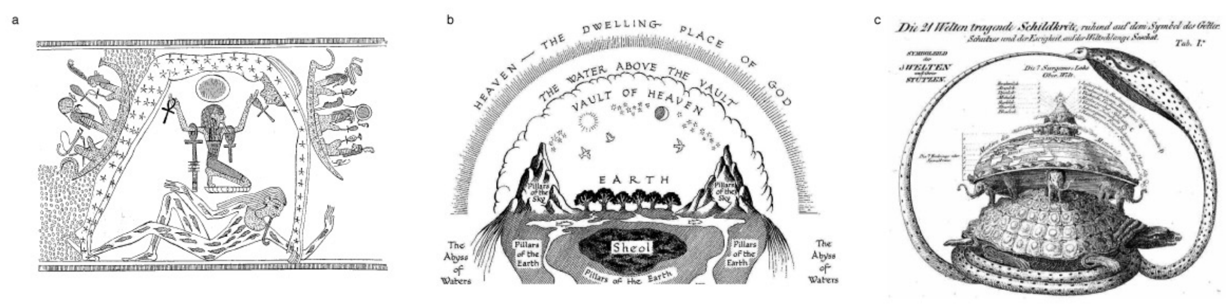
The Origins Of Astronomy and Astrophysics

1. Ancient Astronomy



A selection of ancient cosmologies. a) Ancient Egyptian Creation myth. The earth is the leaf adorned figure lying down. The sun and moon are riding the boats across the sky. b) Ancient Hebrew Conception of the universe c) Hindu: The earth was on elephants which were on turtles. (And of course a divine cobra)

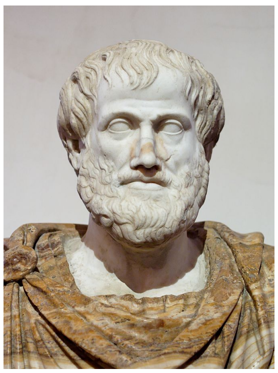
(public domain images)

Since the earliest recorded histories, humanity has attempted to explain its position in the universe. Societies and cultures have described many varying pictures of the universe. Often, there would be some deity or certain animals involved that were responsible for holding various parts aloft or keeping regions separate or moving things like the sun around the earth. Humans and their civilizations were almost aways located at the center of each universe.Generally there was some sorting to do - put the heavy stuff down there, the light stuff up there.

Celestial Sphere Sim.

The early western views of the universe held that the earth was fixed in place and motionless at the center of the universe. The stars were all located on a sphere much bigger than the earth that rotated daily around the earth. The sun was on another sphere that rotated, as was the moon and the planets such as Mars and Venus. These were the celestial spheres. Aristotle laid out the basics of this worldview, and subsequent scholars built of it and refined parts, but largely kept it intact. This framework was used to build the system of the world known as the Ptolemaic system.

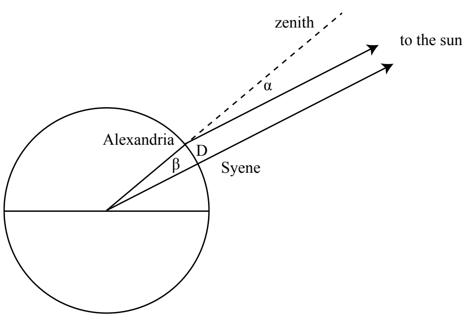
Aristotle



Aristotle

Aristotle [384–322 BC] was an ancient greek philosopher. He wrote many volumes on topics ranging from natural sciences to metaphysics, to ethics and philosopher. His writings in natural science heavily influenced the approach to science for over a thousand years.

2. A Spherical Earth



The method of Eratosthenes for estimating the circumference of the spherical earth.

Many classical philosophers believed in a spherical earth. That wasn't really in question by any advanced western civilizations. (Although sometimes the story is distorted.) Even though a casual look around will give the impression that our world is flat, there are plenty of examples of phenomena that gave indications that we were indeed on a sphere.

