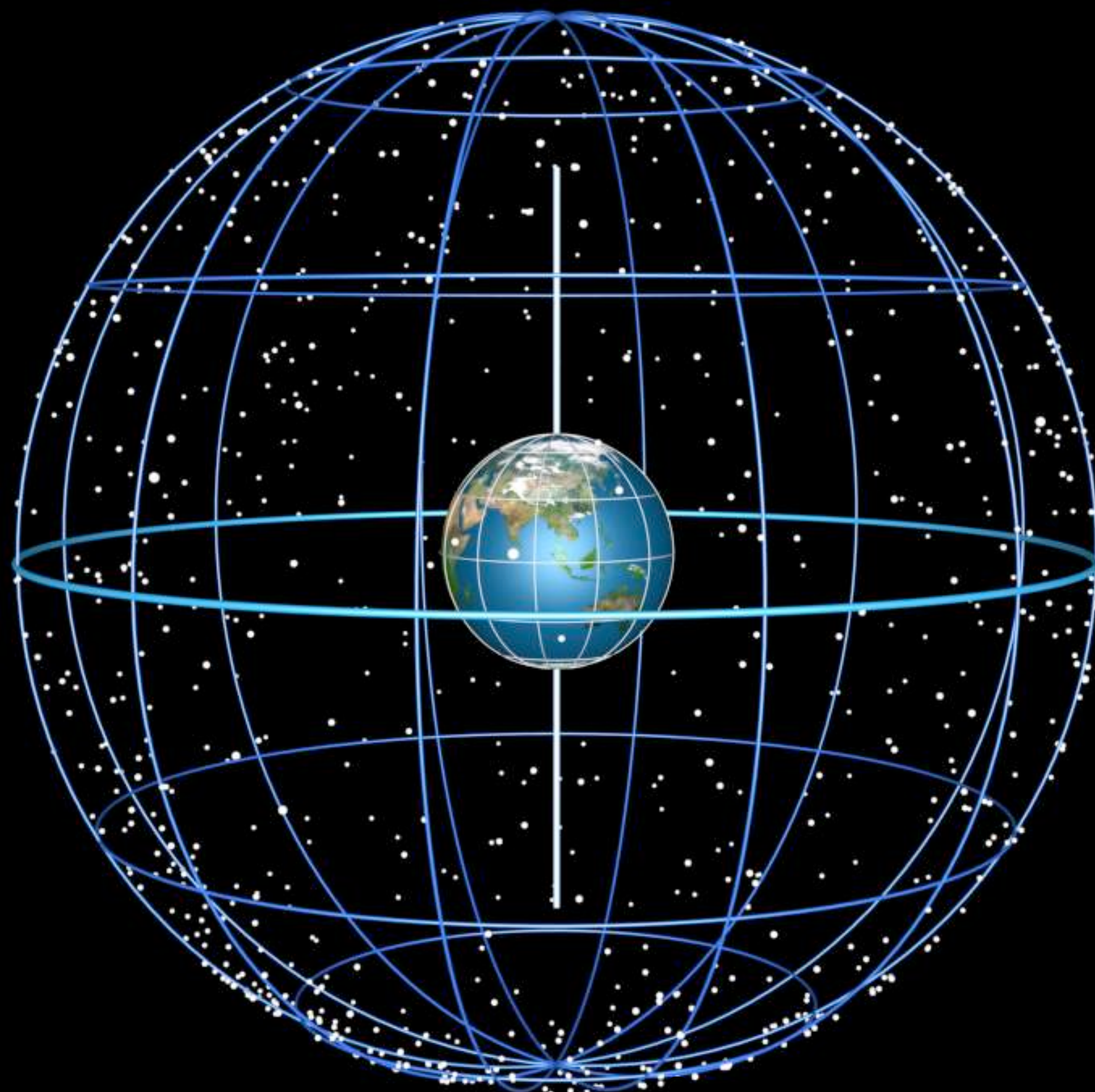
Coordinate Systems for Astronomy



AVN Observational & Technical Training 2017

Aletha de Witt, HartRAO

General Coordinate Systems

Identifying each position in space uniquely => 3 numbers required => space is 3-D

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Cartesian coordinates: for physical laboratories and everyday purposes

(0,0,0) Reference point (**origin**)

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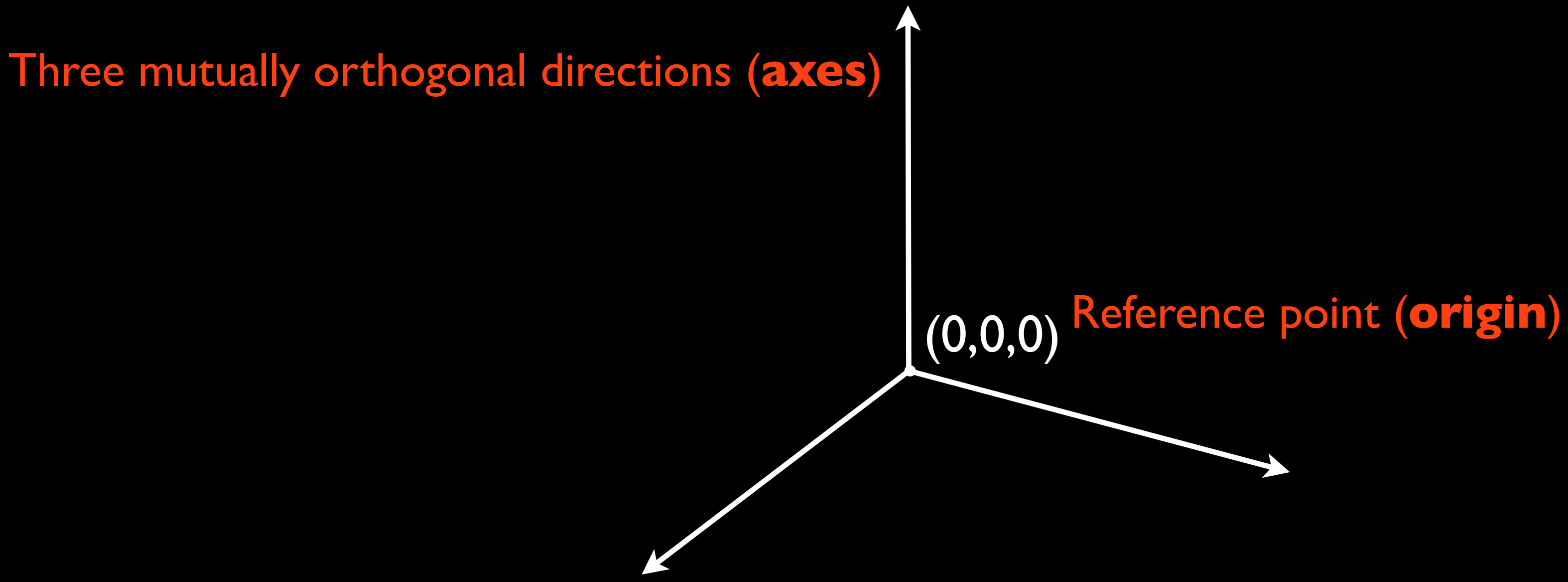

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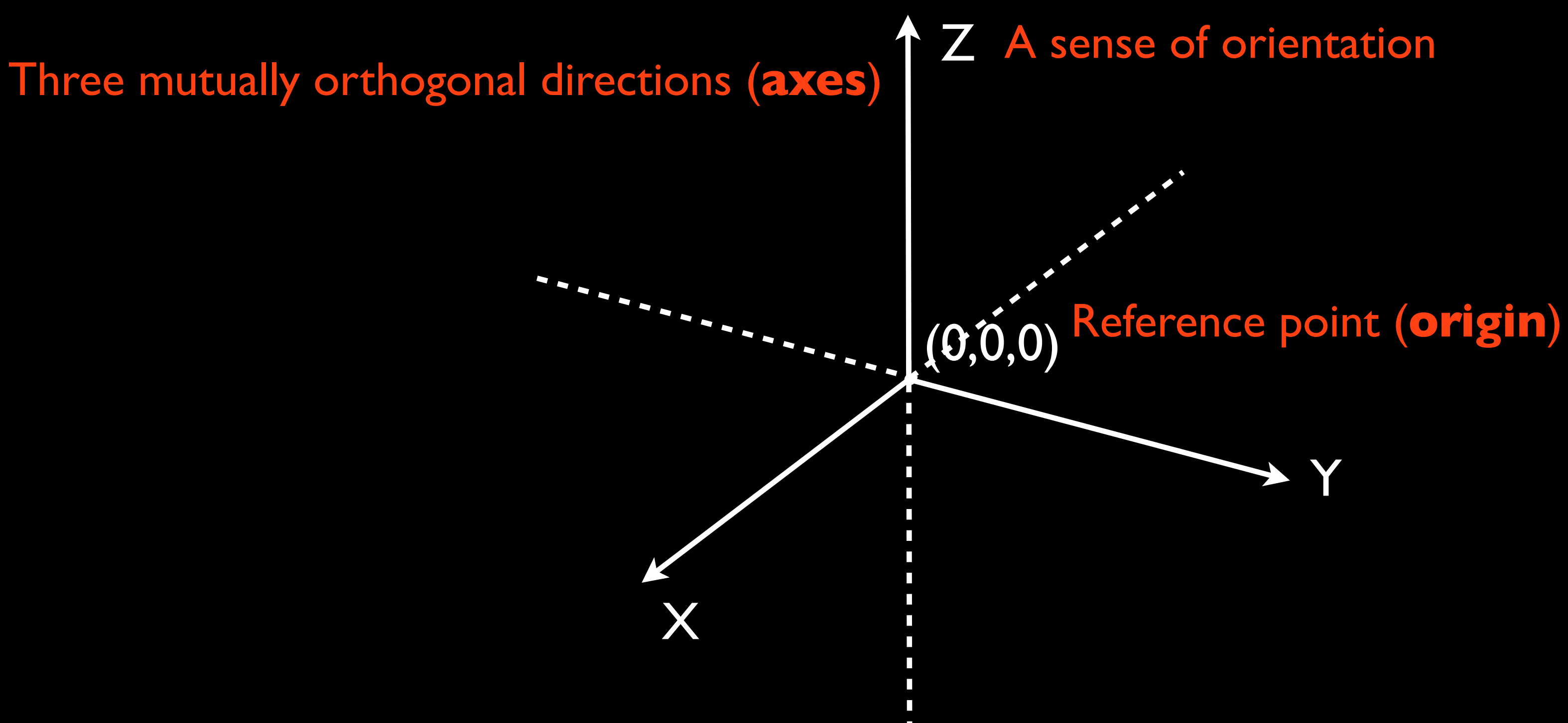

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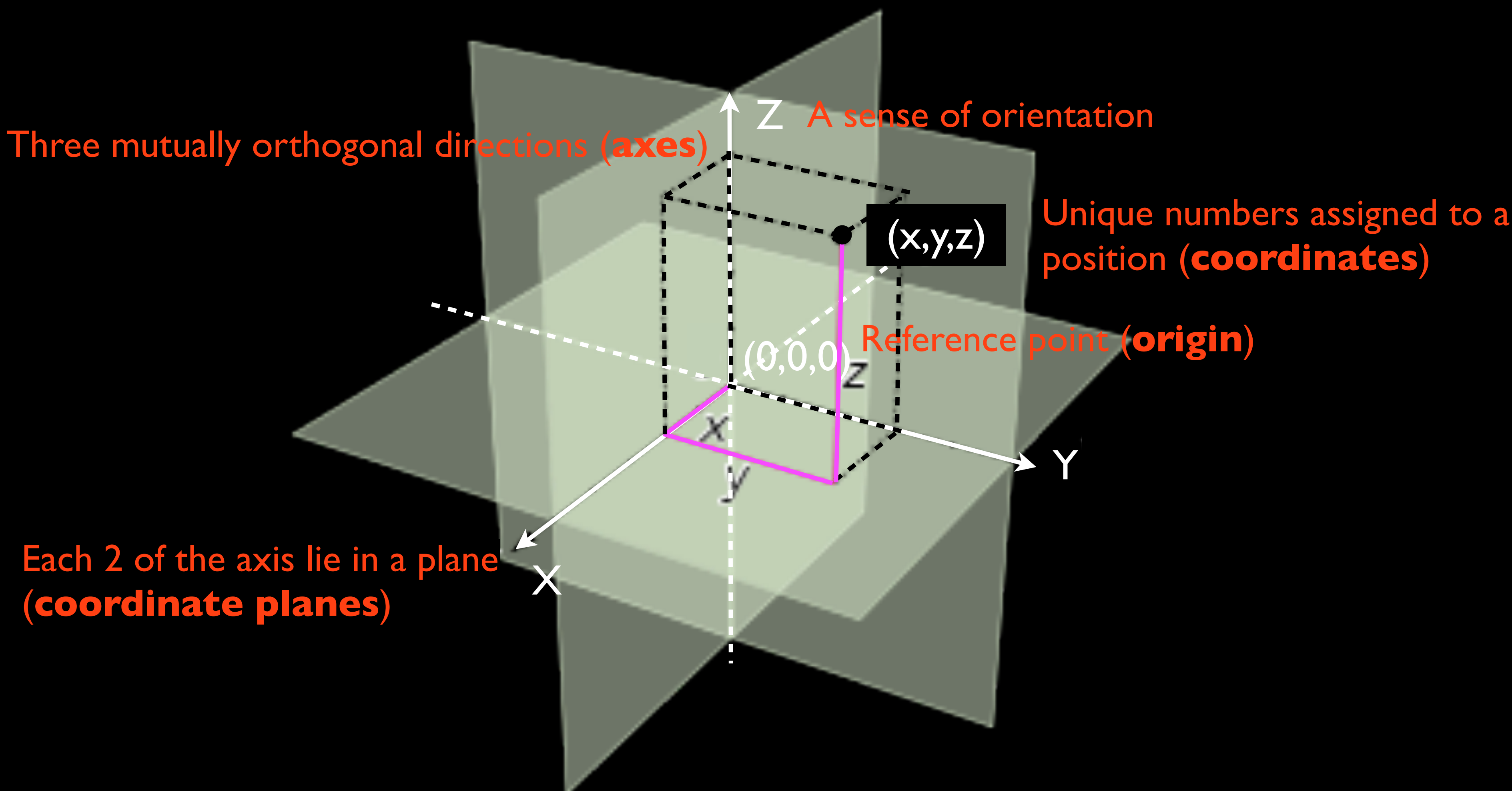
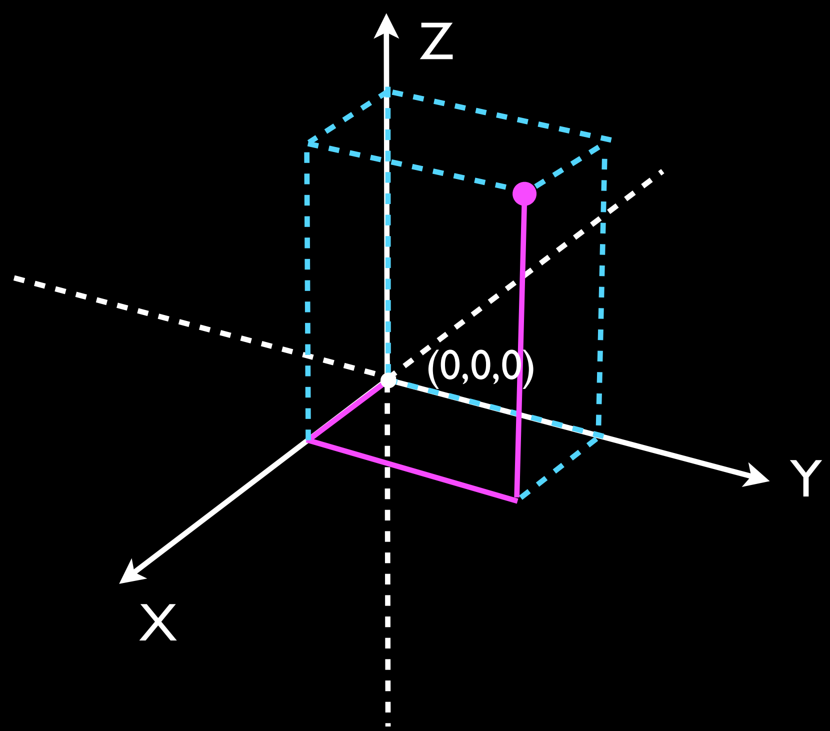


General Coordinate Systems

Each coordinate system is uniquely determine by:

- the origin or reference point
- the axes fixed w.r.t. the origin => 3 coordinates
- reference / preferred direction



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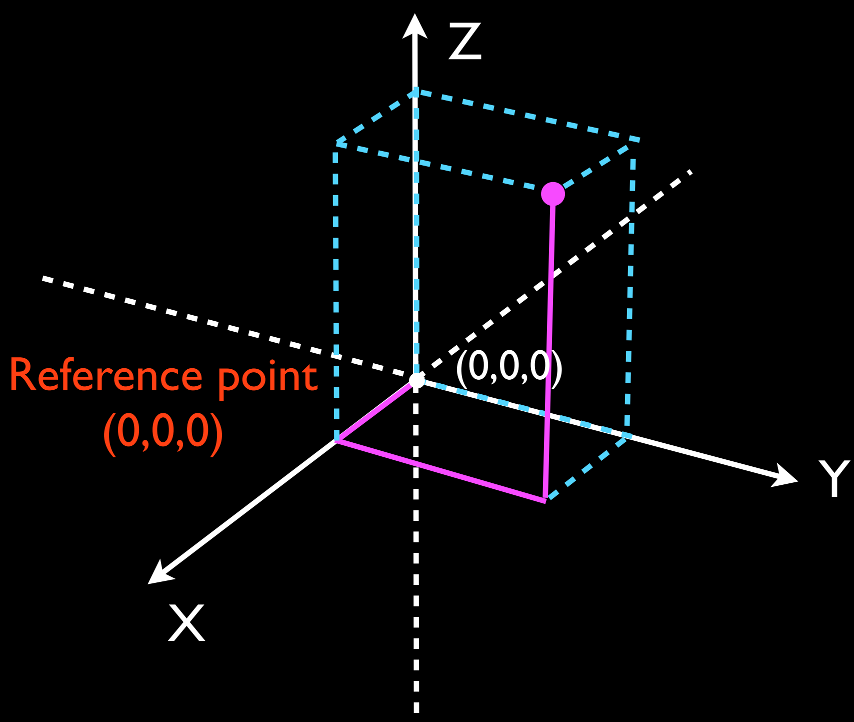

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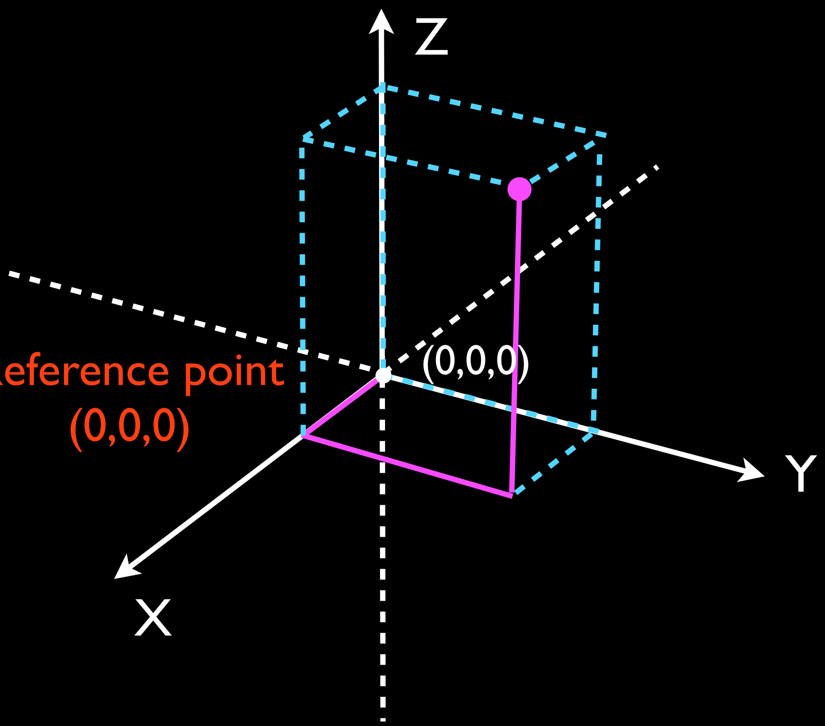

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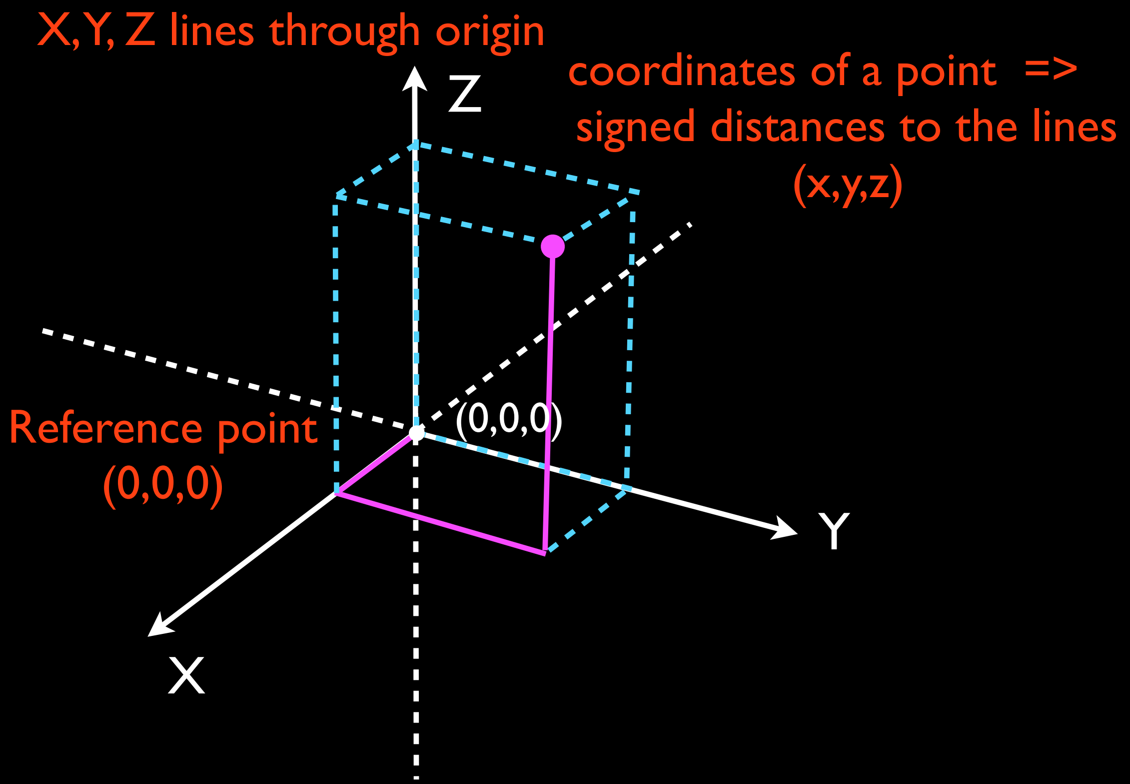

