorian calendar.
  - Among other reasons, because they felt that they lost 11 days of their lives.

Names of the Months

Month	Days	source of the name
January	31	Named after the god Janus.
February	28/29	Named after Februa, the purification festival.
March	31	Named after the god Mars.
April	30	Named after the goddess Aphrodite.
May	31	Named after the goddess Maia.
June	30	Named after the goddess Juno.
July	31	Named after Julius Caesar in 44 B.C.E. Prior to that time its name was Quintilis from the word quintus, fifth, because it was the 5th month in the old Roman calendar.
August	31	Named after emperor Augustus in 8 B.C.E. Prior to that time the name was Sextilis from the word sextus, sixth, 6th month in the old Roman calendar, and had 30 days. After naming it August a another day was added to make it 31 day month and February was make 28 days.
September	30	From the word septem, seven, because it was the 7th month in the old Roman calendar.
October	31	From the word octo, eight; 8th month in the old Roman calendar.
November	30	From the word novem, nine; 9th month in the old Roman calendar.
December	31	From the word decem, ten, because it was the 10th month in the old Roman calendar.

In the Julian calendar, the first day of the year was taken as January 1st, instead the day of spring equinox which was the traditional beginning of the year.

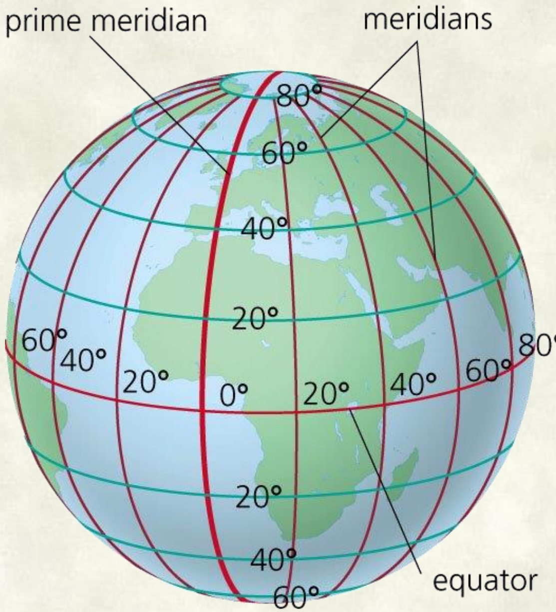
Astronomy in Navigation

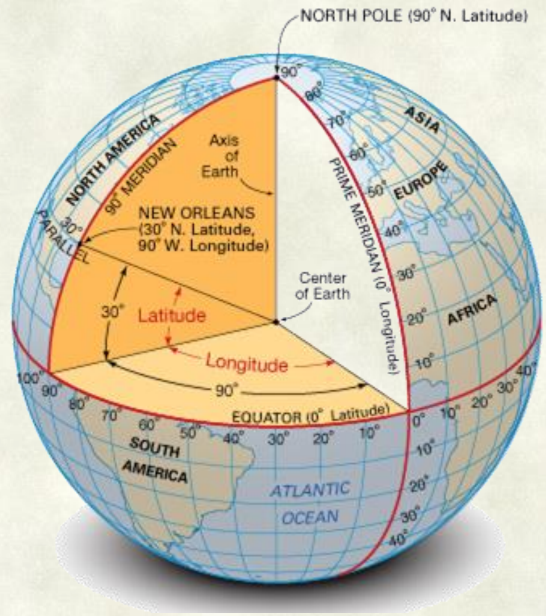
...Glorious Odysseus, happy with the wind, spread sails and taking his seat artfully with the steering oar he held her on her course nor did sleep ever descend on his eyelids as he kept his eye on the Pleiades and late-setting Bootes and the Bear, to whom men give also the name of the Wagon, who turns about in a fixed place and looks at Orion, and she alone is never plunged in the wash of the Ocean. For so Kalypso, bright among goddesses, had told him to make his way over the sea, keeping the Bear on his left hand…

-Homer, The Odyssey

- Using Sun and stars as navigational aids dates back to prehistory.
  - From Polynesia to the Mediterranean all seafaring civilizations had used their familiarity of the sky to guide them in the sea where there are no other landmarks.
  - Even some migratory birds seemed to be using stars for navigation.