1. Ships mast in the distance
2. Different star/sun positions based on latitude.

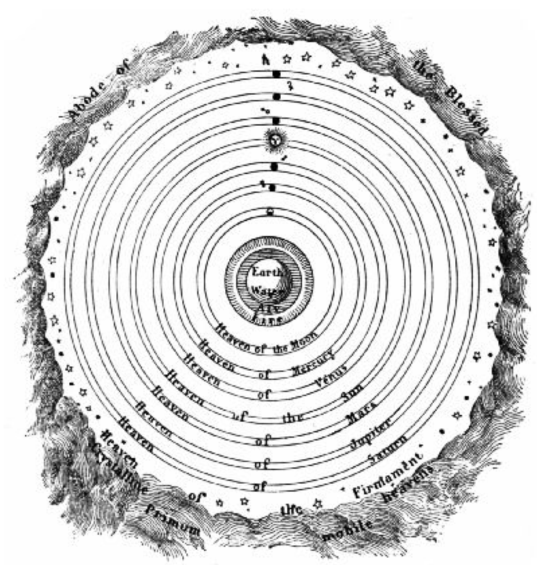
Estimating the exact size of our sphere, however, would prove to be somewhat challenging. The first to find a method that actually produced a reasonable value (based on today's understanding) was the greek philosopher Eratosthenes.

Demonstration: Show how Eratosthenes could estimate the radius of the earth.

3. The Ptolemaic System

Much has been written about the history of our understanding of the universe, in particular regarding the position of the earth with respect to the other celestial bodies. Briefly, early astronomers (or natural philosophers) relied on religious principles to create their world views. Western religious traditions considered man to be very important, thus the earth was located at the center, and was stationary. This model fit not only with the religious contexts, but since it is *very hard to see* the effects of the earth's rotation in other ways besides looking at the stars, seemed to fit well with observations. Aristotle's work provided the basis for many systems of the world. Since church edit demanded that any cosmology be aligned with Aristotle's teachings, western science was forced to work with the following constraints:

1. the earth was at the center of the universe and was to remain motionless,



The Ptolemaic system

Title: Pioneers of Science
https://www.gutenberg.org/files/28613/28613-h/28613-h.htm

2. everything moves around the earth,
3. celestial bodies are divine and must move in perfect circles.

These views were adopted by western religions and any deviations from them were considered to be against the religious order: i.e. bad, and punishable. So, astronomers built systems of the world that adhered to these principles. For many years, things were fine. Consider the most basic observations: that once a day, both the Sun and the Stars seem to move around the earth. This is completely explainable by having the sun and the stars move around the earth, once a day, on a **diurnal** motion.

Claudius Ptolemy

Representation of Ptolemy

Par Andre Thevet angoumoysin, premier cosmographe du roy., premier tome, livre II, chap. 41, "Claude Ptolemee Pelusien", p. 87. Published by Blanche Marantin and Guillaume Chaudiere, Paris, 1584.

Claudius Ptolemy was a mathematician, astronomer, geographer, astrologer who lived under Roman rule in Egypt. There were also many people named 'Ptolemy' in the ruling dynasty of ancient Egypt. The astronomer was not one of these rulers.

3.1 Ptolemy's Arrangement

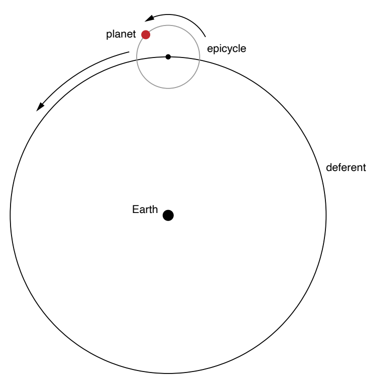
Starting with the a stationary earth, Ptolemy had to build a system that would account for as many of the observed phenomena of the celestial bodies. The most basic was the diurnal motion of everything. Once every 24 hours, the stars, sun, moon and planets would appear to travel all the way around the earth. Explaining this could be done simply by having their respective celestial spheres rotate once every 24 hours. This *explained* diurnal motion. (We should note that what counted as an explanation 2000 years ago would probably not carry much weight today.)

Next, one obvious thing people could see was the change in the sun's path through the sky over the course of the year. In summer, the sun was high in the sky at noon. During the winter, it was lower. To explain this, Ptolemy would just need to add another motion to the sun's sphere. Done. (again, no one felt compelled to really probe the obvious follow-up question: why does this sphere do this?)