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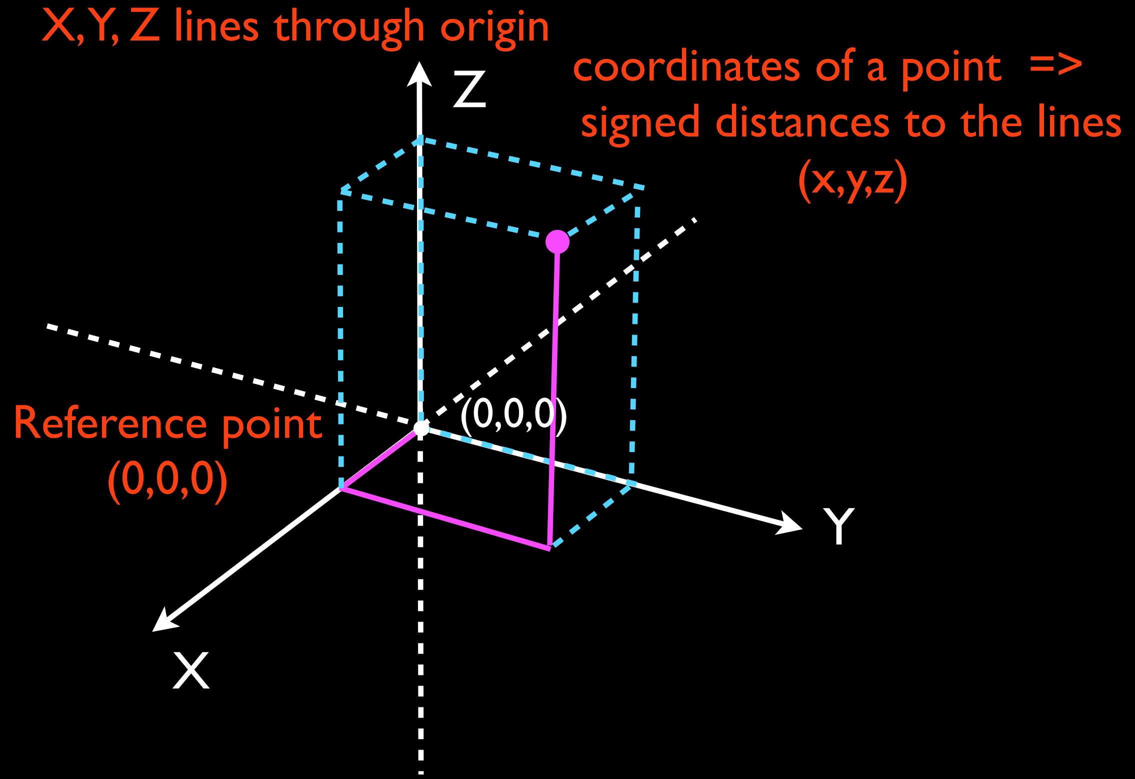

positive X,Y and Z axis form a
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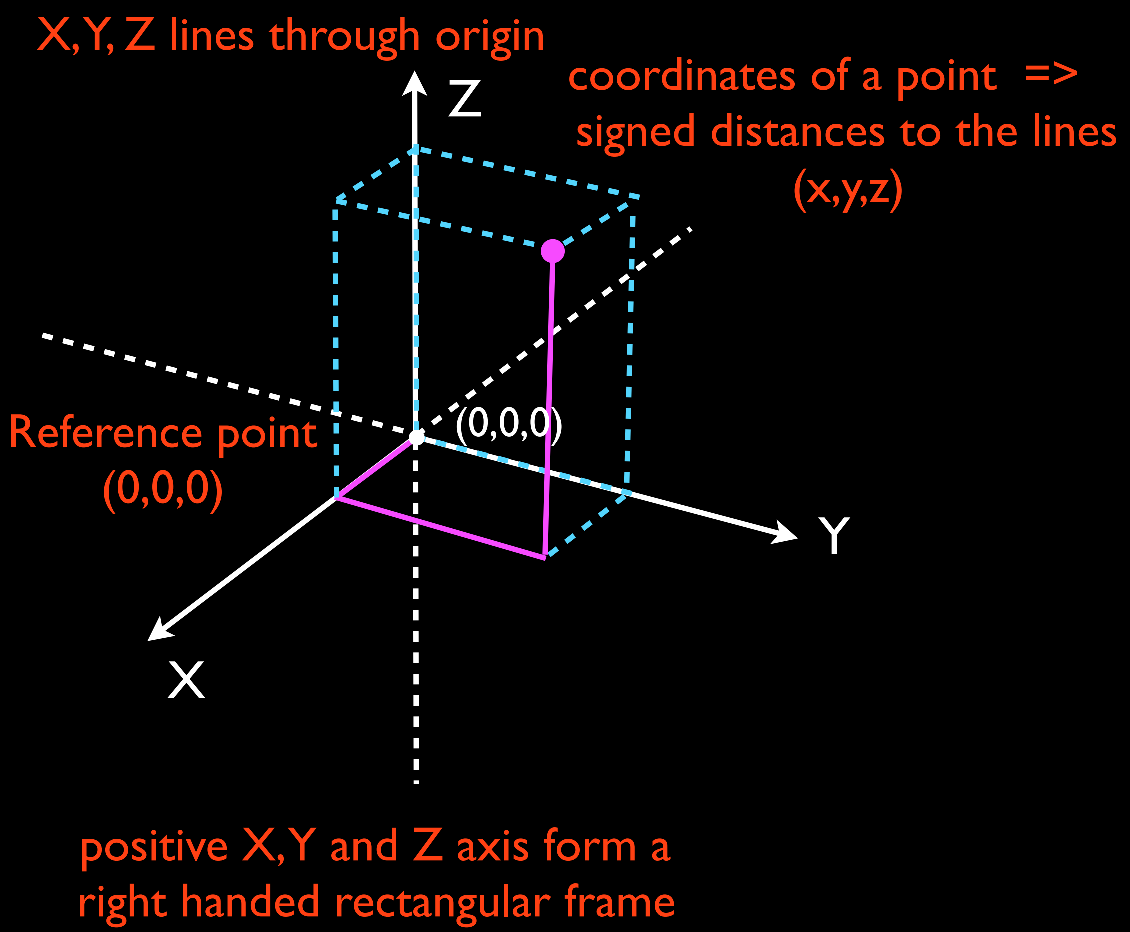

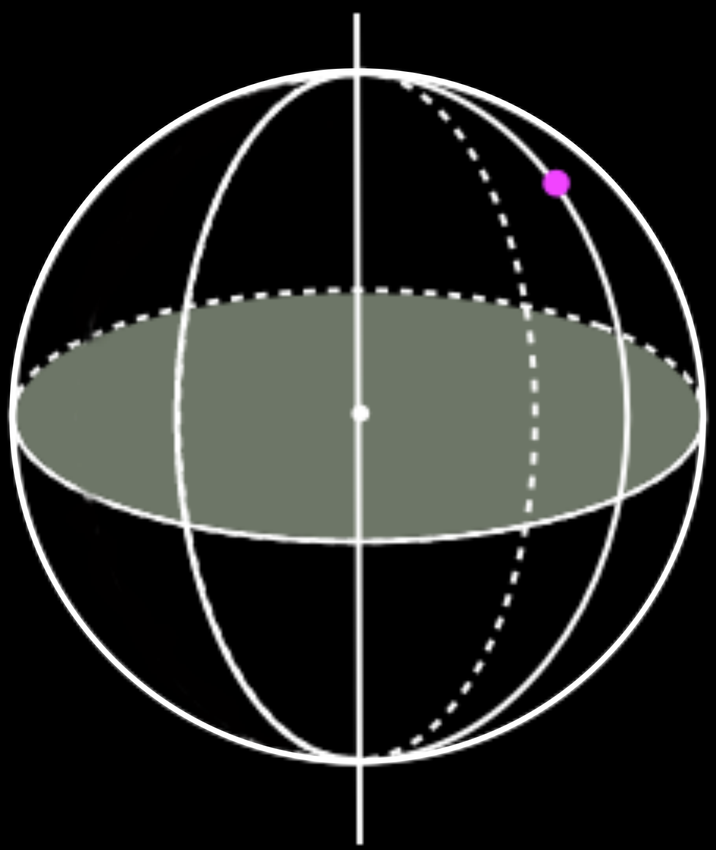

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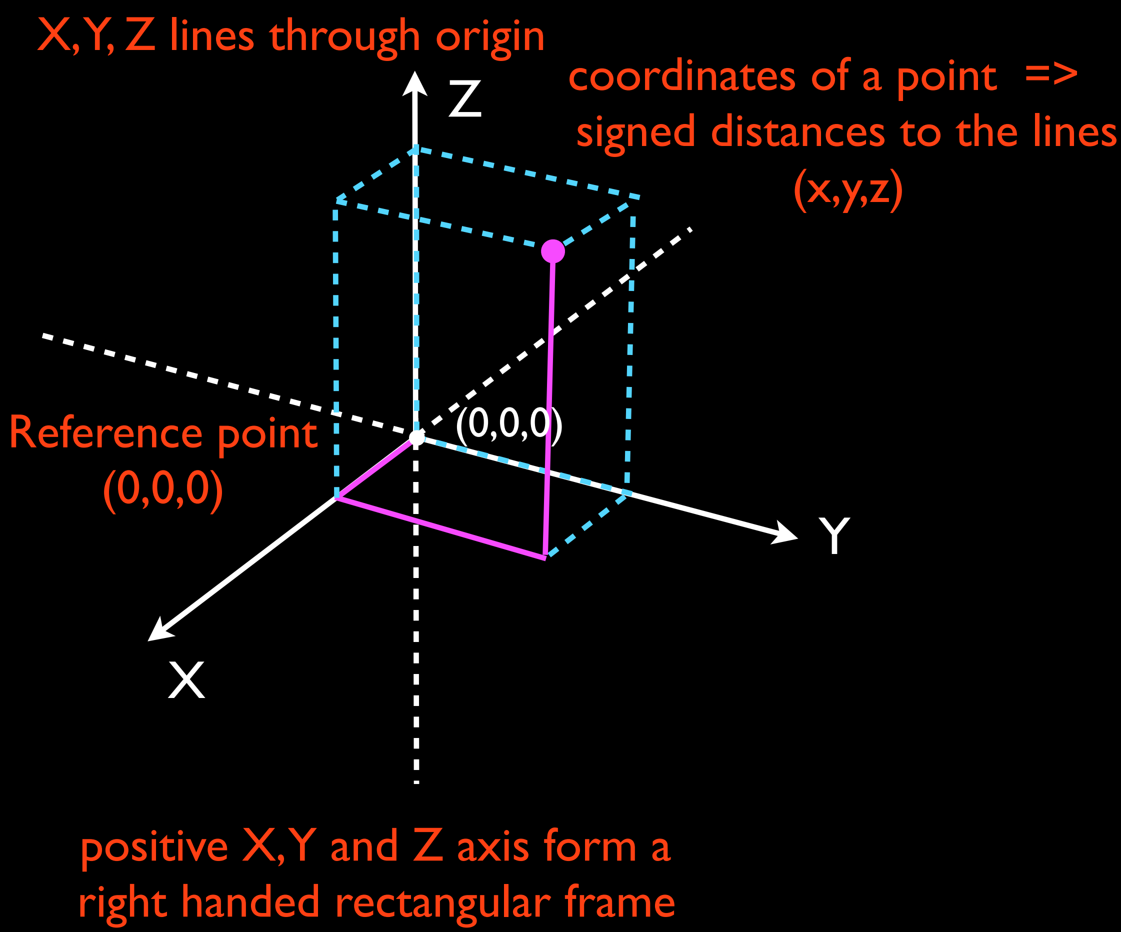

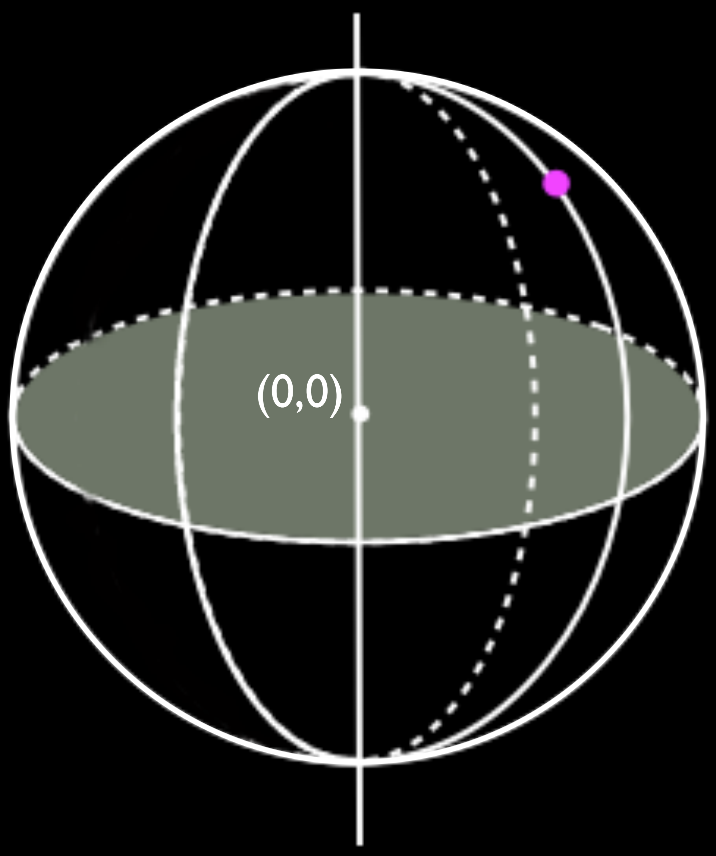

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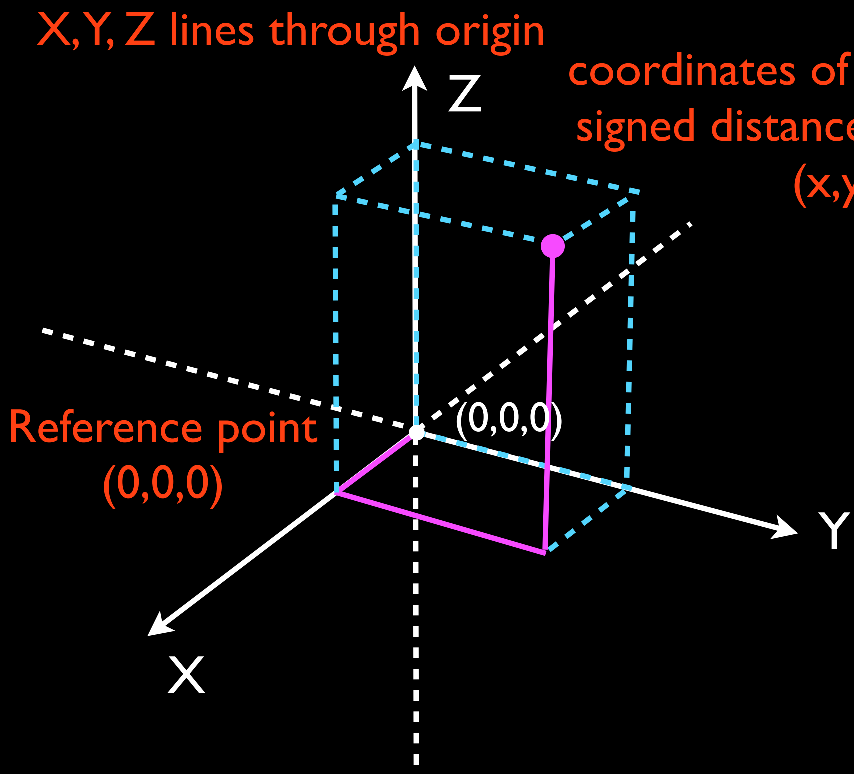

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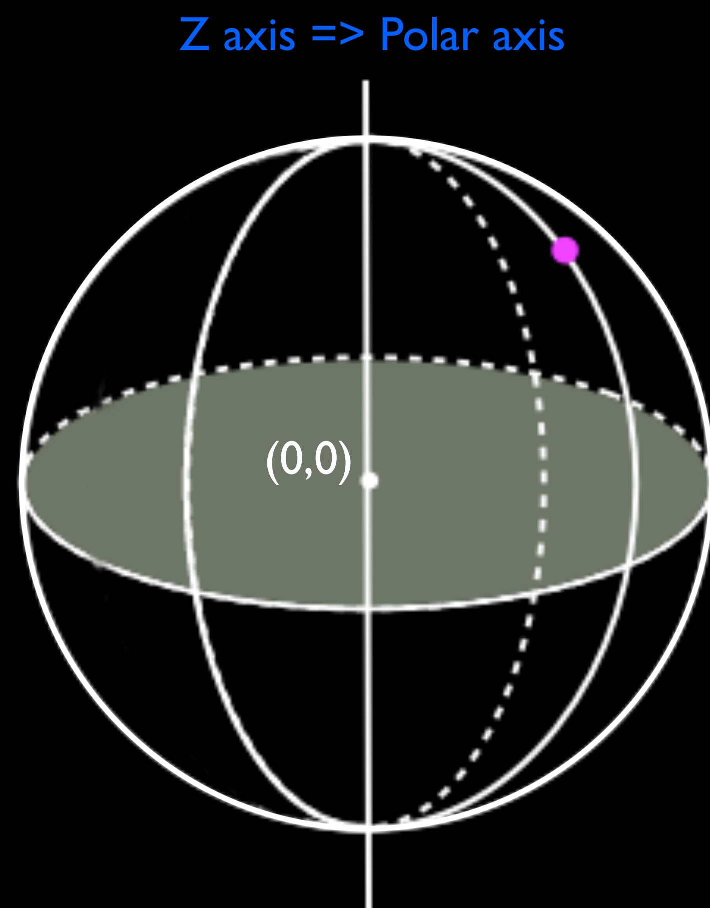

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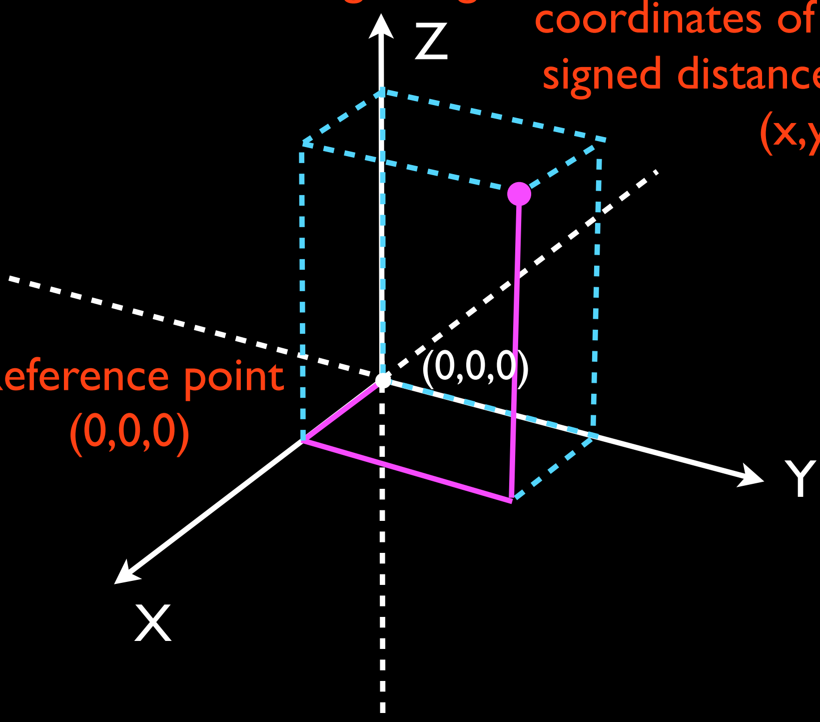

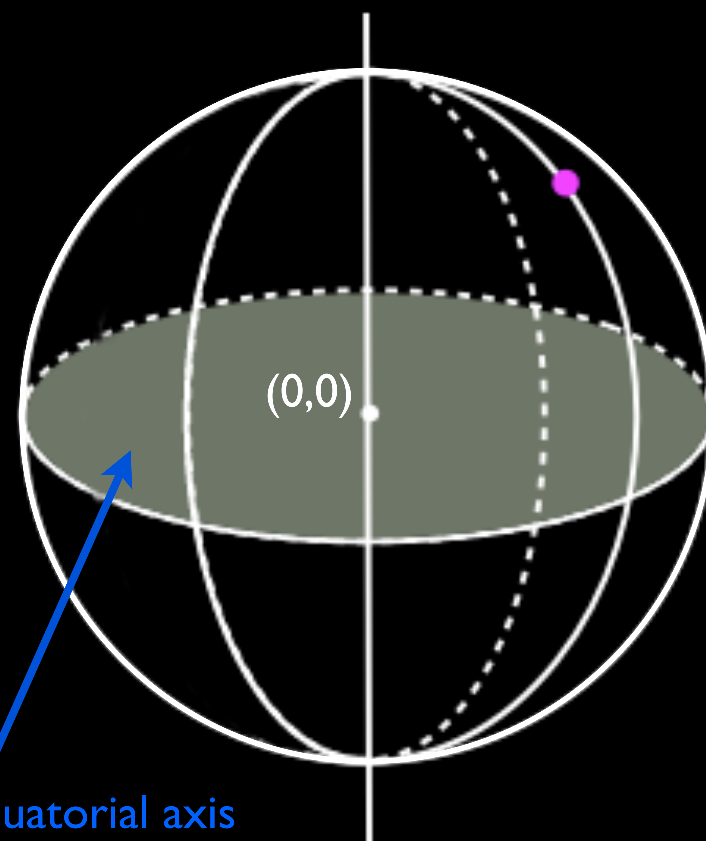

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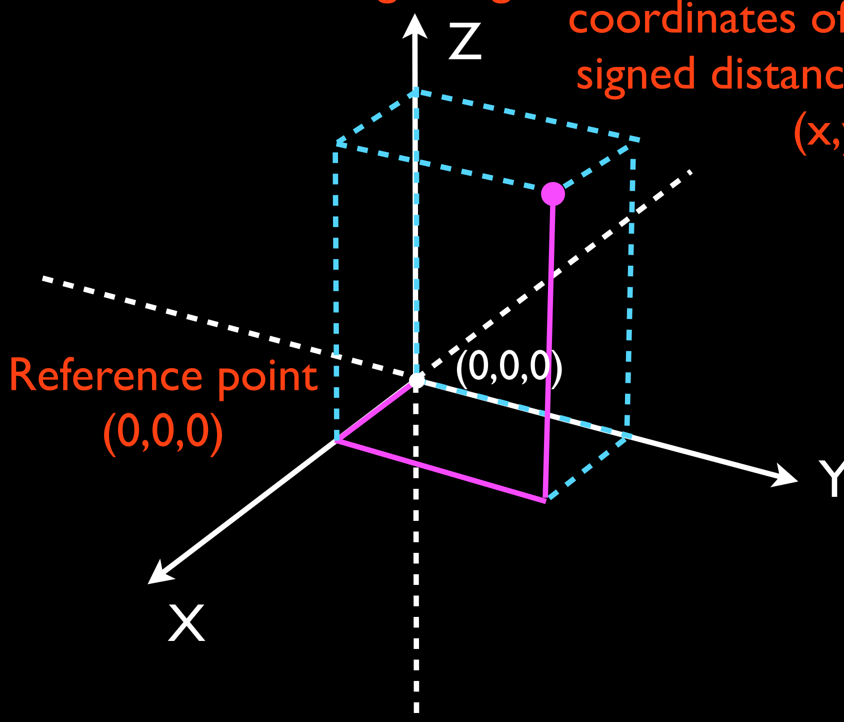