Geographic coordinates

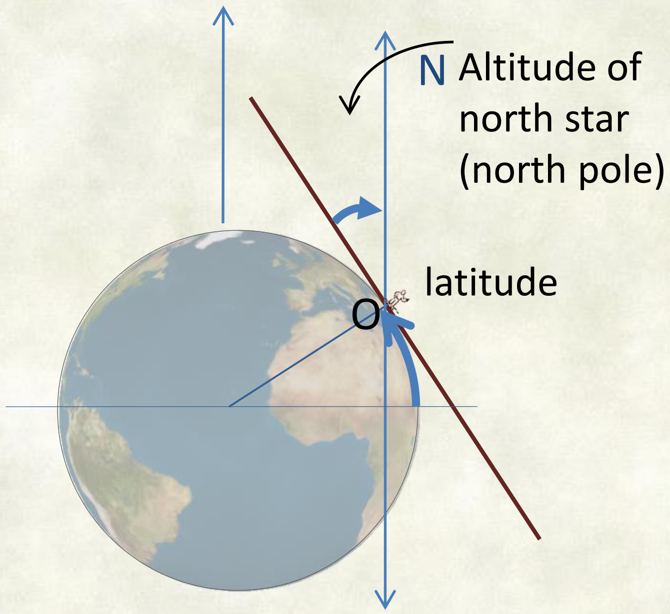


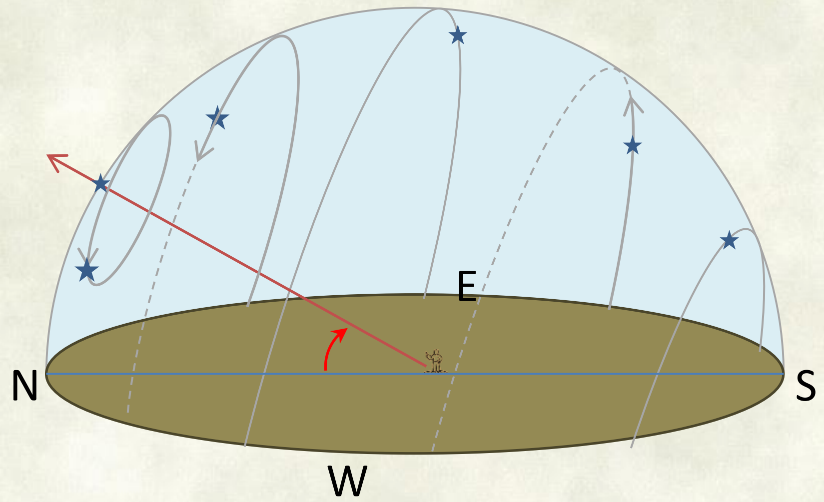


- **Latitude:** The angular distance to the equator from a given location on the Earth.
- **Longitude:** The angle between a reference meridian to another meridian that passes through the location