4. Retrograde Motion

It didn't take too long for the careful observers of the night sky to realize that sometimes, the planets would appear to move backwards in their tracks along the stars. If you took note of the note of position of Mars at the same time every night, over the course of several months, you would observe its motion to at times be in the same direction as the fixed stars, and at other times, it would appear to be moving in the opposite direction as the stars. This feature became known as retrograde motion. The planet appears to move backwards. What could possibly explain that?

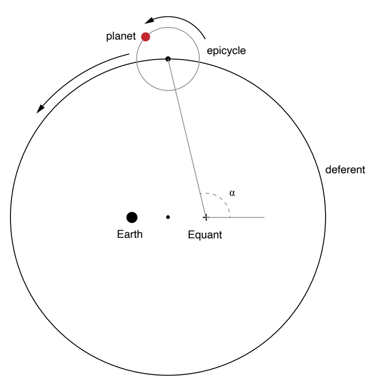
4.2 Epicycles



A basic epicycle scheme showing the earth (at center), the deferent, and a planet on its epicycle.

Celestial bodies had to move in circular paths because they were divine and circles were the most perfect shape. One way to explain the retrograde motion of the planets was to add a second circle on which the planet actually orbited. This second circle, called an epicycle, would be carried around the earth by a larger circle, known as the deferent. With careful adjustments of the diameters of the deferent and epicycle, as well as their respective angular velocities, Ptolemy was able to predict with decent accuracy the observed retrograde motion. This structure, the deferent/epicycle, became the hallmark of the Ptolemaic system.

4.3 Equants



The equant is an offset from the deferent's center around which the epicycle will move with constant angular velocity.

Another tool to 'save the appearances' was the *equant*. It permitted Ptolemy to explain why planets moved faster sometime and slower other times, which still moving in uniform circular motion. The earth (or center of the universe) was offset from the center of the deferent, and the the epicycle was said to move in regular circular motion around a third point, the equant, on the other side of the deferent center from the earth. The result was when the planet was closer to the earth, it moved faster, when farther away, it would move across the sky slower.

Equant Sim

Epicycles Sim

4.4 Ptolemaic System

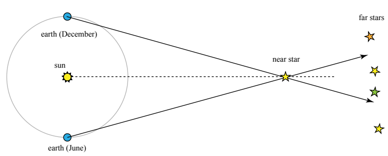
1. We can't feel the motion of the earth.
2. Humans are the best, and therefore should be at the center.
3. No stellar parallax was observed.

Regarding point 1: At the equator, the surface of the earth is moving at about 460 meters per second. Surely, we should be able to feel this, right? Consider the acceleration due to gravity: roughly 9.8 m/s^2. The rotation of the earth would lead to an accelertion towards its center given by: $a_c = \frac{v^2}{R_E}$, where R_E is the radius of the earth: about 6371 kilometers. The give a centripetal acceleration of approximately 0.033 m/s^2. Which is about 1/3 of a percent the acceleration due to gravity. If you remember measuring little g in the first year labs, you should recall it was difficult to get a very precise measurement, even using modern technology. Thus, it would be very hard to measure such a change several thousand years ago.

Regarding Point 2: The universe doesn't owe us any favors. Justifying physical laws based on our supposed greatness is never a good idea. (we know that now)

Regarding Point 3: Parallax was hard to measure and it even took a century or two after the telescope was invented to measure it accurately, so it's hard to blame them back then!

Parallax

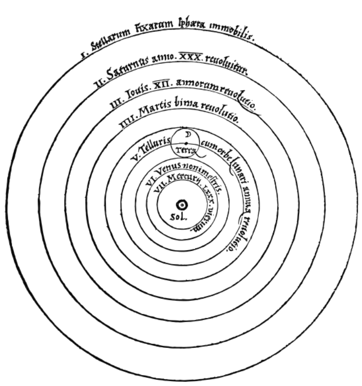


The relative position of near and far stars would appear to change if the earth was in motion due to **parallax**

No such parallax was observed by the ancients. This gave more support to the Ptolemaic system.