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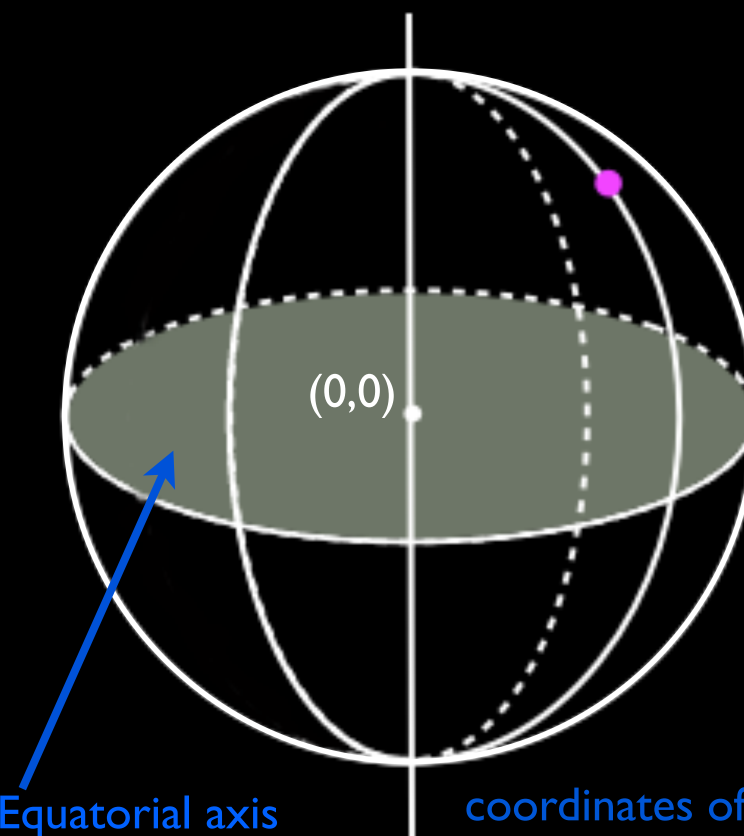

X,Y Plane => Equatorial axis perpendicular to polar axis

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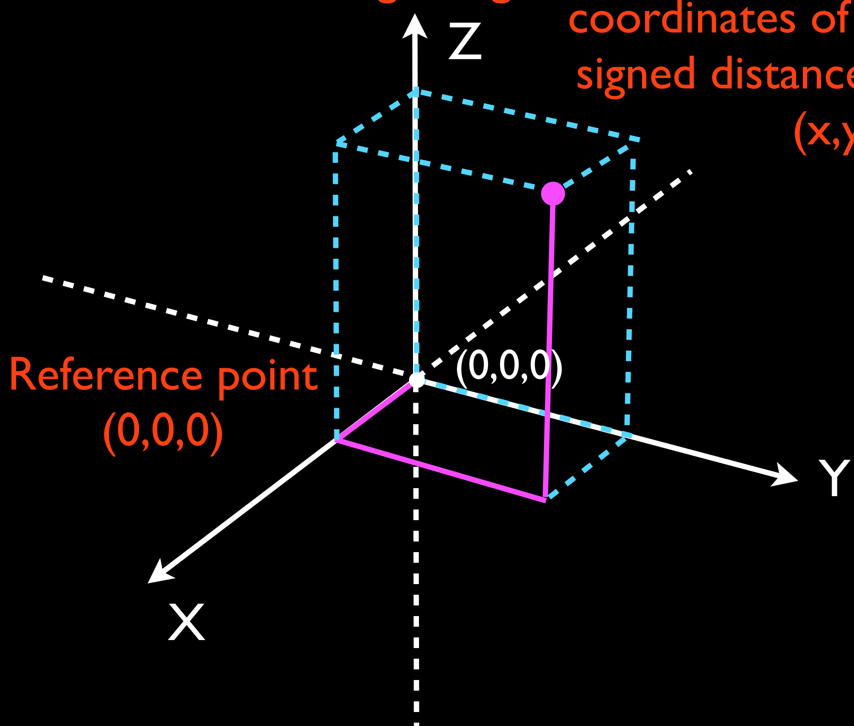

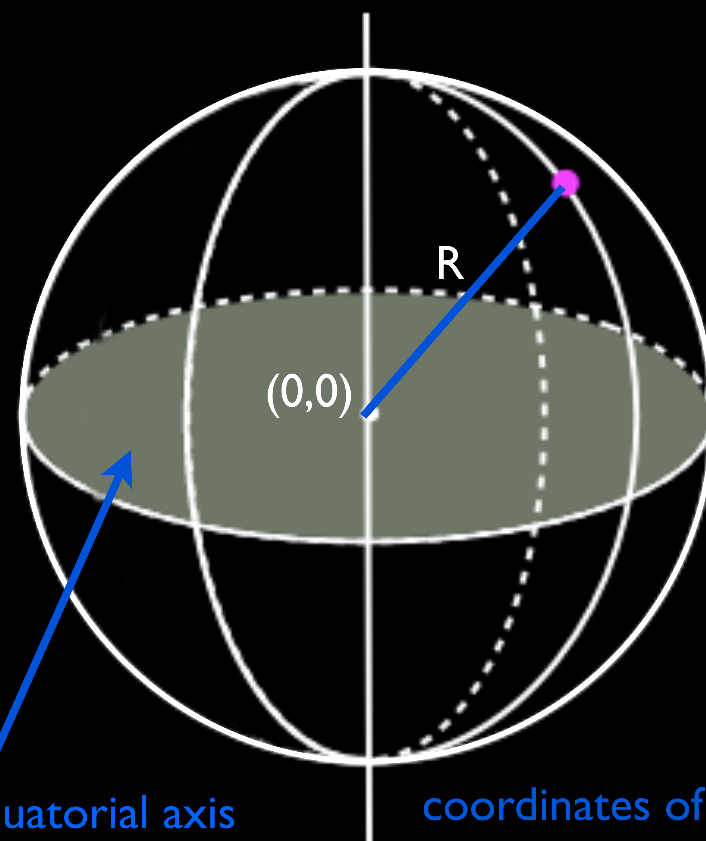

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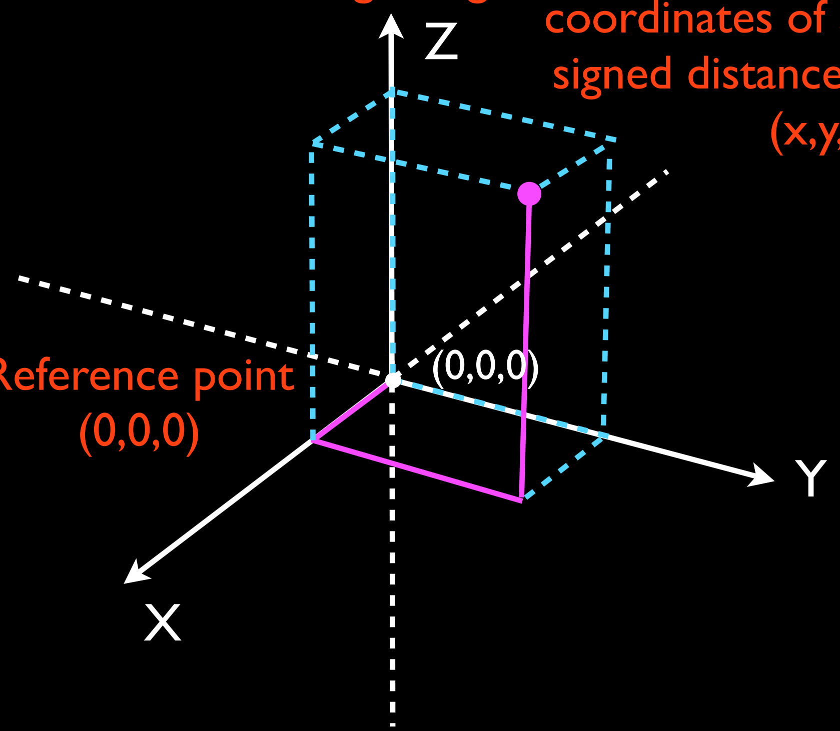

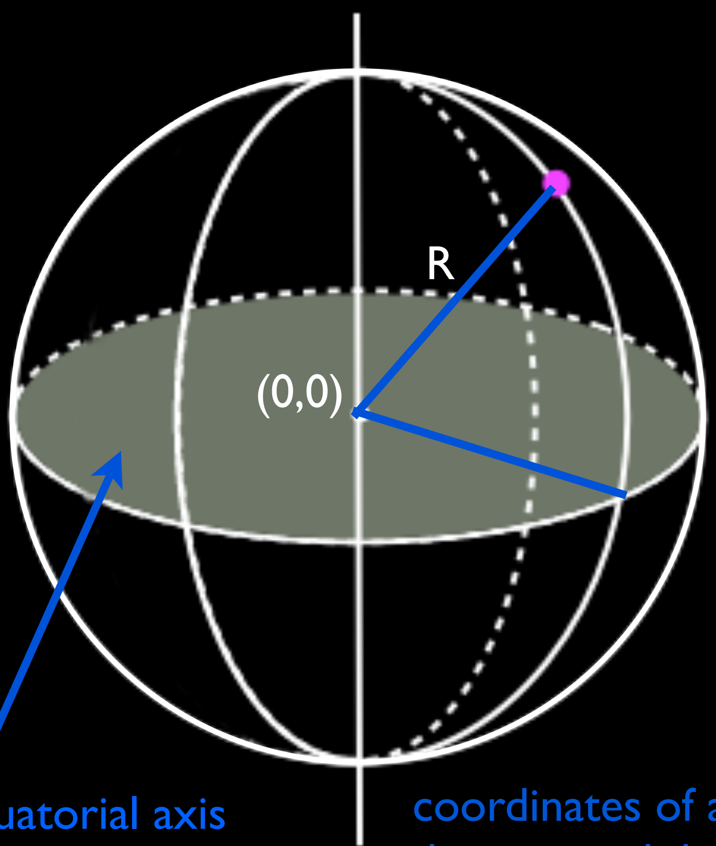

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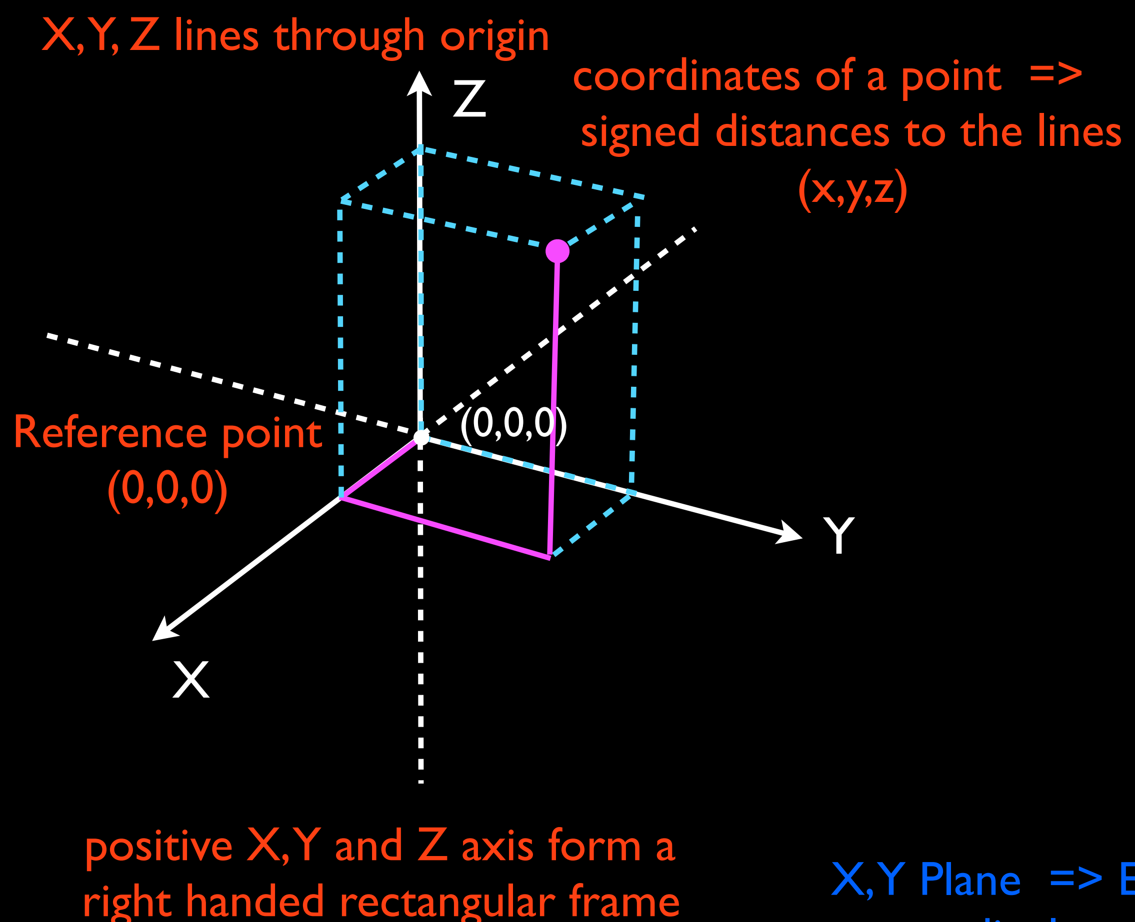

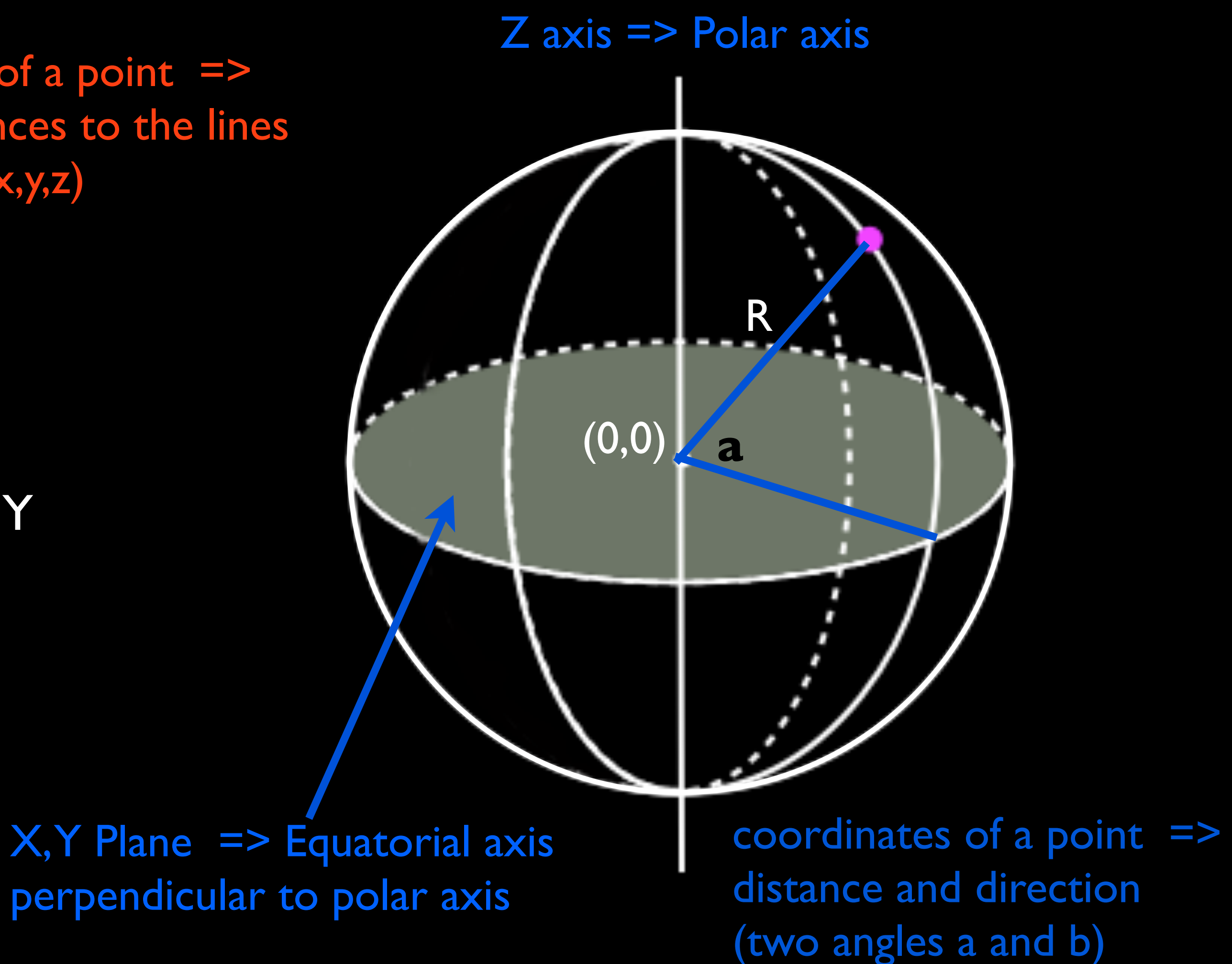

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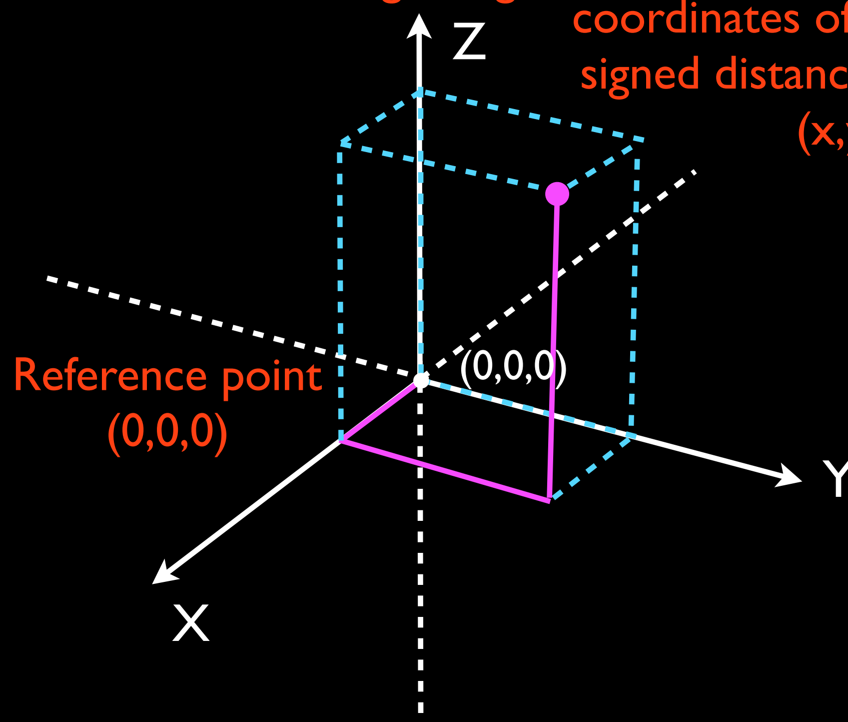

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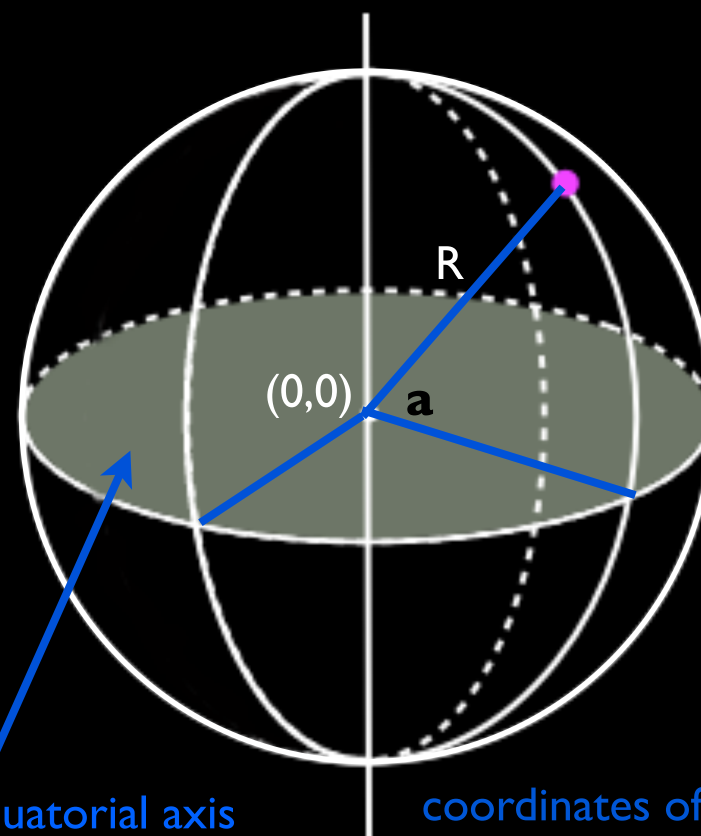

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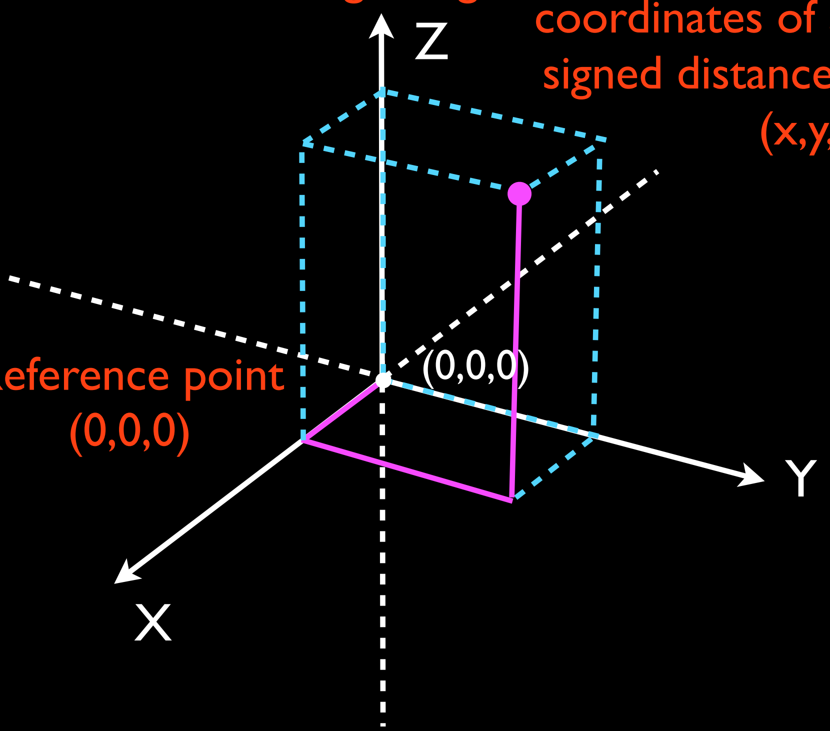

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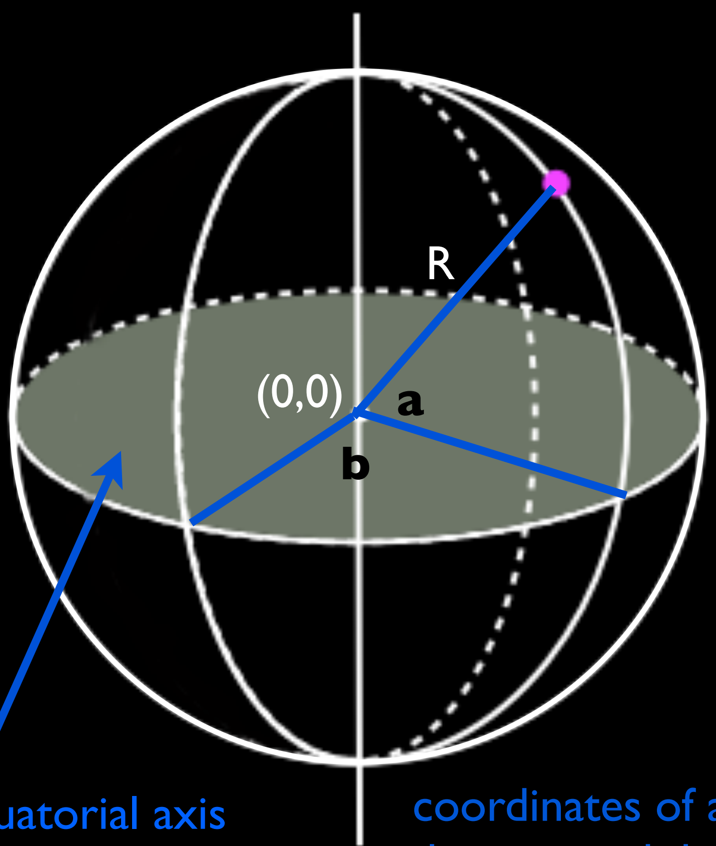