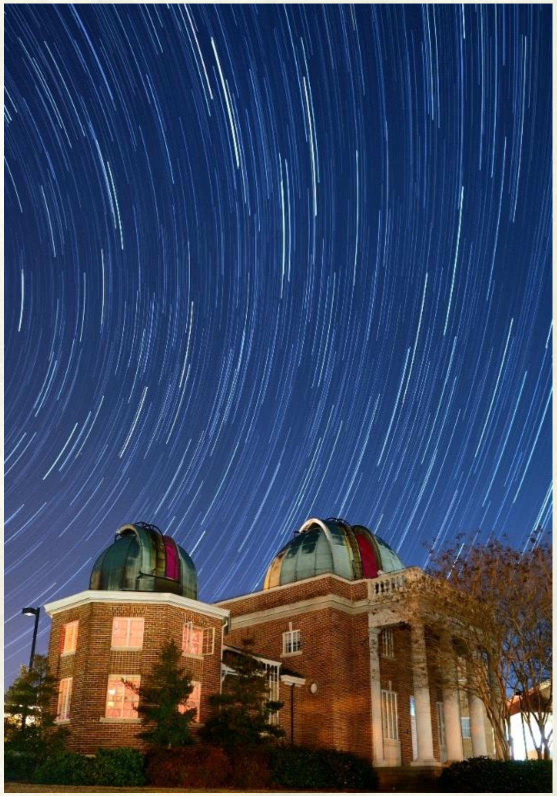
- The meridian through Greenwich, England is chosen as the reference meridian(prime meridian) of longitude 0º

Determining the latitude

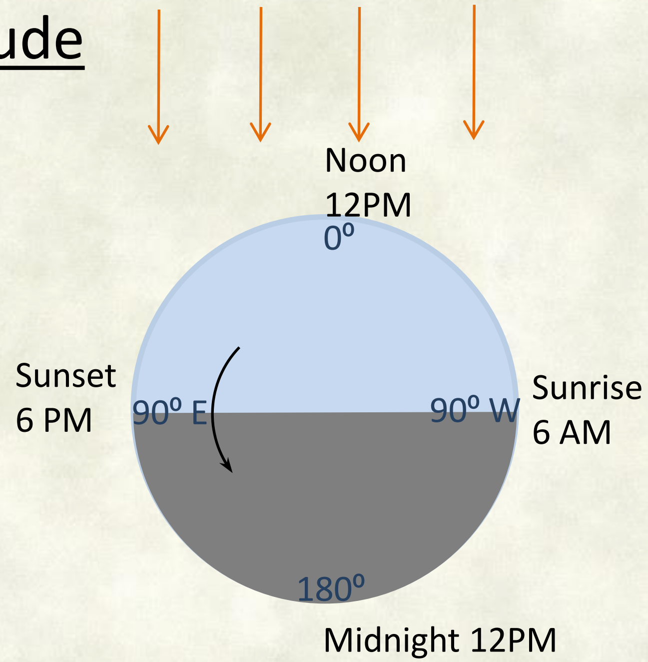




- The altitude of the celestial pole is equal to the latitude of the location.
  - In the northern hemisphere there is the North star
  - (North star is actually ~ 45 arc minutes off the north celestial pole)
- It is not necessary to see the North star (or pole) by following the movement of other stars its location can be found.



Finding the Longitude



- Since Earth rotates in W-E direction, it is not possible to determine the longitude by just observing stars or the sun.
- However one can easily use time to calculate the longitude.
  - Suppose an observer sees the sun is at the meridian (ie. noon at local solar time).
  - He immediately calls a friend in Greenwich, England, and ask what the local solar time there?
  - The friend says it is 4PM according to local Greenwich solar time.
  - Since one day is 24 hours long, one hour of time difference corresponds to 15° of longitude difference.
  - So his longitude is 4x15 = 60° West.
- So if you know local solar times at two locations, it is possible to find the (longitude) separation between them.