Parallax Sim

5. Heliocentric



From De revolutionibus orbium coelestium (On the Revolutions of the Heavenly Spheres), 1543. The copernican world view gets an illustration

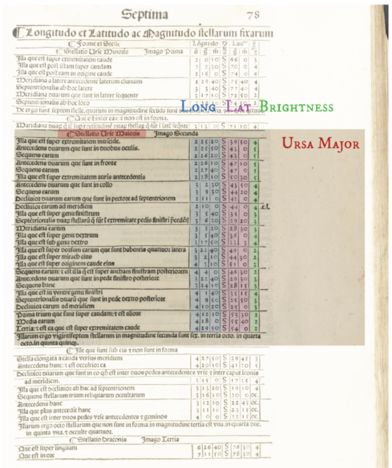
While not the first to suggest it, Nicolaus Copernicus was the first to provide a compelling argument for the heliocentric model of the solar system. He was hesitant to release his manuscript however, and it did not get printed until he was on his deathbed.

6. Geocentric vs. Heliocentric

Now we know that neither of these is true. Our current understanding of the universe suggests (requires) that there is no center.

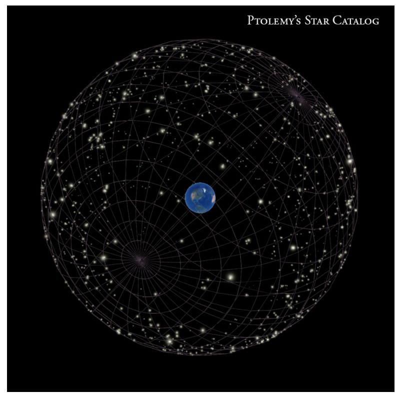
7. Positions of Celestial Objects

How can we describe where things are?



A page from Ptolemy's star catalog

The positions of the stars where recorded by constellation groups, with reference to the sun. Also included where the brightness's, ranked on a rudimentary 6 tier scale.

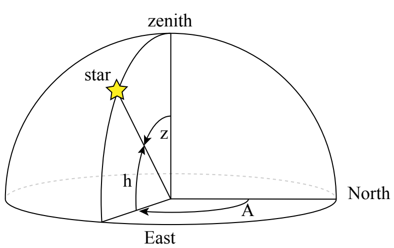


Ptolemy's catalog in 3d space

More on this here:

https://ccnyplanetarium.org/posts/2020/11/02/ancient-star-maps.html

7.5 The Altitude-Azimuth Coordinate System

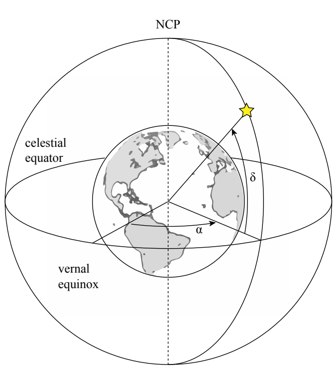


The altitude-azimuth measurement scheme. Only useful if everyone is located at the same point on the earth, which they are obviously not.

The most basic method of describing the position of a celestial body is to use the **altitude-azimuth coordinate system**. All that is required is two measurements: the **altitude** (h) which is defined as the angle measured from the horizon to the object along a **great circle**, and the **azimuth**, (A) which is the angle measured eastward along the horizon from the north pole to the great circle used for the altitude measurement. One can also use the **zenith distance** (z) to indicate the angle measured from the **zenith** to the object. Note that $z + h = 90°$.

This method is also called the **horizon coordinate system** since it is based on the observer's horizon. This implies that the measurements will be different for different observers, which is a major limitation of this coordinate system.

7.6 The Equatorial Coordinate System



RA and Dec are a more universal way to describe positions in the sky. Rather than the earth serving as the reference, the

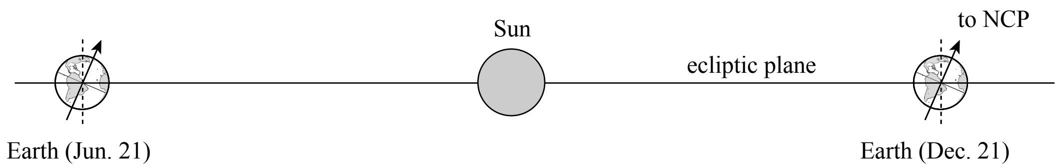
The **equatorial coordinate system** is able to overcome the limitations of the altitude-azimuth system by defining positions with respect to features in the sky and is therefore not dependent on the observers position.