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$$X = R \times cos(a) \times cos(b)$$
$$Y = R \times cos(a) \times sin(b)$$
$$Z = R \times sin(a)$$

$$R^2 = X^2 + Y^2 + Z^2$$
$$tan(b) = Y/X$$
$$sin(a) = Z/R$$

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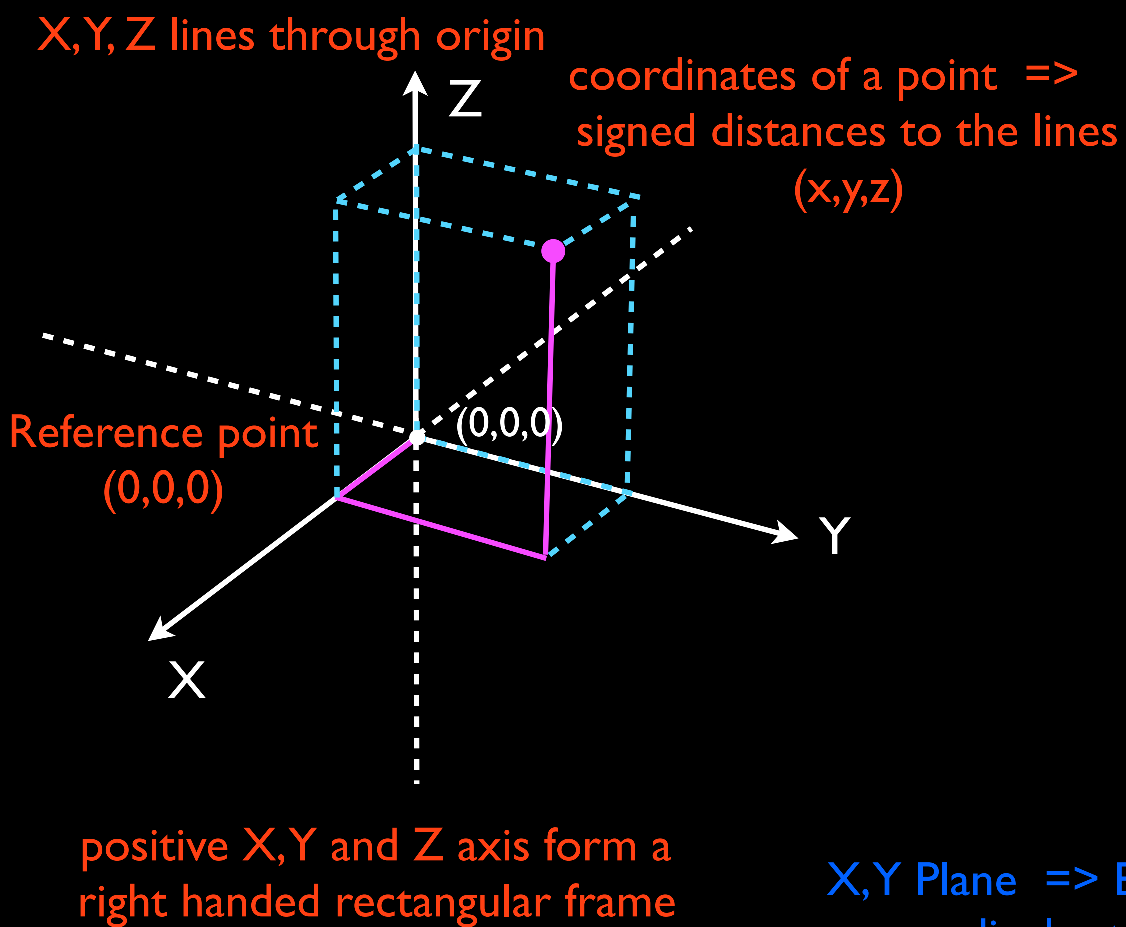
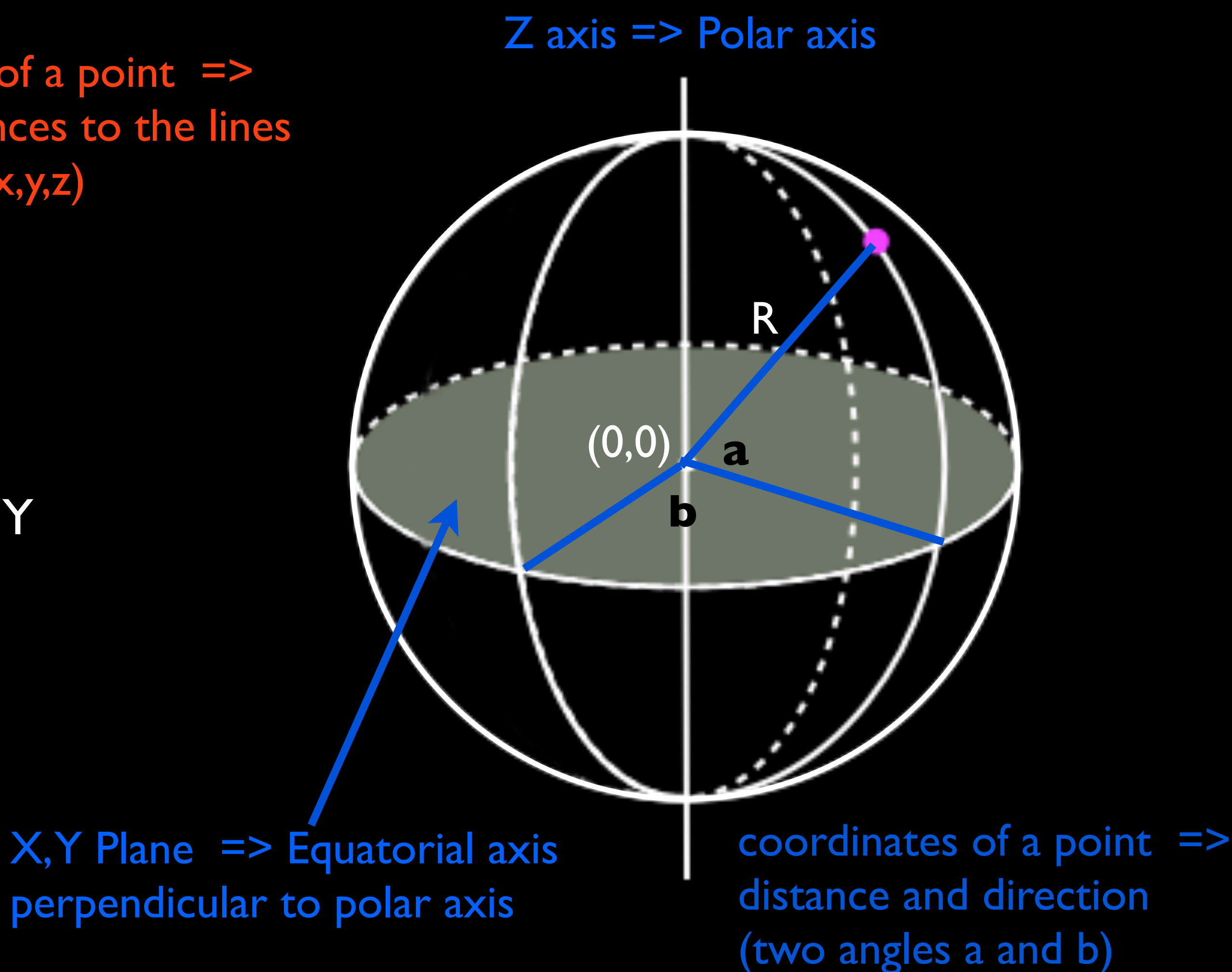
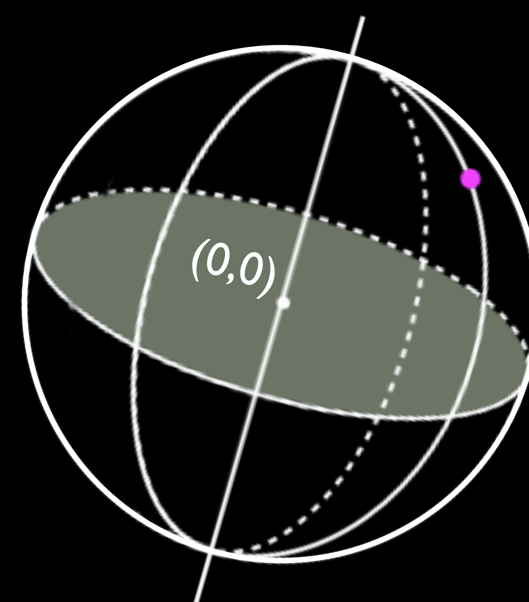




Coordinates on Earth

Origin: Center of the Earth
Reference plane: Earth Equator => Equatorial plane
Reference Axis: Rotational polar axis => cuts the Earth's surface at the North & South pole

Great circles which passes through the north and south poles are known as **meridians**
Reference Meridian: prime meridian passes through Royal Greenwich Meridian, London
Great circles which lie parallel to the equator are known as **parallels**



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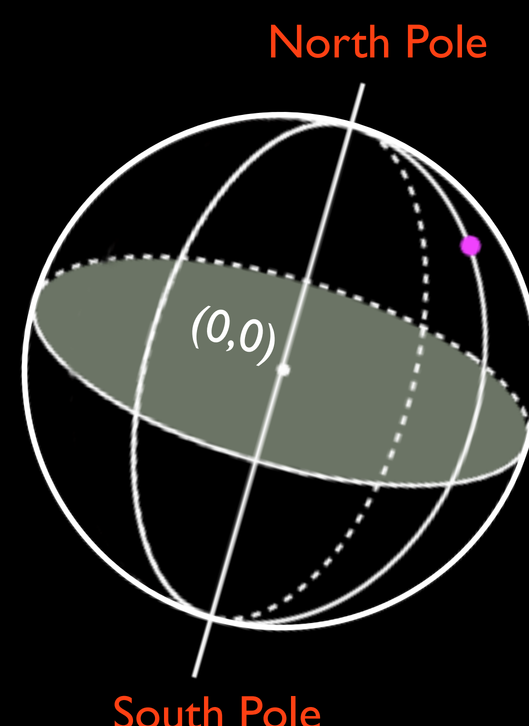

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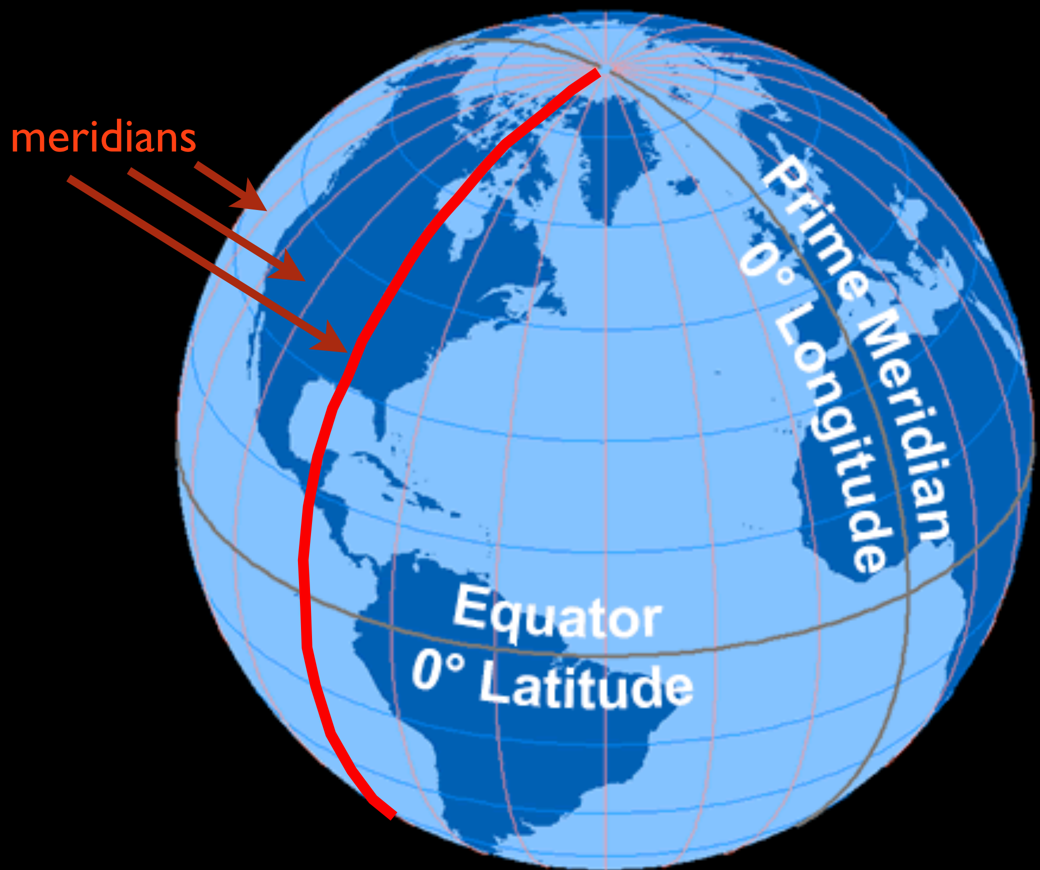

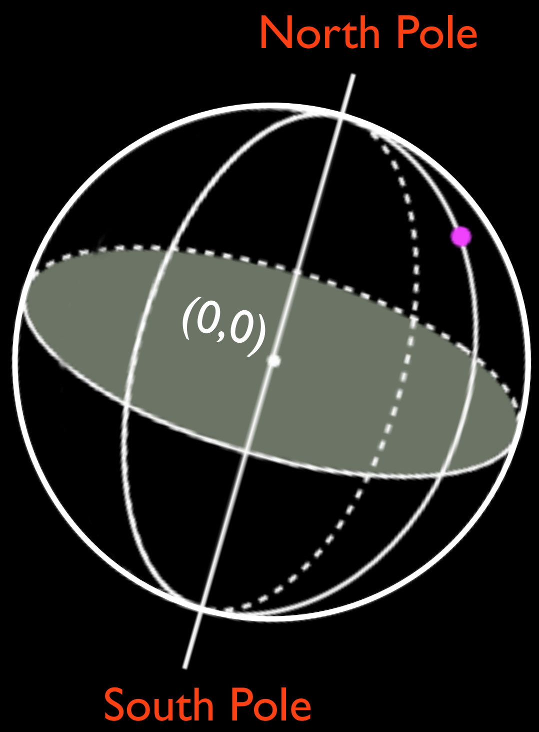

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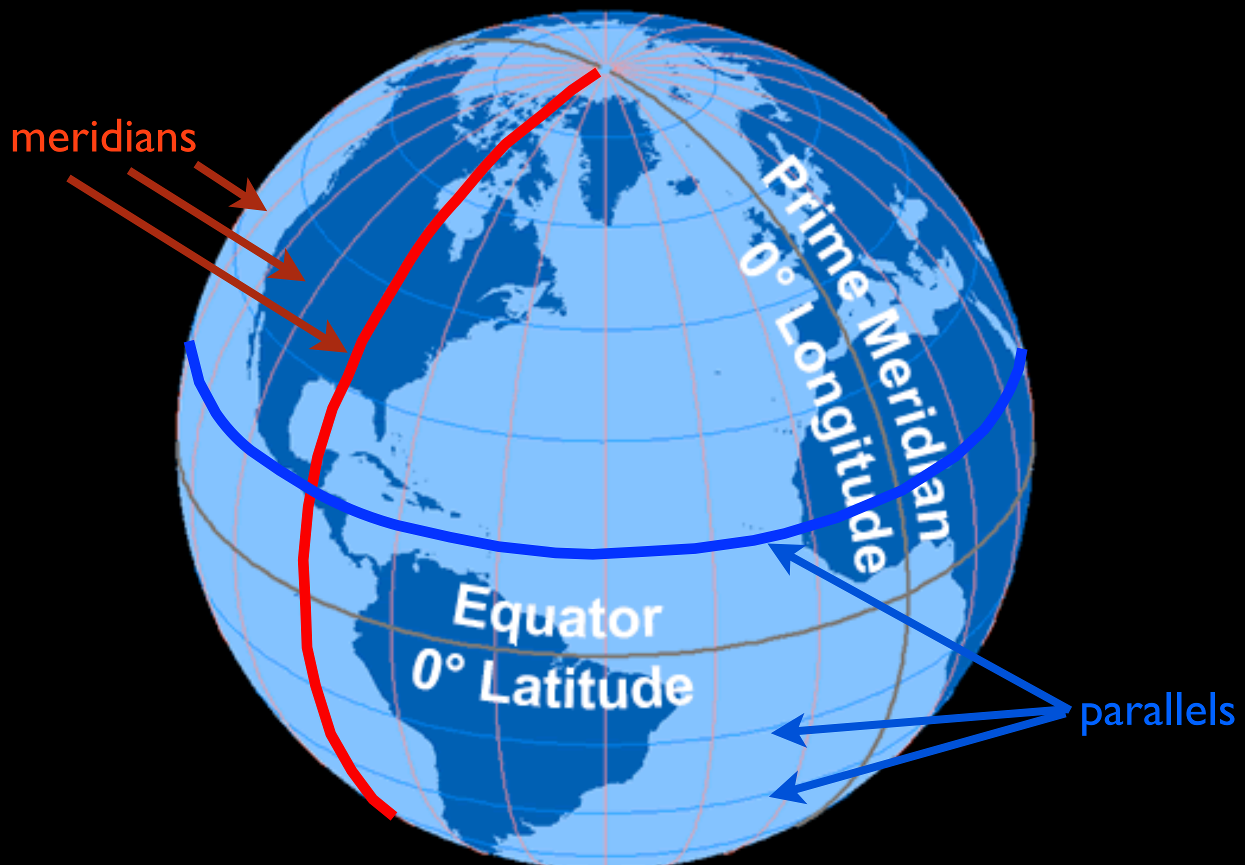

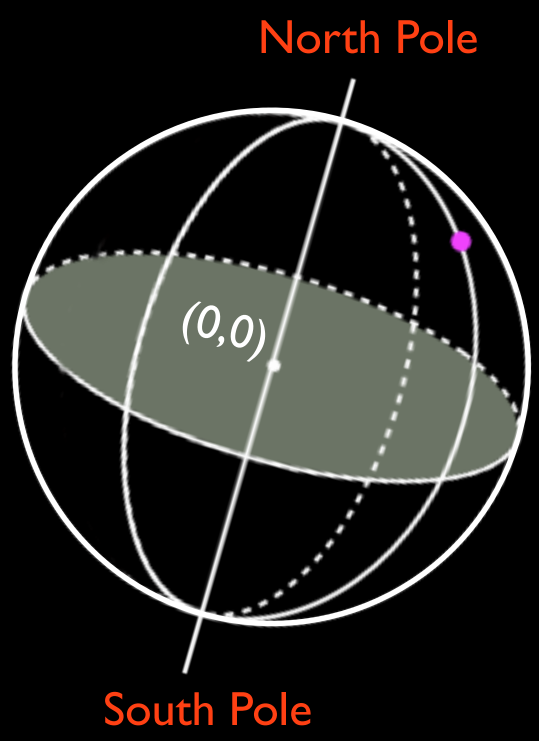

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On Earth, positions are usually given by two angles, the longitude and the latitude coordinates on the surface of the Earth (elevation).

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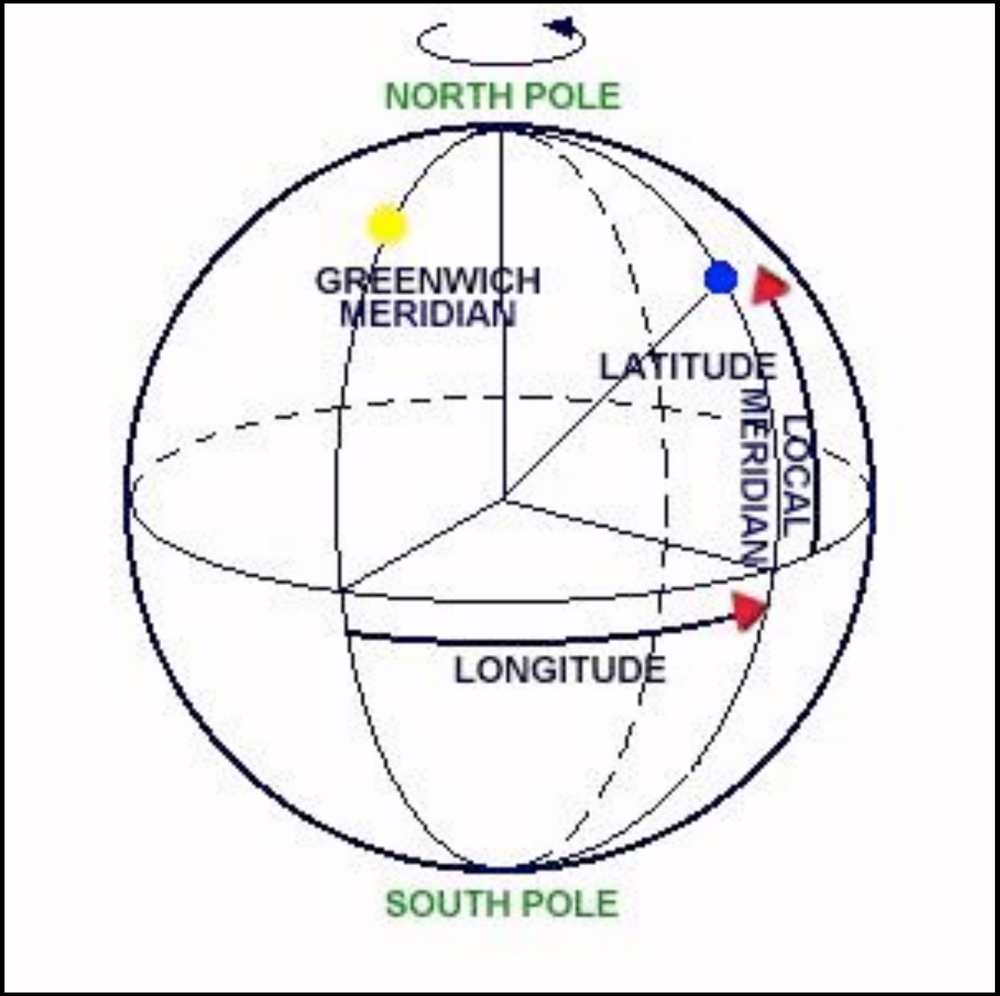