The Longitude Prize

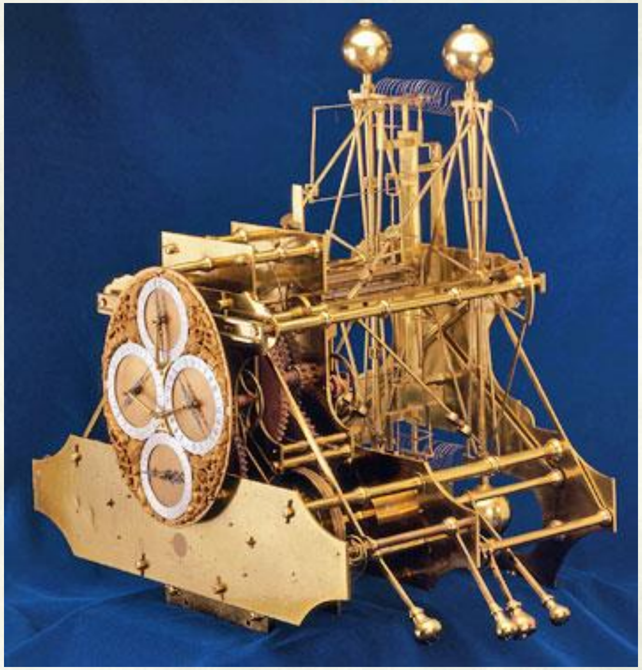
- Before the development of radio communications in early 20th century, only way to know the time at another location was to carry an accurate clock with time at that location.

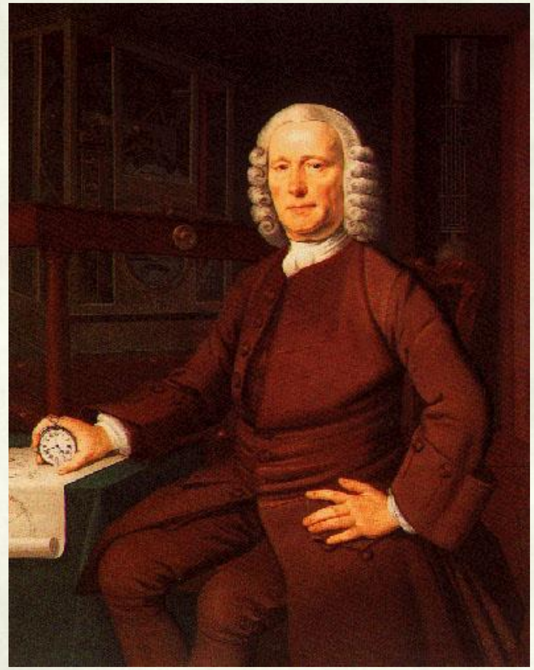
- Determination of longitude at sea was a major problem in 16-18 centuries.
  - many seafaring nations of the time (Spain, Netherland, England) offered prizes for an invention that would reliably determine the longitude at sea.

- Many methods were proposed,
  - observing occultation's of stars (eclipses) by moon, movement of the satellites of Jupiter as reference time events,
  - using an accurate clock to keep the reference time

- Most accurate clocks of the day were pendulum clocks. But they were not suitable to keep accurate time in a ship to determine the longitude.

The Longitude Prize





John Harrison, his Marine chronometer and the sea watch.

- 1774 British government offered a prize £20,000 for an invention to solve the problem.
- John Harrison, a self-taught clockmaker (eventually) won the prize for an innovative new type of clock he built.
  – His clocks were able to keep accurate enough time to determine the longitude in a ship –
- by 1850 sea clocks were the way to find the longitude at sea.

Review Questions

- What is the Sidereal day?
- What is the Solar day? Why is it different from the sidereal day?
- Why isn't the solar day always exactly 24 hours long?
- What is the time we usually use (clock time)?
- What is the time given by a sundial.
- Does the Sun always cross the meridian 12PM clock time.
- Sundial is the oldest type of time keeping device. Why isn’t the time given by a sundial is not for general use now.
- Why is it necessary to to have leap years? Way are some of the leap years are omitted in the Gregorian calendar.
- How does the precession affect the seasons and the calender.
- Where did the names of days of the week come from?
- Some people opposed the adoption of the Gregorian calendar because they thought it would mean their lives would be shortened by 11 days. Is there any rational to that argument?
- How do you find the latitude of a location using the north star?
- Why isn’t it possible to determine the longitude from the position of stars in the sky alone?