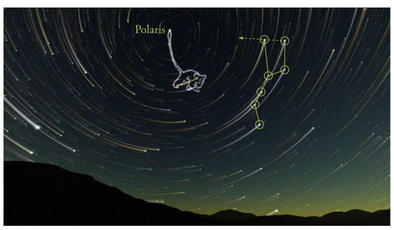
The two variables we will use are the **declination**: (δ) and the **right ascension** (α). To understand what these two angles are measured with respect to, we need to understand the earth's orbit in more detail.

locations of celestial objects becomes the reference framework.

earth-simple-orbit sim

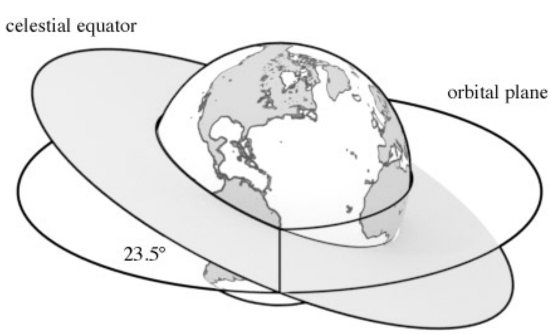
7.7 Basics of the earth's orbit





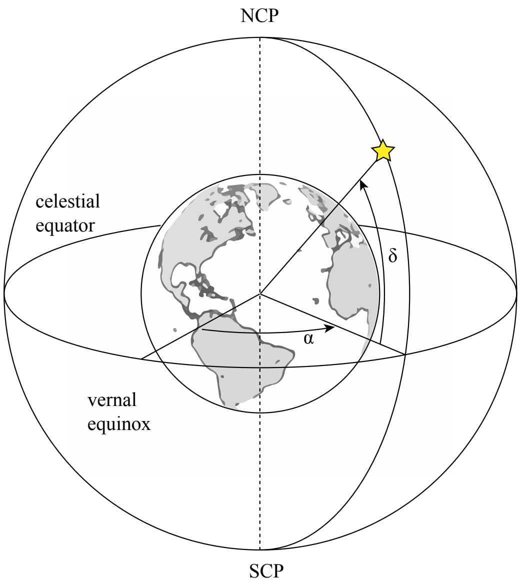
The north celestial pole is near the star called Polaris. (This changes though)

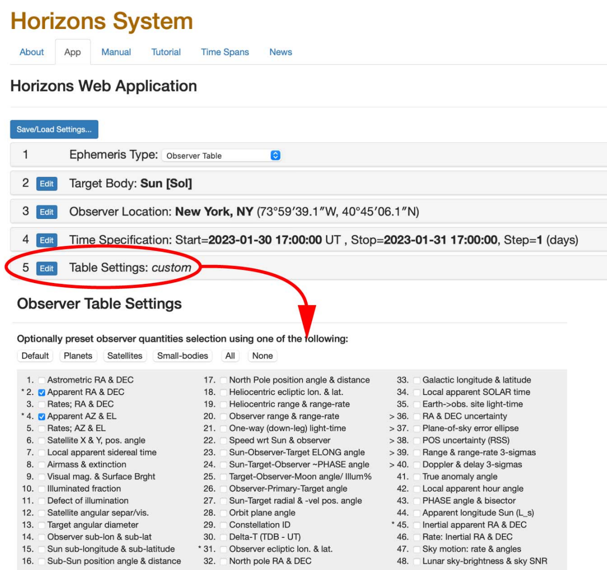
7.8 Celestial equator



The earth is titled with respect to its orbital plane. If we imagine a plane that passes through the equator of earth, and extend it outward in all directions, this will be the celestial plane.