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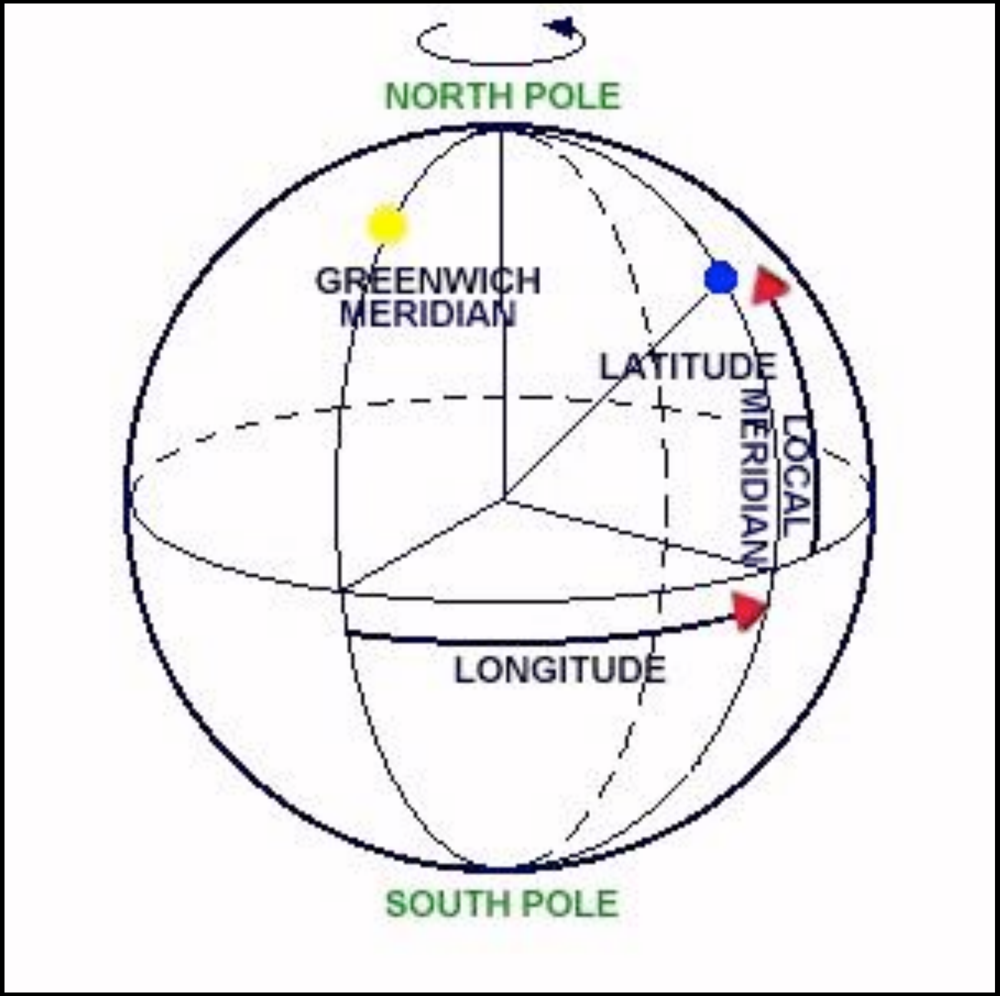

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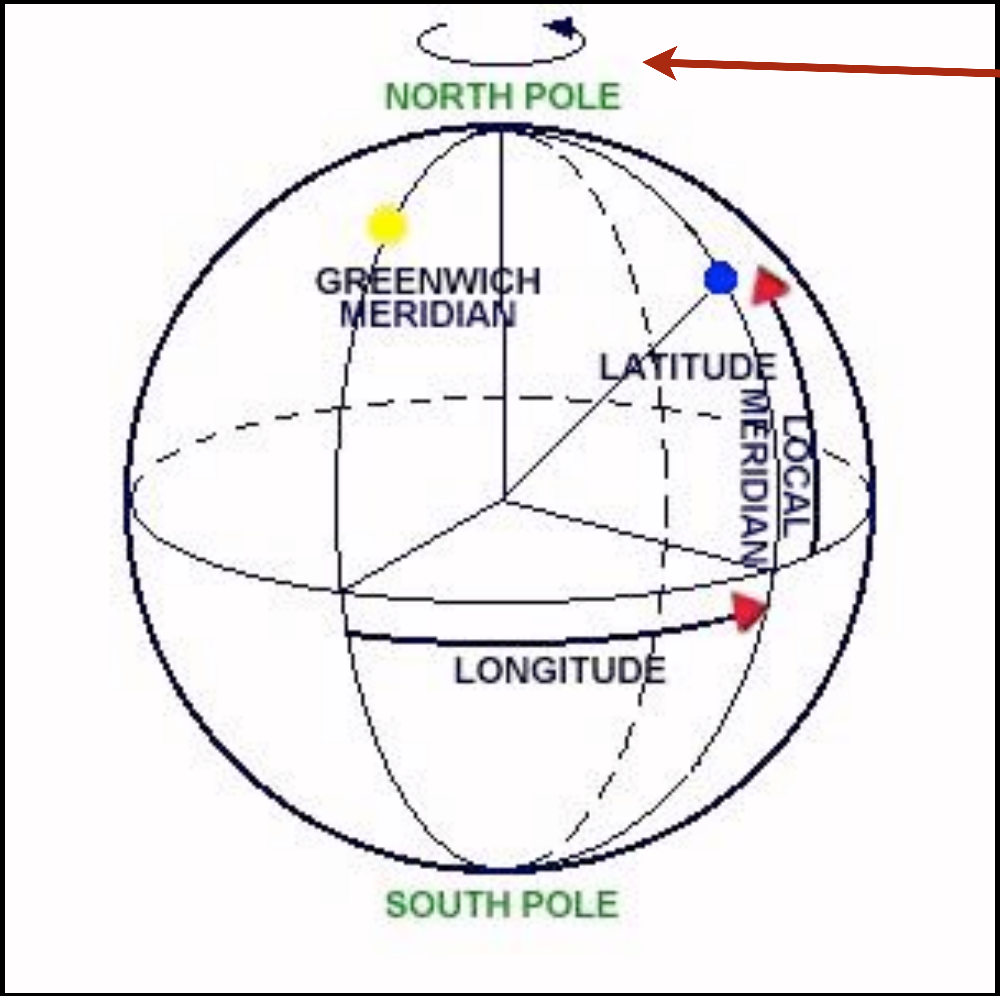

The Earth rotates on its own axis => positive sense of rotation

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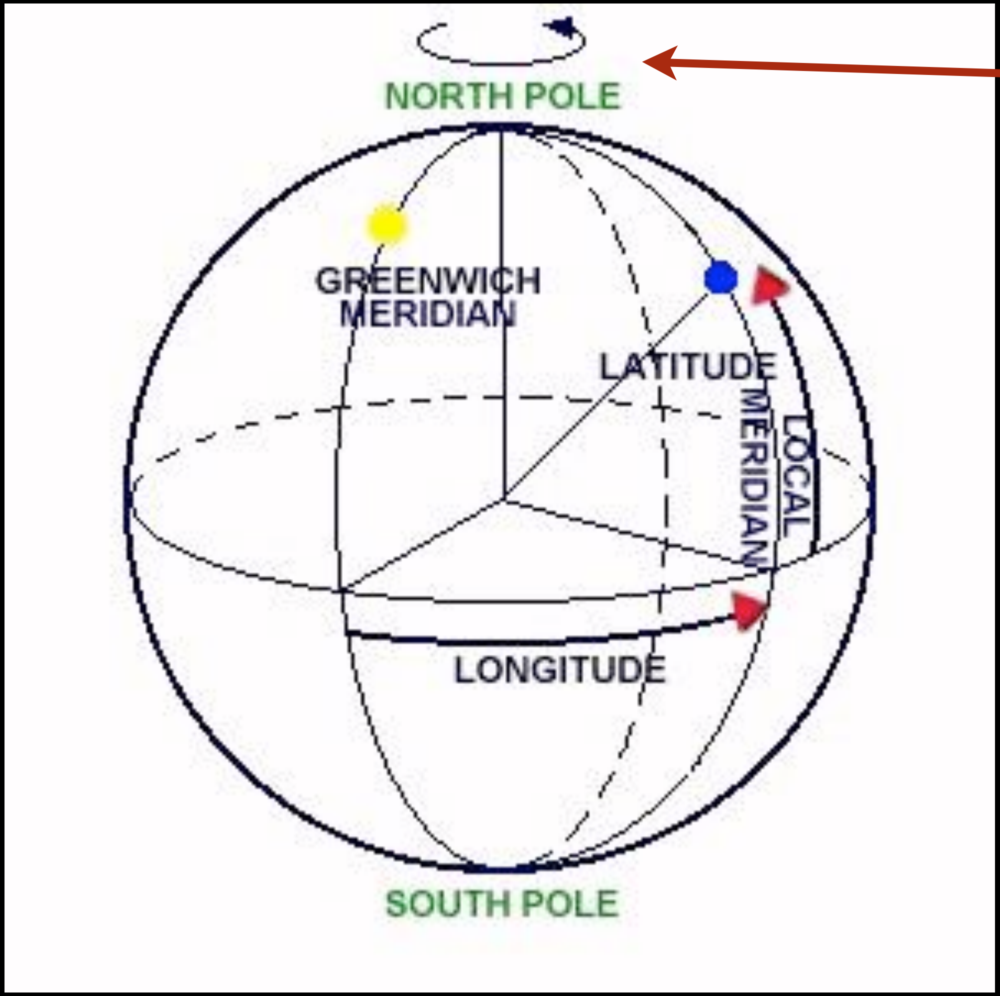

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Thus longitude can be expressed in time units and angular units.

The Earth rotates 360° in 24 hours

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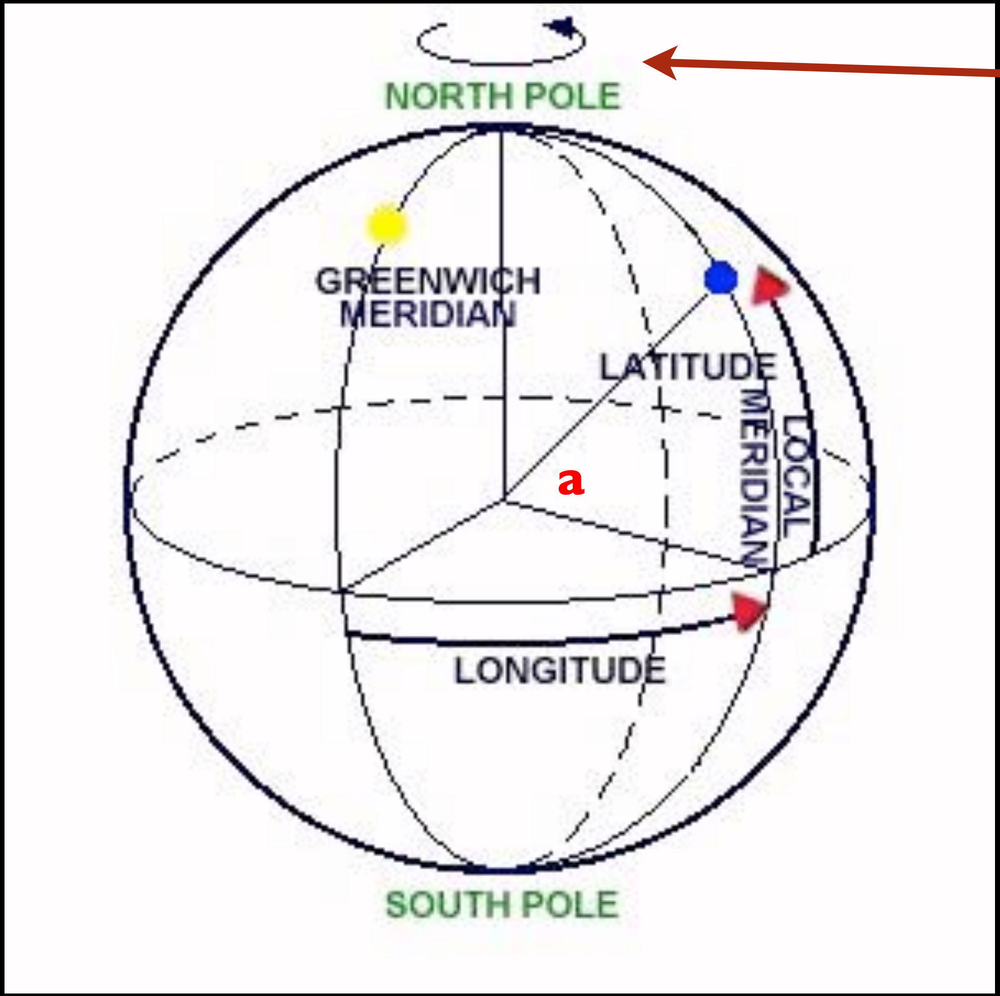

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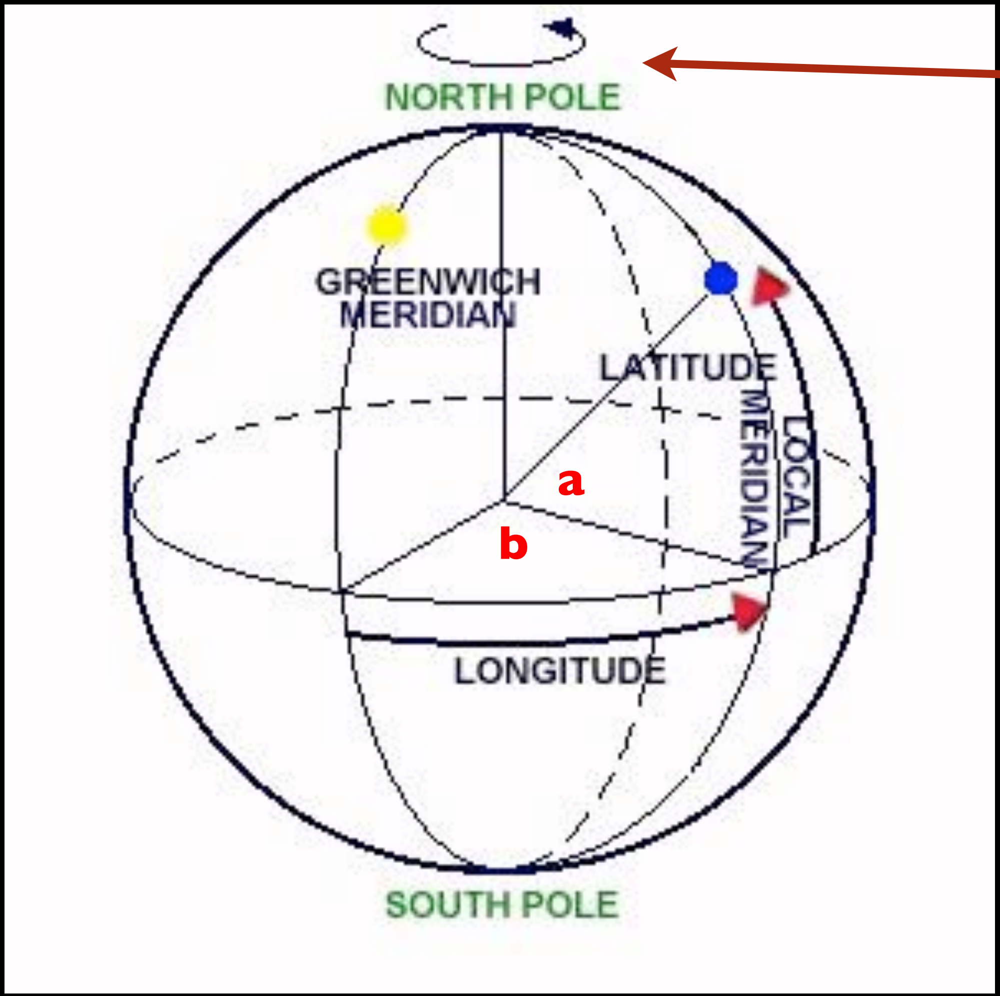

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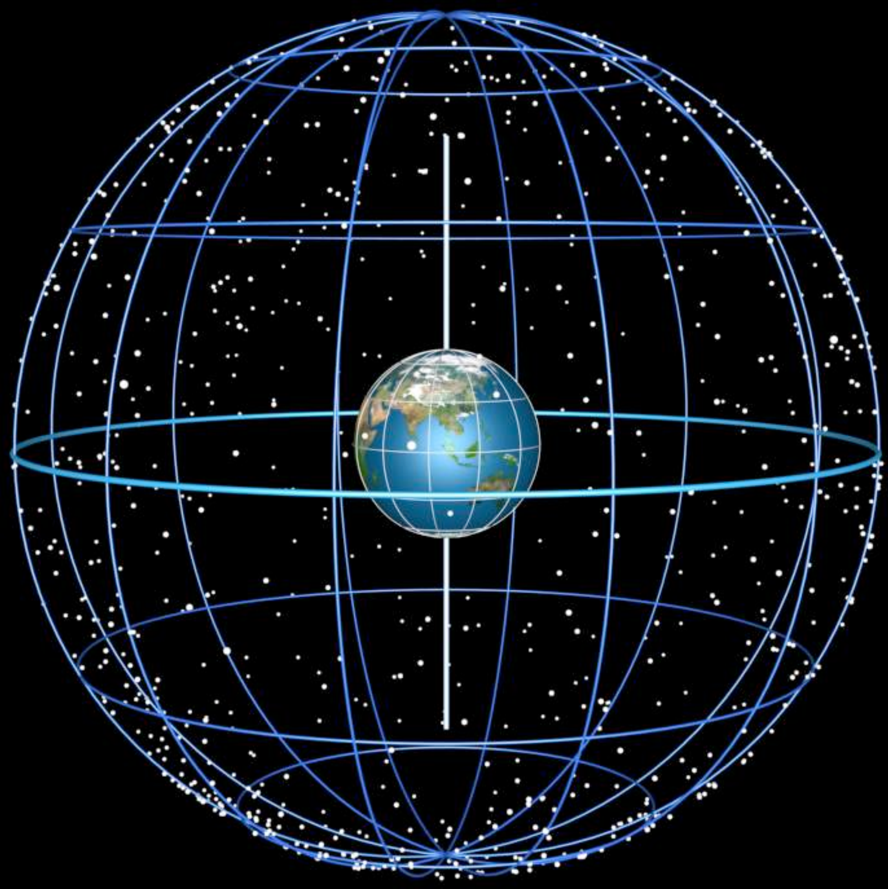
What is the approximate longitude and latitude of HartRAO ?

The Celestial Sphere

Compared to the size of the Earth, all celestial objects are far away.
An observer can look at the skies as being manifested on the interior of a big (virtual) sphere => **Celestial Sphere**

Each direction away from the observer will intersect the celestial sphere in one unique point, and thus positions of celestial objects can be measured on this virtual sphere



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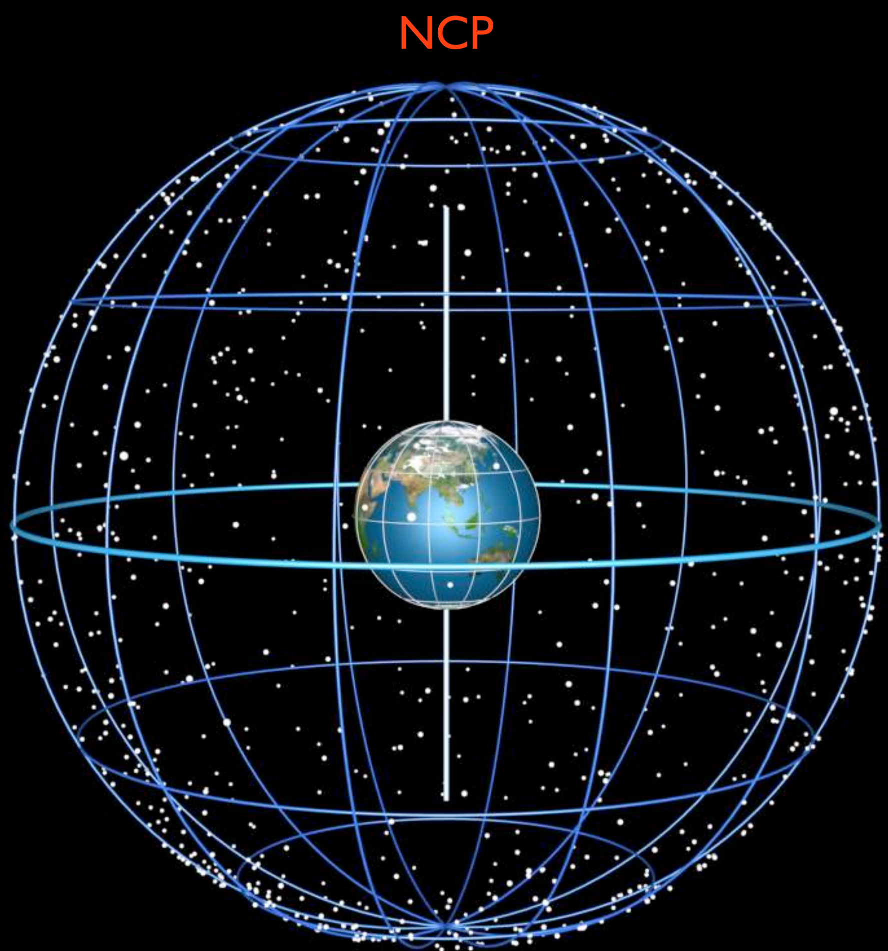

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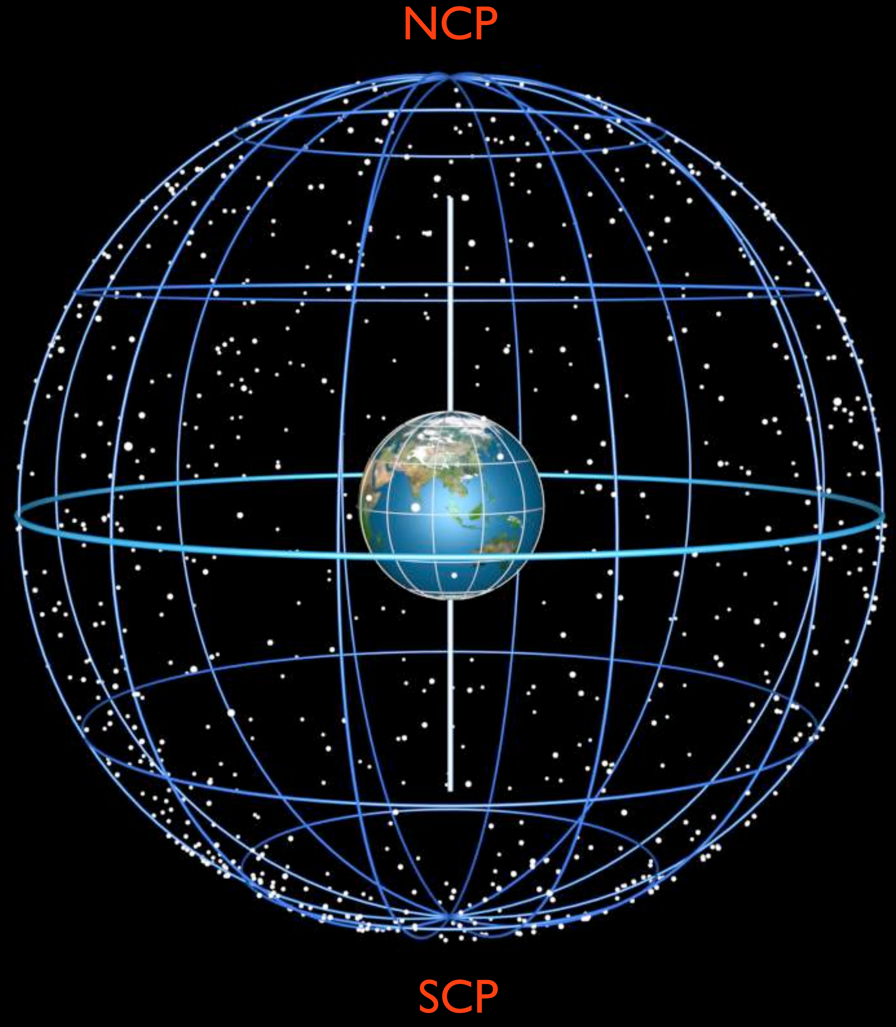