8. Equatorial System





JPL Horizons

Here is some output from JPL Horizons database:

```
 ******************************************************************************
 Date__(UT)__HR:MN     R.A.__(a-apparent)__DEC  Azi____(a-app)___Elev
*******************************************************************
$$SOE
 2023-Jan-30 17:00 *m  20 51 55.49 -17 35 56.9  177.420437  31.609851
 2023-Jan-31 17:00 *   20 56 01.16 -17 19 16.2  177.366060  31.886346
$$EOE
*******************************************************************************
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Tool is here: https://ssd.jpl.nasa.gov/horizons/app.html#/

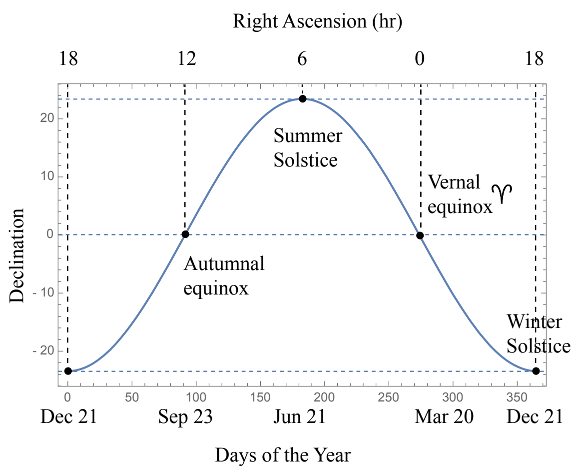
Units

Deg Min Sec

Hours Min Sec

Decimal

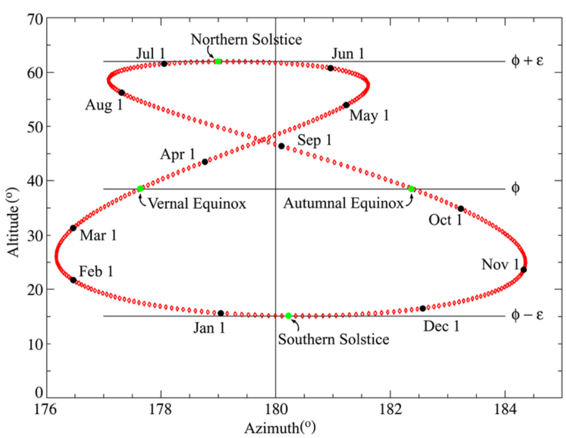
8.9 Special Times of the year



The position of the sun in the sky varies throughout the year. The position of the sun at the time of the vernal equinox is one of our main reference points for determining the position of the object. We'll say that that location has a **right ascension** of 0. A declination of 0 will be given by position aligned with the celestial equator.

The Ecliptic

8.10 Analemma

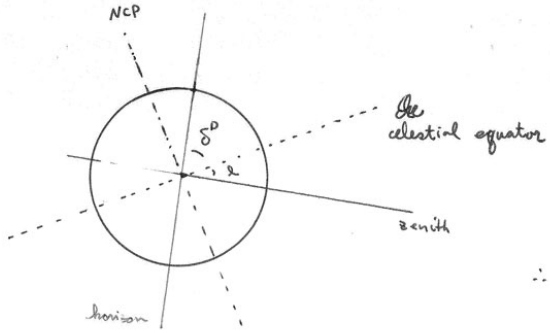


The plot here shows the position of the sun at 12pm over the course of one full year. The day when the sun is the highest in the sky is called the **summer solstice**. When it is at the lowest point is called the **winter solstice**. The two days right in the middle of the solstices are called the equinox: autumnal and vernal. (or fall and spring)

An Analemma Plot:

> Example Problem #1:
>
> What is the lowest latitude from which all the stars of the big dipper are visible? Below which latitude is the big dipper never visible at all?

Big dipper visibility



$\delta^\circ + l < 90^\circ$

$\therefore\ l < 90 - \delta^\circ$

Completely Visible:

Northernmost star: Dubhe : $\delta^\circ = +61^\circ 45'$

$\therefore\ l_{(\text{completely visible})} < 90^\circ - 61^\circ 45' = 28^\circ 15'$

$\boxed{-28^\circ 15'}$

totally hidden:

Southernmost star: Alkaid : $\delta^\circ = +49^\circ 19'$

$\therefore\ l_{(\text{totally hidden})} = 90 - 49^\circ 19' = 40^\circ 41'$

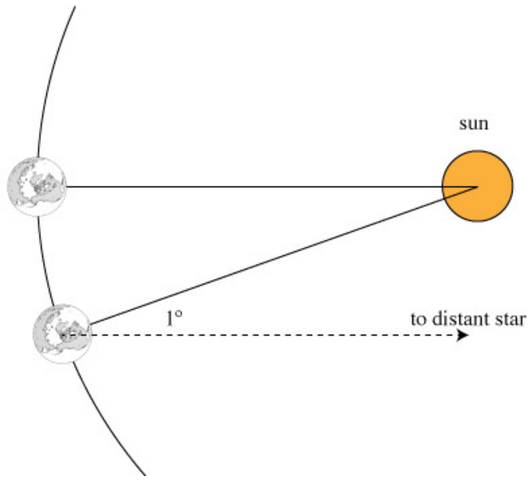
$\boxed{-40^\circ 41'}$

9. Time

Time keeping and astronomy are linked. The *day* is defined by the change in position of the sun.

Warren Field, Aberdeenshire Scotland, 8th Millennium BC. Used to track lunar

10. Solar vs. Sidereal Time



Solar and Sidereal time compared. The earth has to rotate about 1 degree more for the sun reach the same point in the sky, than the rotation needed for the fixed stars to return to the same point.