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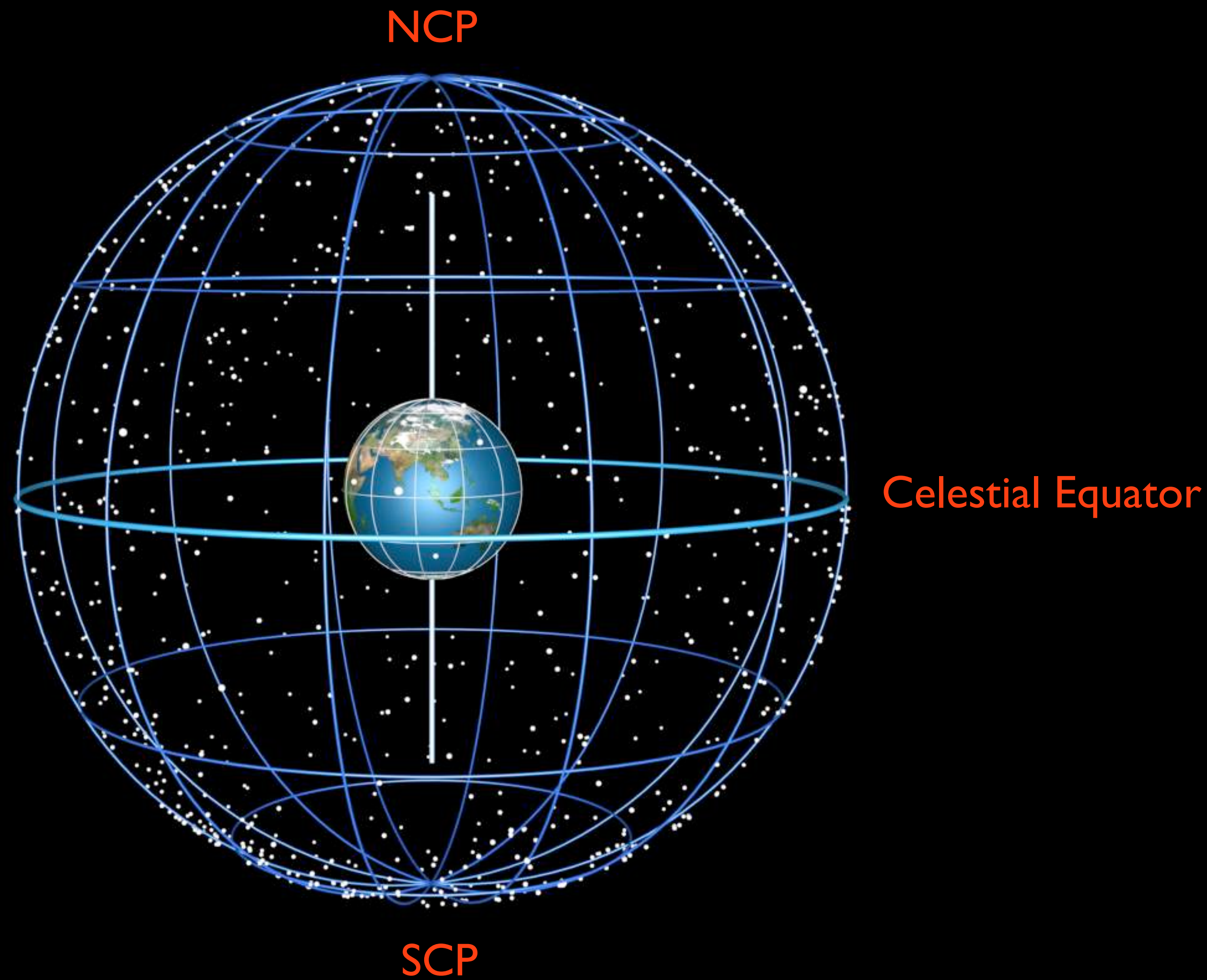
Each direction away from the observer will intersect the celestial sphere in one unique point, and thus positions of celestial objects can be measured on this virtual sphere



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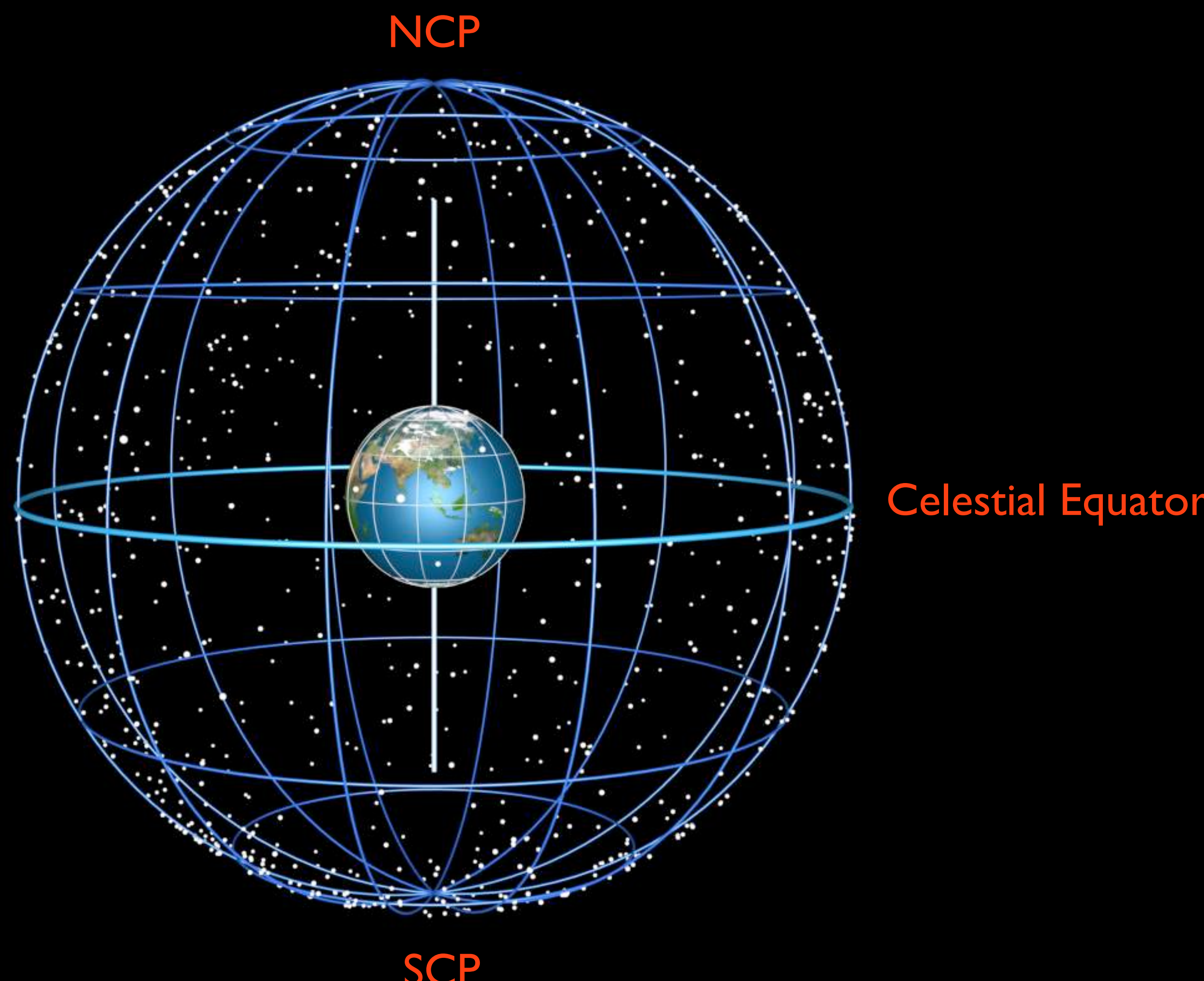
Similar to longitude and latitude



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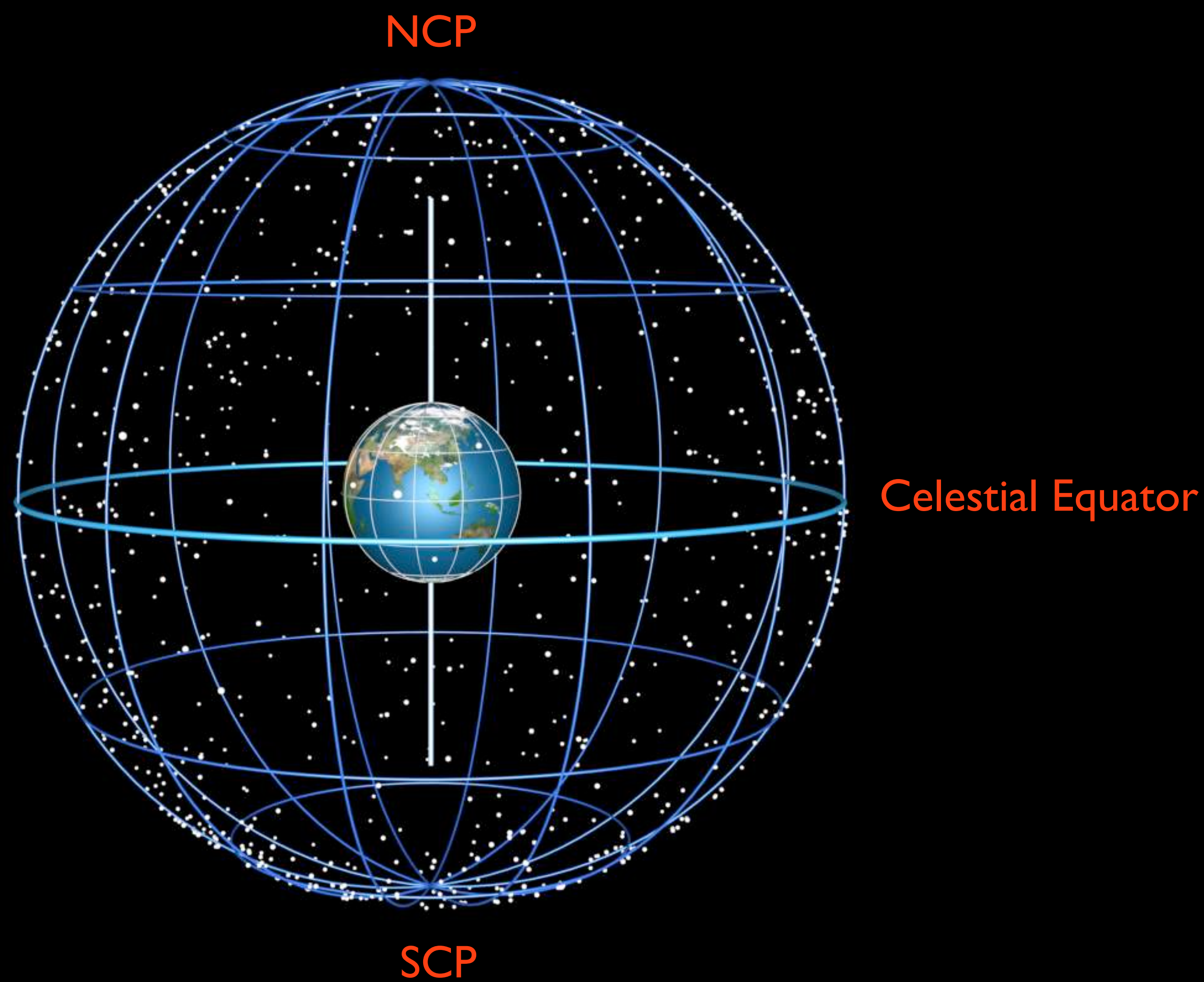
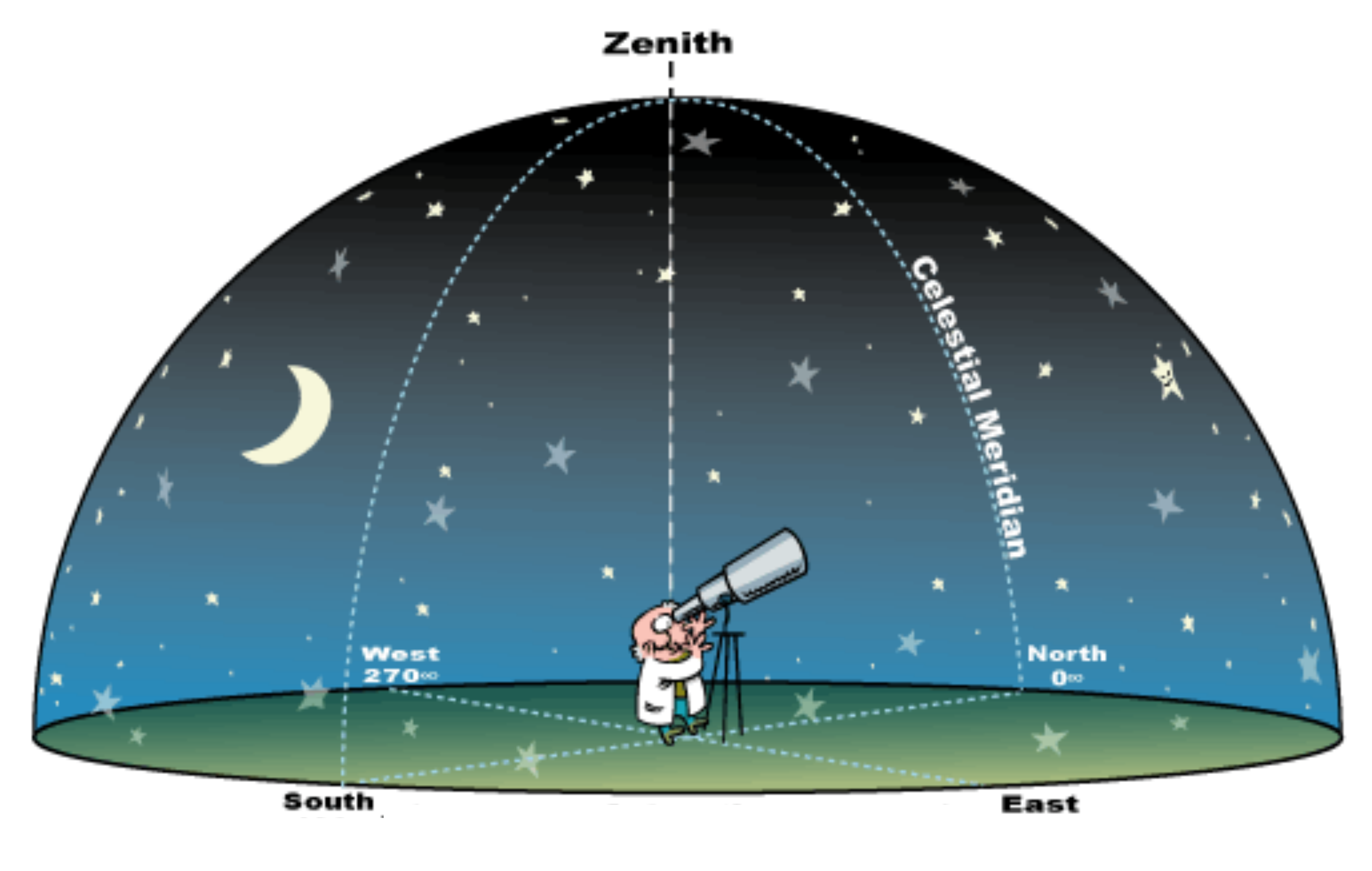


This can be done without knowing the actual distances to the stars

Celestial Coordinates: The Horizon System

The **horizon system** is defined locally for each observer on Earth and is based on the observers location.

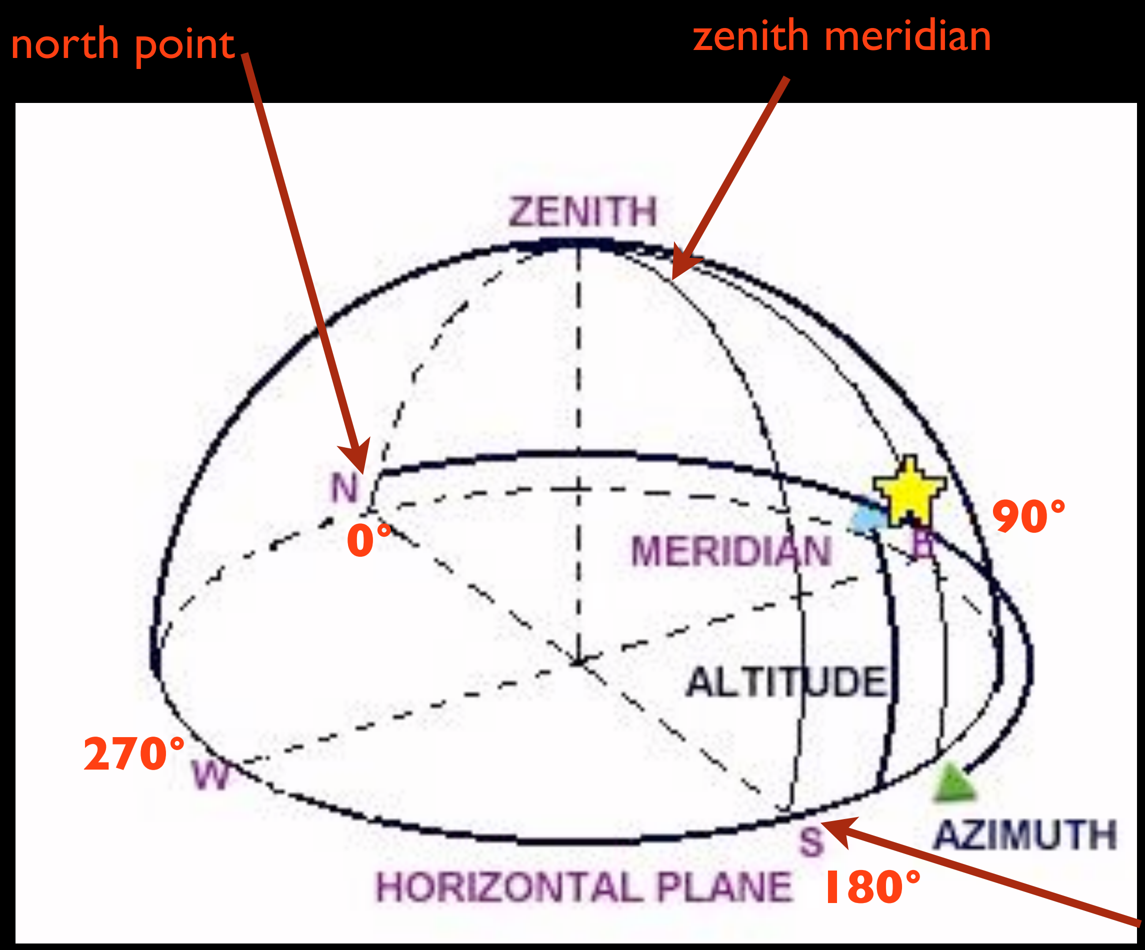
Origin: Observer's location
Reference axis: the direction directly above the observer => **zenith**
Reference plane: the horizon perpendicular to the reference axis
Reference Meridian: The vertical circle through the zenith and north/south celestial pole cuts the horizon at the north point and the south point => **zenith / local meridian**

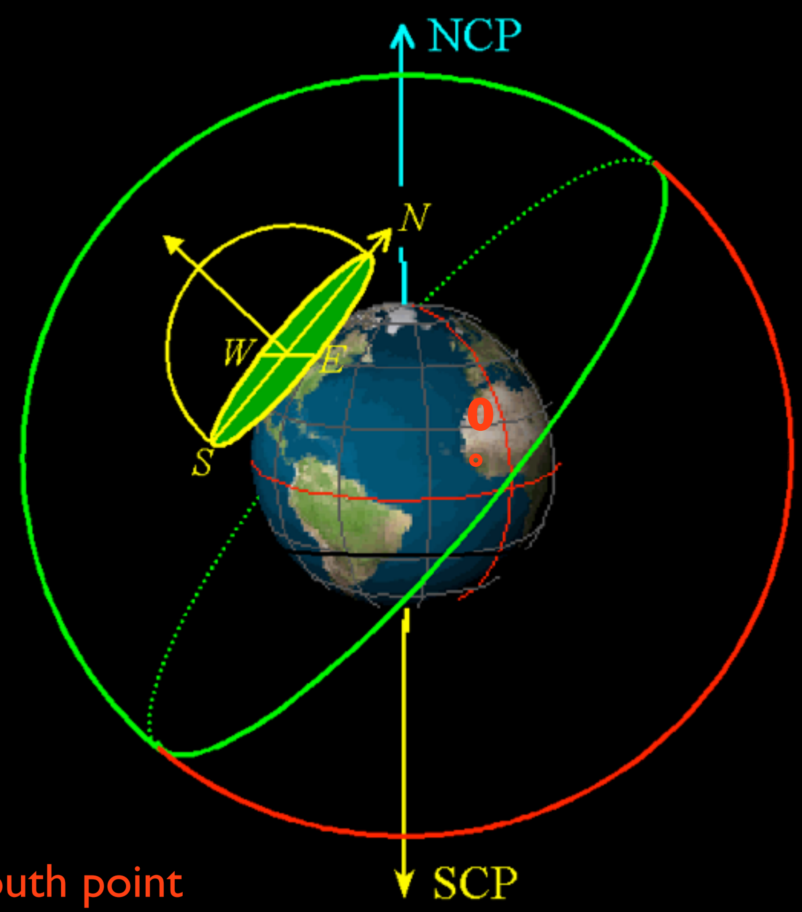


Celestial Coordinates: The Horizon System

Altitude (elevation) => angular distance along a vertical circle from the horizon and is measured in degrees. All objects above the horizon have positive altitudes and the horizon can be defined as a set of all points for which the altitude is 0°.

Azimuth => angular distance measured eastward from the north point along the horizon from 0° to 360° up to the point where the vertical circle of the position cuts the horizon.

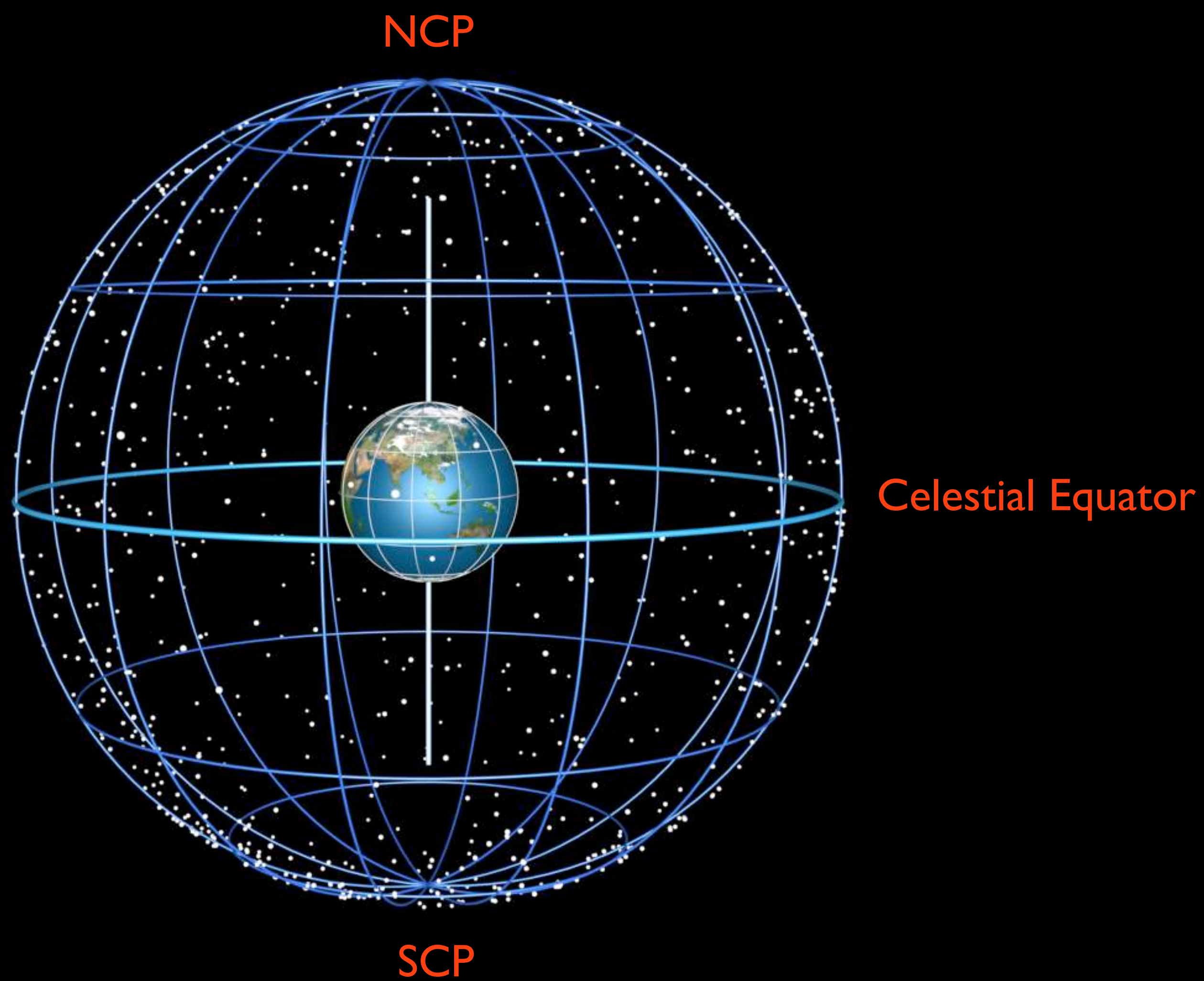




Celestial Coordinates: The Equatorial System

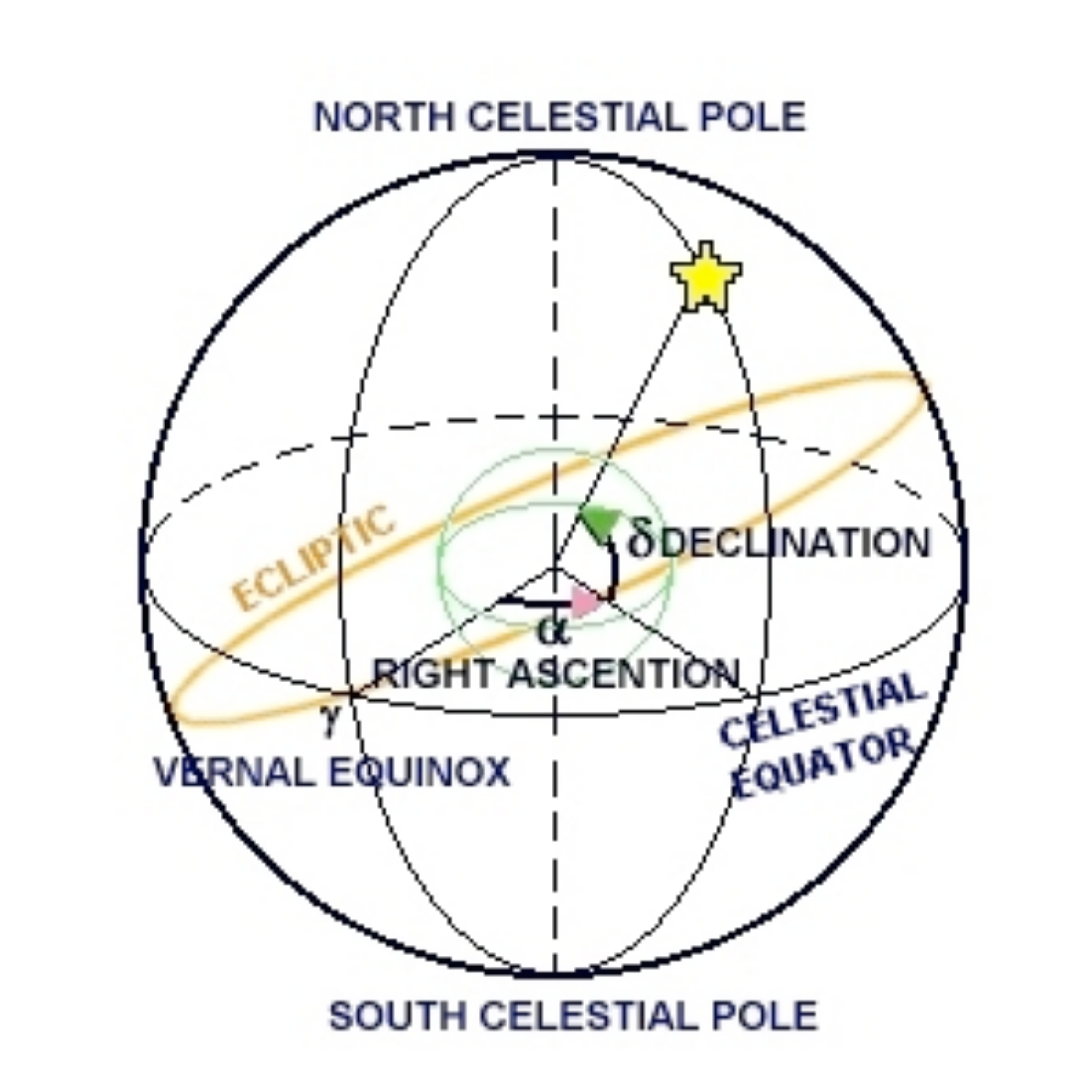
A more useful coordinate system for locating celestial objects is one fixed at the celestial sphere.

The equatorial coordinate system => projecting Earth's equator and poles to the celestial sphere by imagining straight lines from the Earth's centre produces the celestial equator and the north and south celestial pole.



Celestial Coordinates: The Equatorial System

Declination (Dec. or δ) => the analogue of latitude on Earth is the angular distance between the celestial equator and the position of an object. It is measured north or south of the celestial equator and ranges from 0° at the celestial equator to +90 at the north celestial pole and -90 at the south celestial pole.



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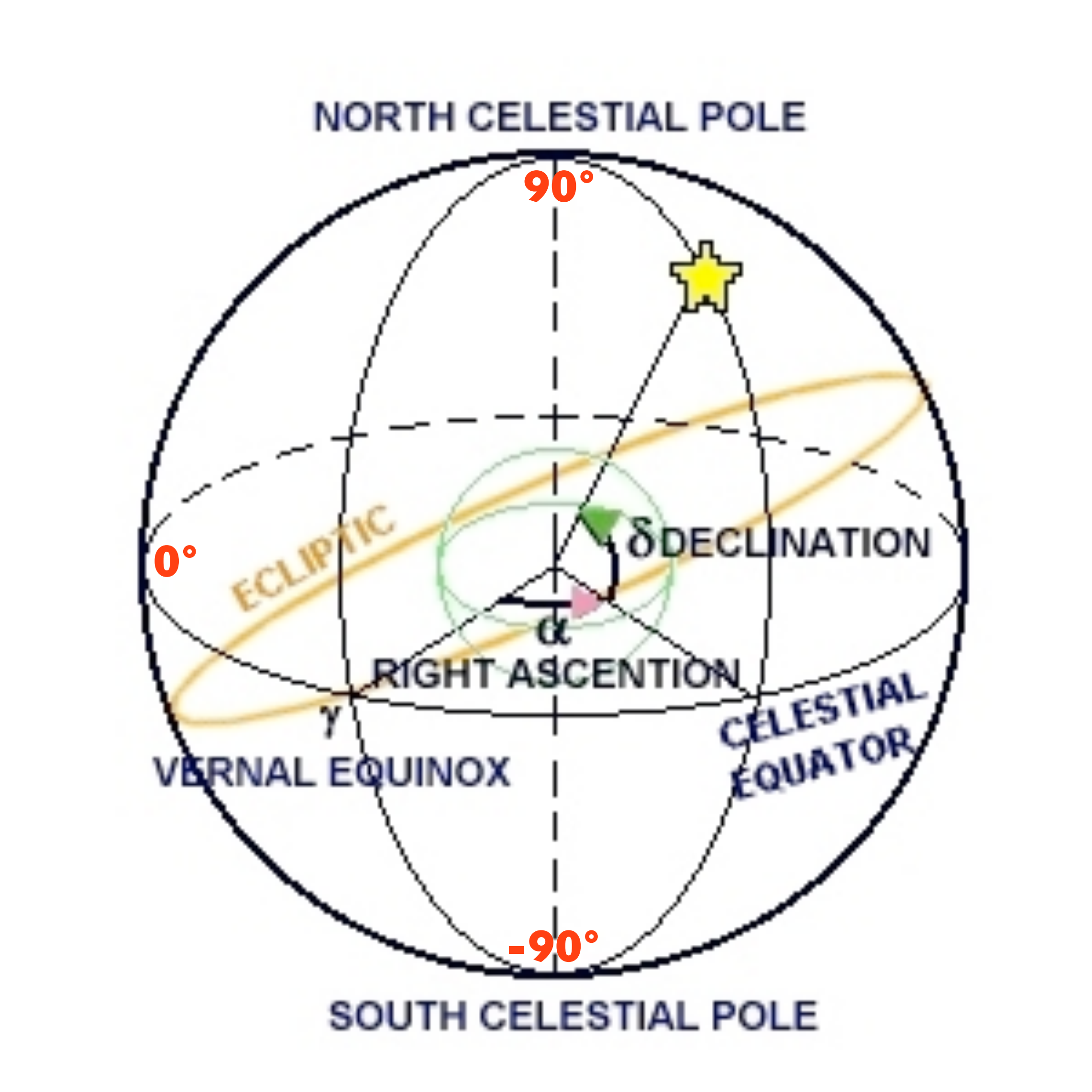
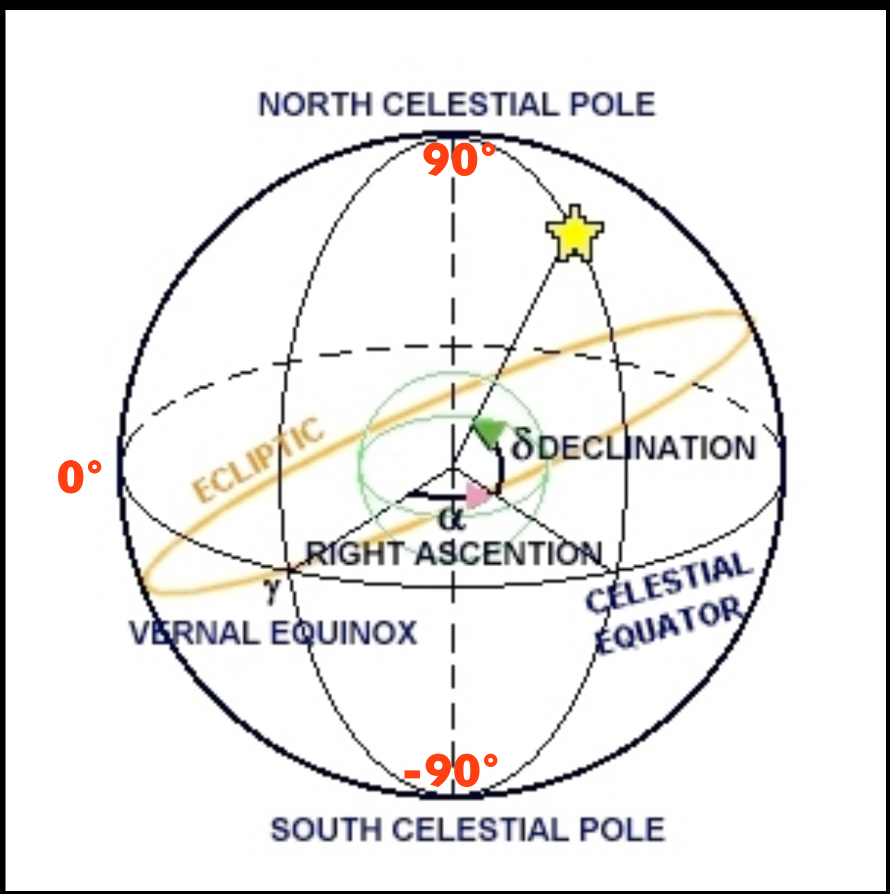


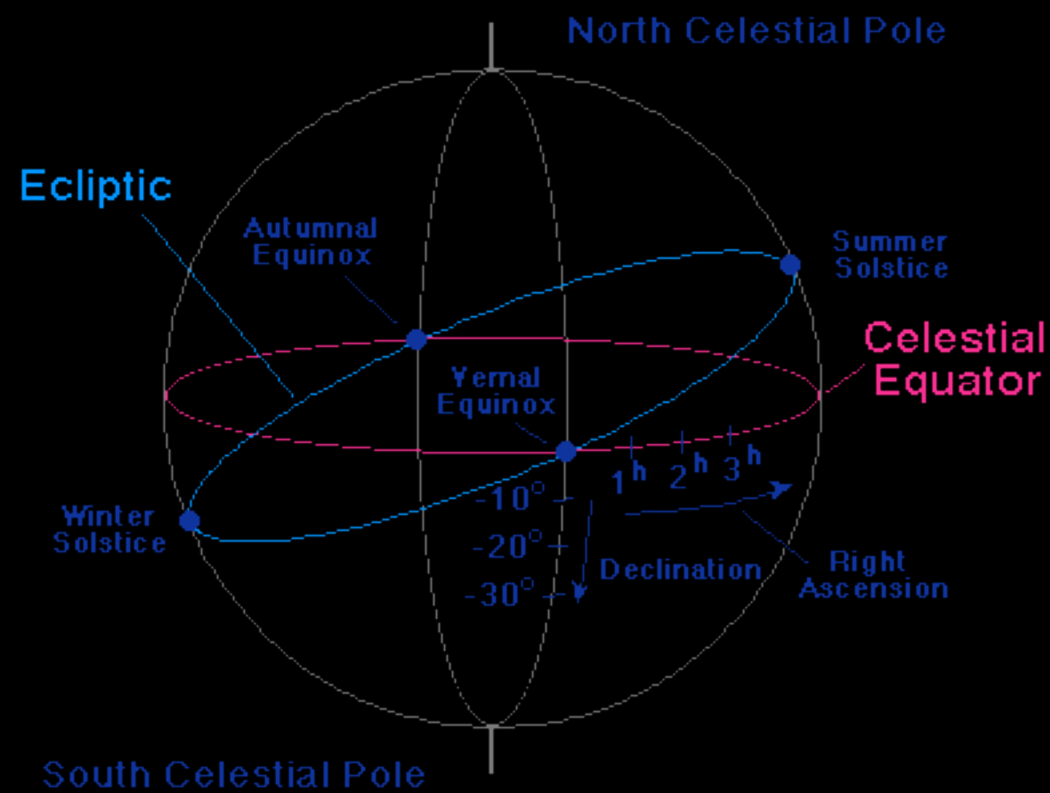
Celestial Coordinates: The Equatorial System

Right Ascension (R.A. or α) => the equivalent of longitude on Earth that is the angle between the reference meridian and the meridian under consideration.

Reference Point => point at which the Sun crosses the equator, on about March 21. This is the so called “First point in Aries, γ” or vernal equinox.

The R.A. is measured in units of time, between 0 and 24 hours along the celestial equator eastward from the first point in Aries.





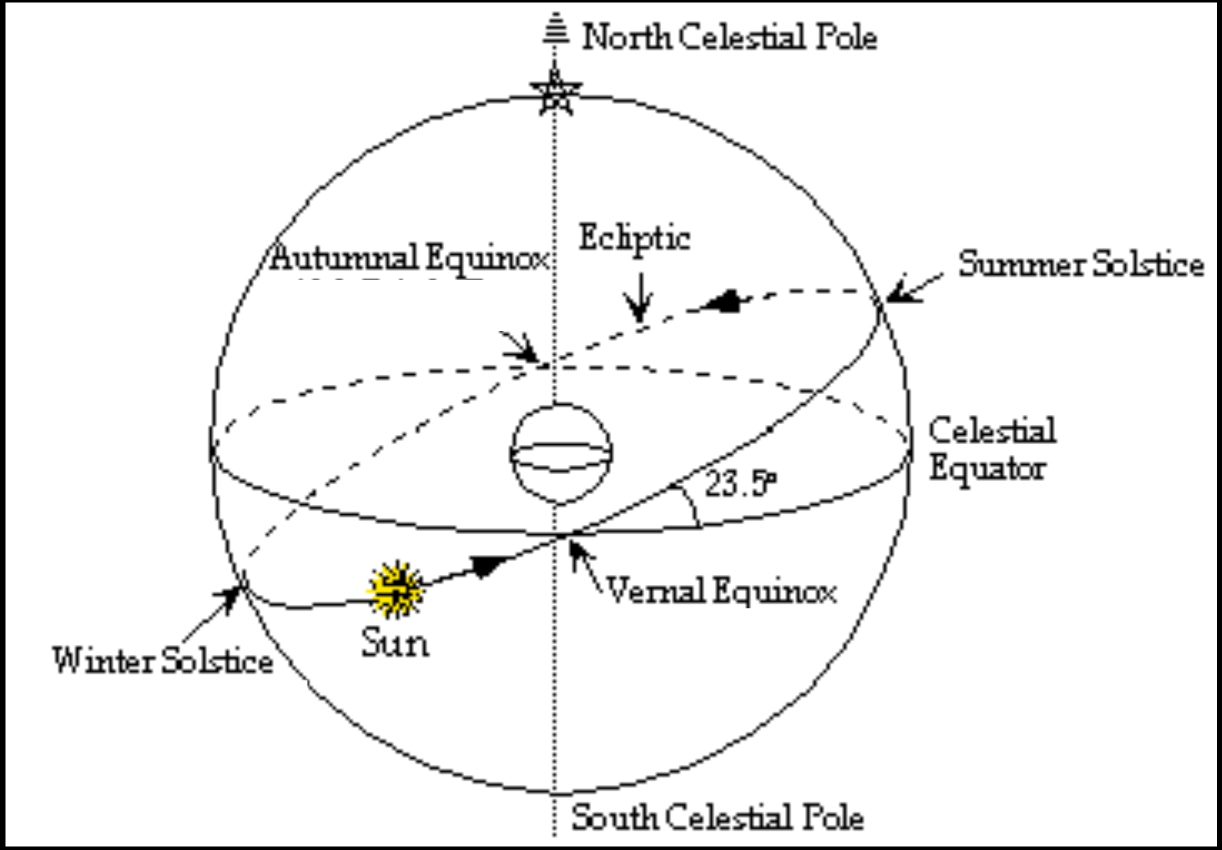
Celestial Coordinates: The Ecliptic

The celestial equator is the projection of Earth's equator on the sky

The ecliptic is the projection of Earth's orbit on the sky

Earth is tipped in its orbit => ecliptic and equator are inclined to each other by ~ 23.5°

The sun moves eastward around the sky and spends half the year in the southern half of the sky and half the year in the northern half.



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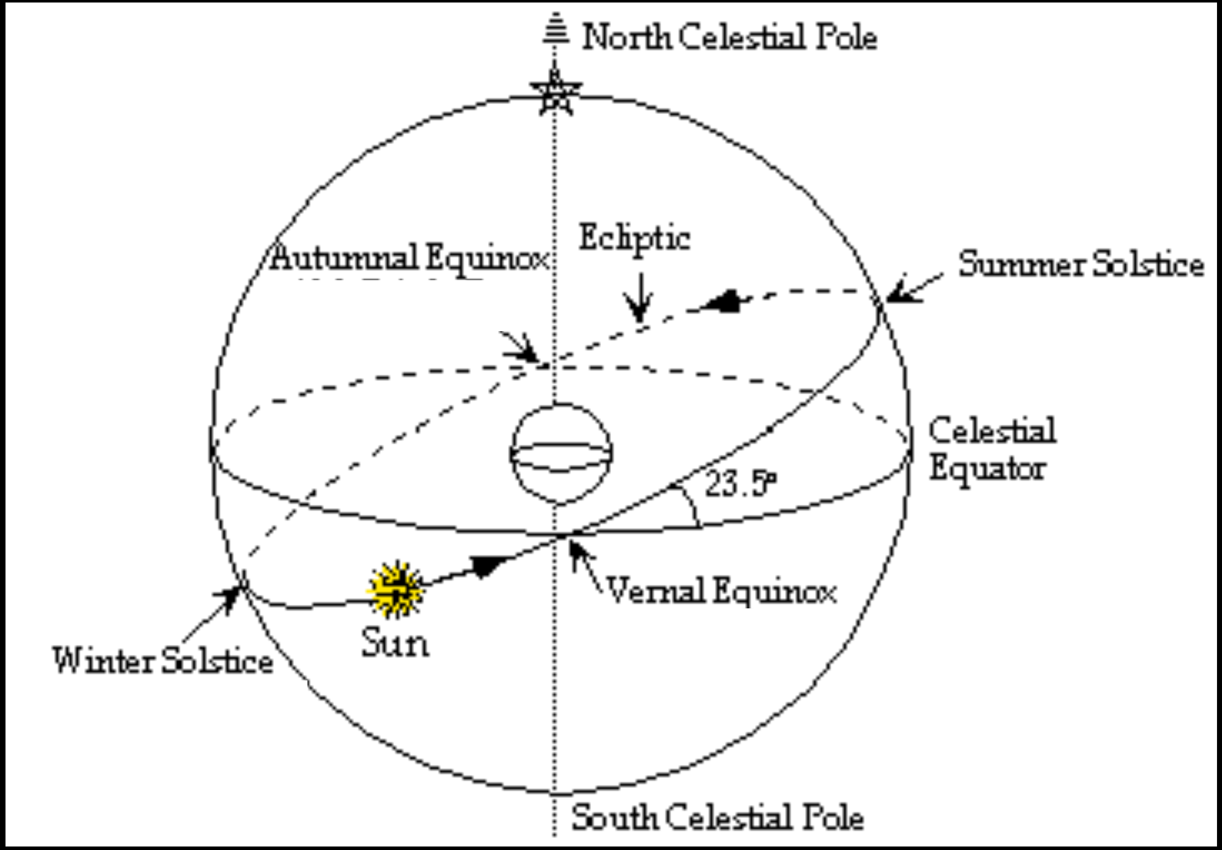

Vernal Equinox March 20

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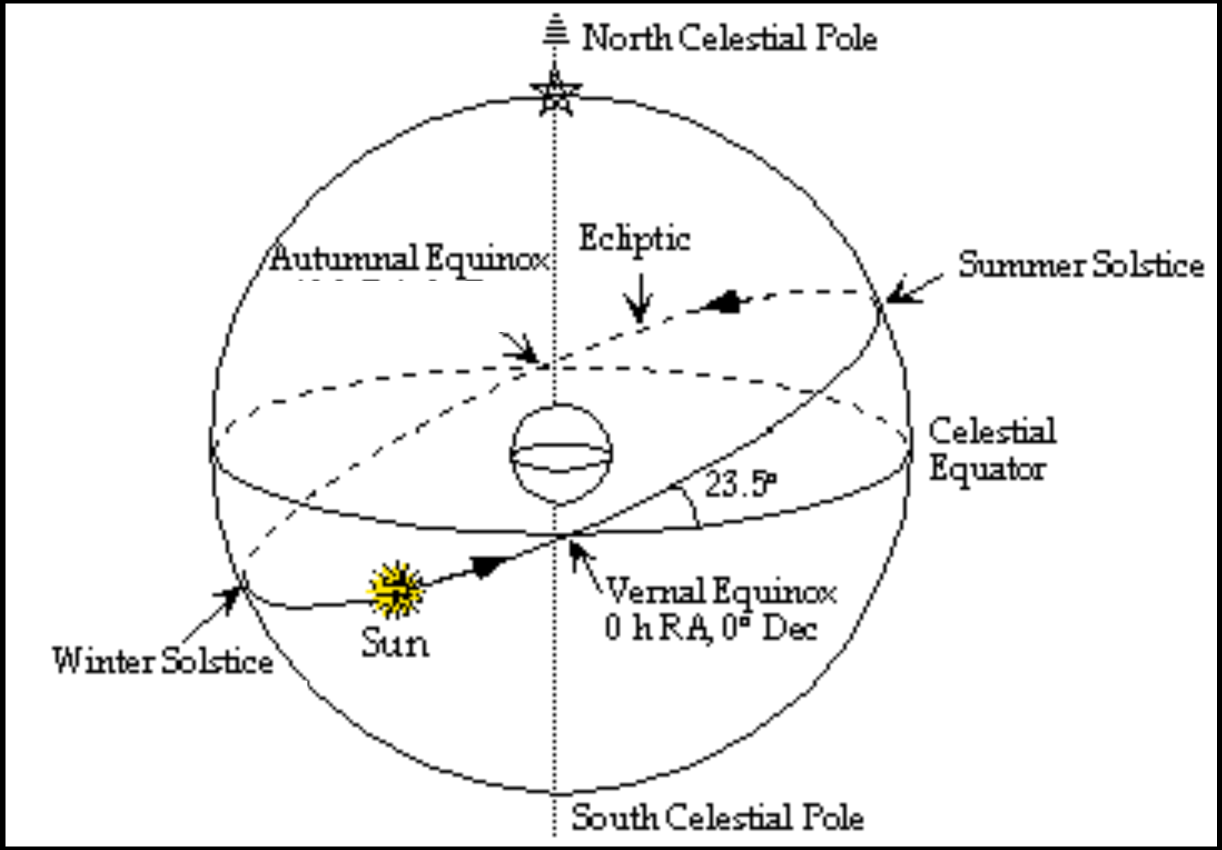