If the Earth rotates around its own axis exactly once, the distant stars will appear to be in the same position. However, the sun will not! The earth needs to rotate about 1 degree more in order for the sun to be in the same place in the sky. Thus we have two 'days'. The **solar day** is the time it takes for the sun to cross the merdian again (24 hours) while the **sidereal day** is the time it takes to rotate exactly once. (It's about 4 minutes less).

Example Problem #2:

Let's call the angular velocity of the Earth in it's orbit, with reference to the stars: $\vec{\omega}_E$. The rotation of the Earth around it's own axis (relative to the stars) will be $\vec{\omega}_{\text{sid}}$. If we asked the sun how quickly the earth was rotating (i.e. in the solar reference frame) we would find that the $\vec{\omega}_{\text{sol}}$ would be equal to the difference between $\vec{\omega}_{\text{sid}}$ and $\vec{\omega}_E$, which leads to the following:

$$\vec{\omega}_{\text{sid}} = \vec{\omega}_{\text{sol}} + \vec{\omega}_E \tag{1}$$

Since the vectors are approximately parallel (the're not, but we can ignore the 23.5°), the we can write a scalar equation:

$$\omega_{\text{sid}} = \omega_{\text{sol}} + \omega_{\text{E}} \tag{2}$$

Since $\omega = \frac{2\pi}{P}$ (P is the period) we can write:

$$\frac{1}{P_{\text{sid}}} = \frac{1}{P_{\text{sol}}} + \frac{1}{P_E} \tag{3}$$

Our definition of the solar period is 1 day, then $P_E \approx 365$ days which is much greater than P_{sol} and we can make the following approximation:

$$P_{\text{sid}} = \left(\frac{1}{P_{\text{sol}}} + \frac{1}{P_E}\right)^{-1} = P_{\text{sol}}\left(1 + \frac{P_{\text{sol}}}{P_E}\right)^{-1} \approx P_{\text{sol}}\left(1 - \frac{P_{\text{sol}}}{P_E}\right) \tag{4}$$

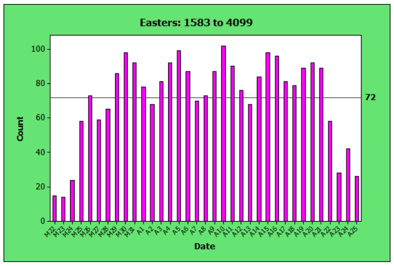
Solving for the difference the P_{sol} and P_{sid}:

$$P_{\text{sol}} - P_{\text{sid}} = \frac{(P_{\text{sol}})^2}{P_E} = \frac{1}{365} \tag{5}$$

which when converted to minutes give about 3.95 minutes difference between a solar day and a sidereal day.

10.11 Julian Date

You can't do math with date formats, so we need to have a different system. We set the 0 day to be January 1 4713 BC, at noon. Every day after that just adds 1. January 1st of 2017 will have been 2457755 days since then so we can say the JD is 2457755 (at noon). Times other noon just get fractional descriptions. The **Modified Julian Date** is very similar, except that it starts at midnight, so noon on January 1st would be 2457755.5 MJD.



Easter over a few thousand years

https://statisticsbyjim.com/fun/when-is-easter-this-year/

11. Summary

- Ptolemaic vs. Copernican
- Position of Celestial Objects
- Basics of Earth's orbit
- Solar vs. Sidereal
- Modern Timekeeping

12. Bibliography and Further Reading

1. Kuhn, T *The Copernican Revolution* (Harvard University Press, 1957)
2. Sobel, D. *A More Perfect Heaven* (New York: Bloomsbury Publishing USA, 2001)
3. Copernicus - De revolutionibus orbium coelestium
4. Ptolemy - The Almagest