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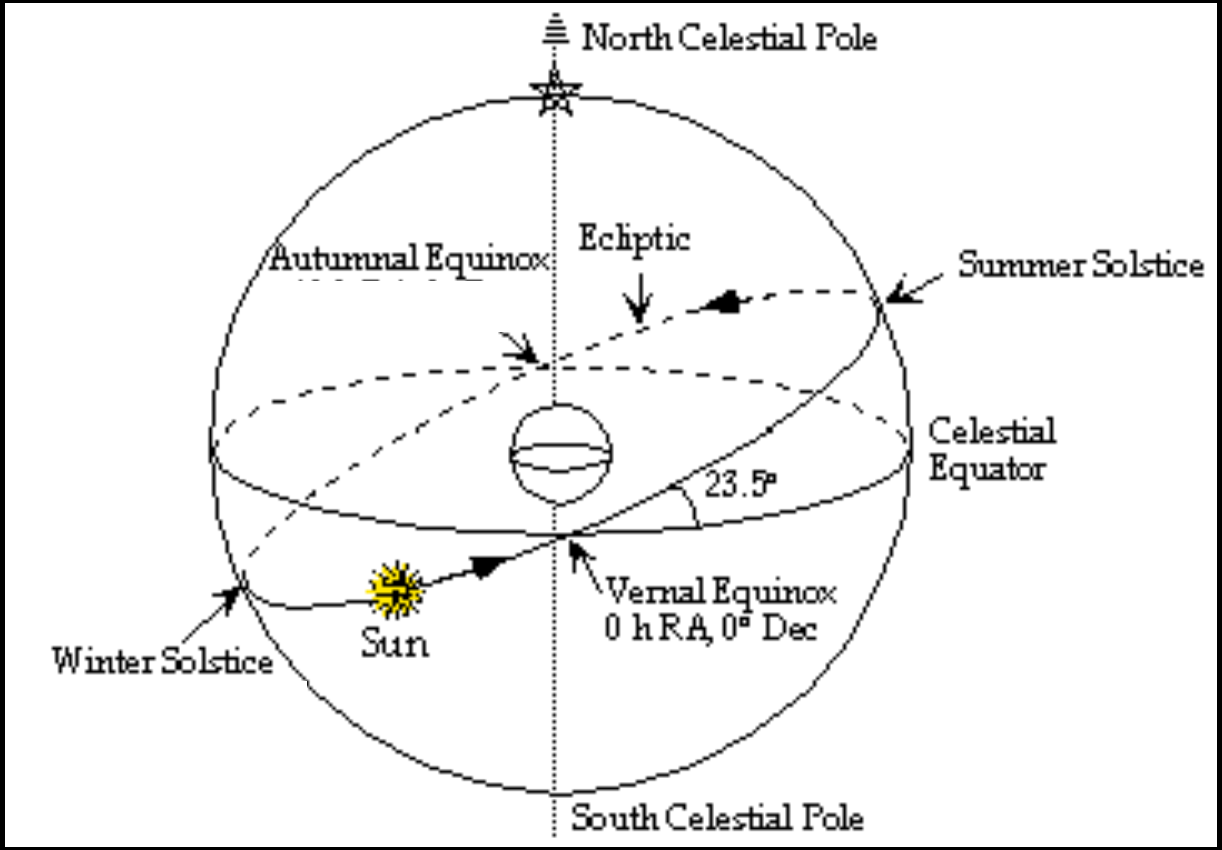

Vernal Equinox	March 20
Summer Solstice	June 22

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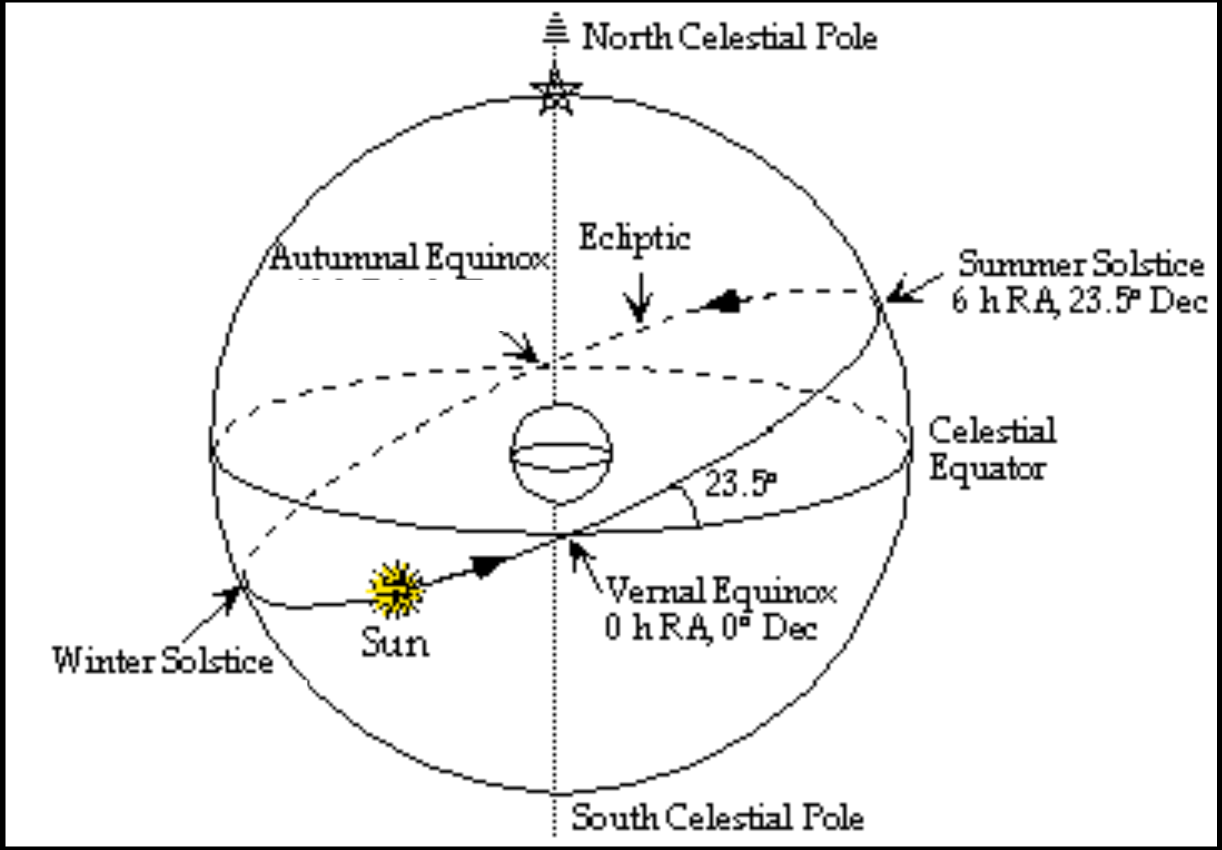

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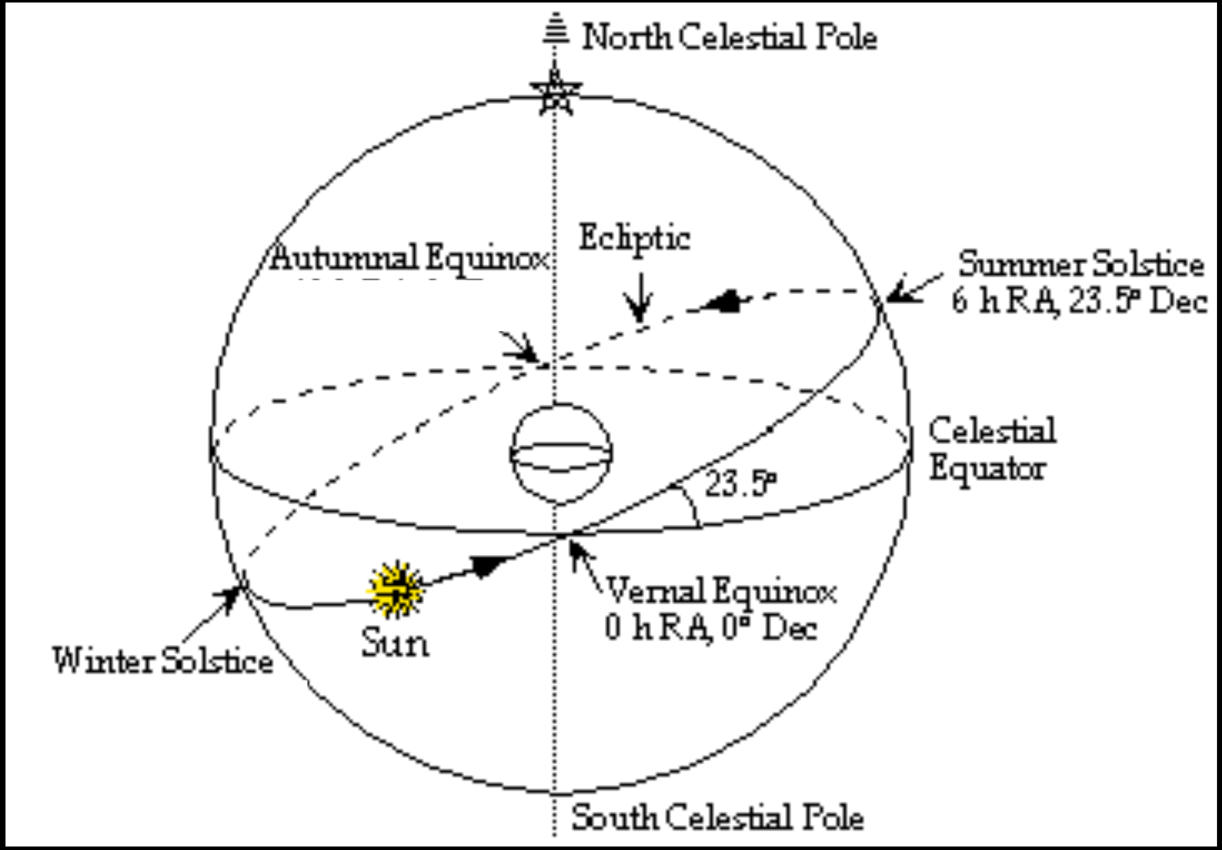

Vernal Equinox	March 20
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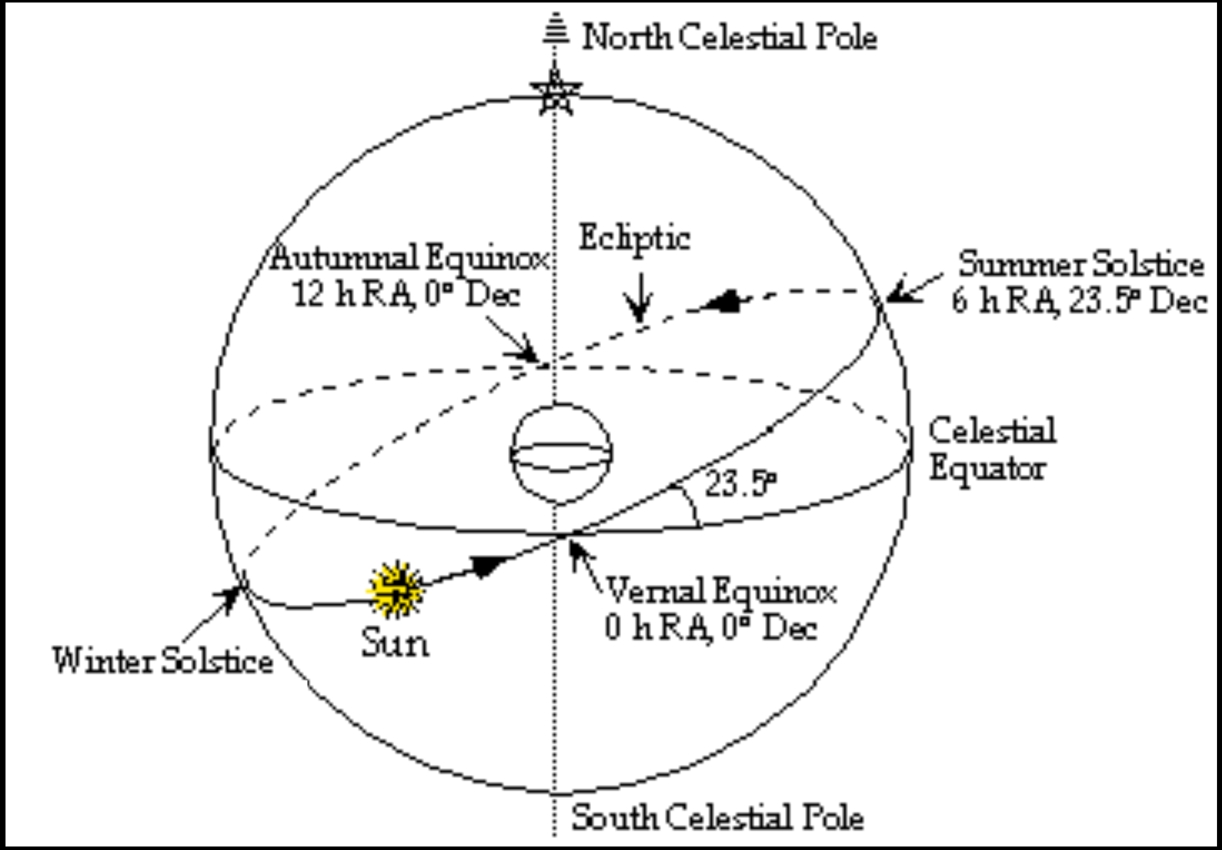

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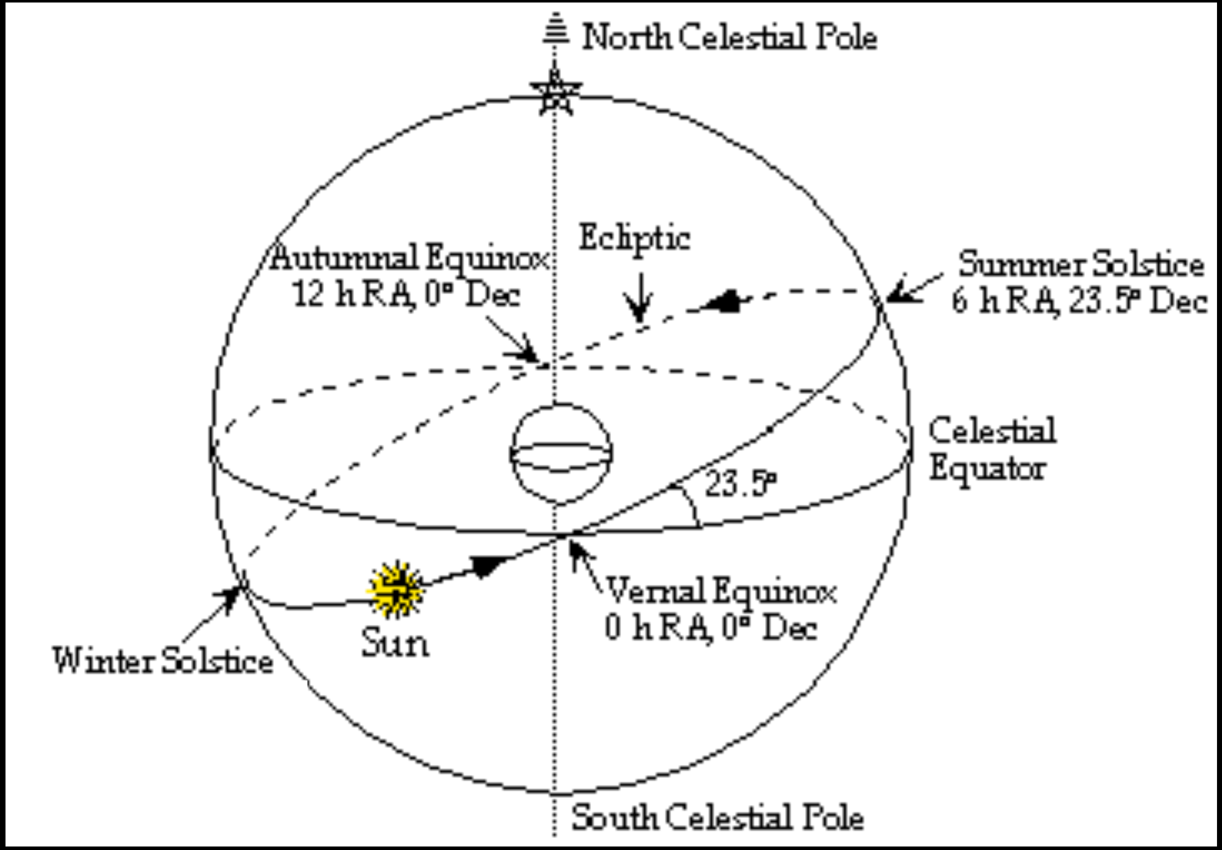

Vernal Equinox	March 20
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Autumnal Equinox	September 22
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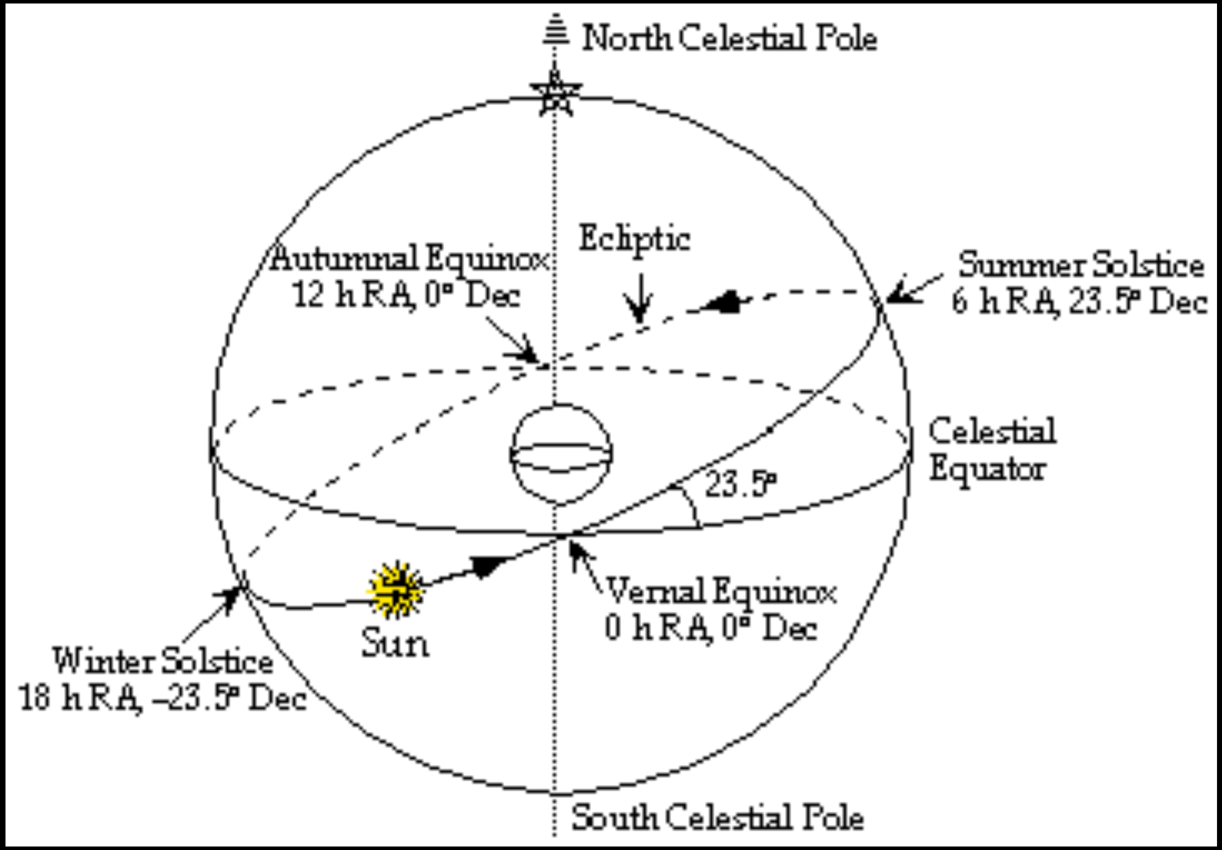

Vernal Equinox	March 20
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Winter Solstice	December 22

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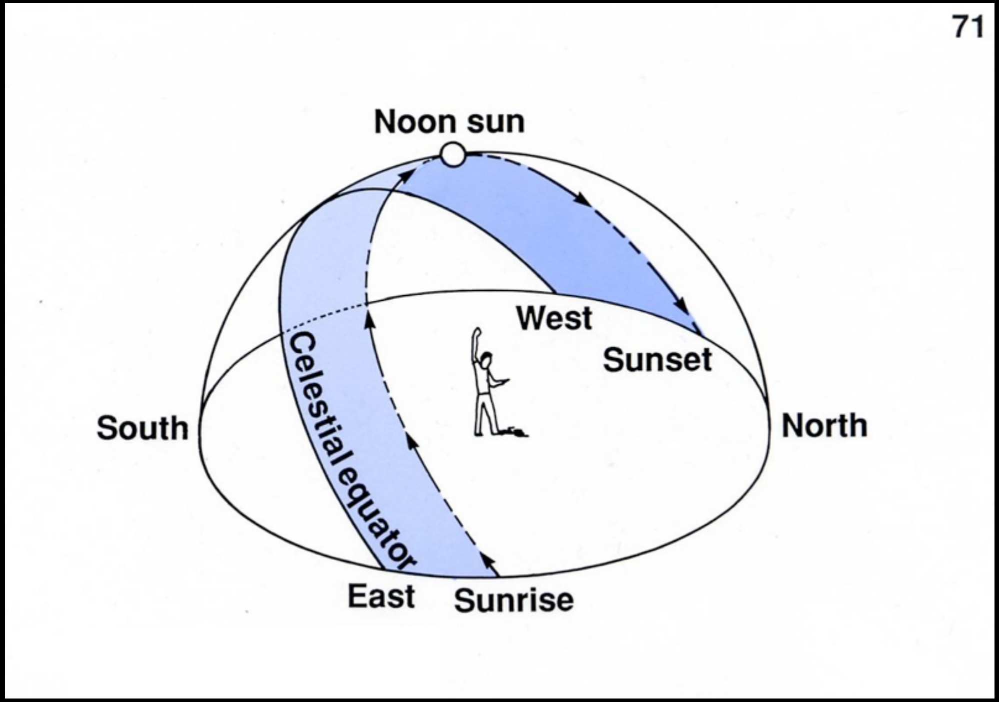
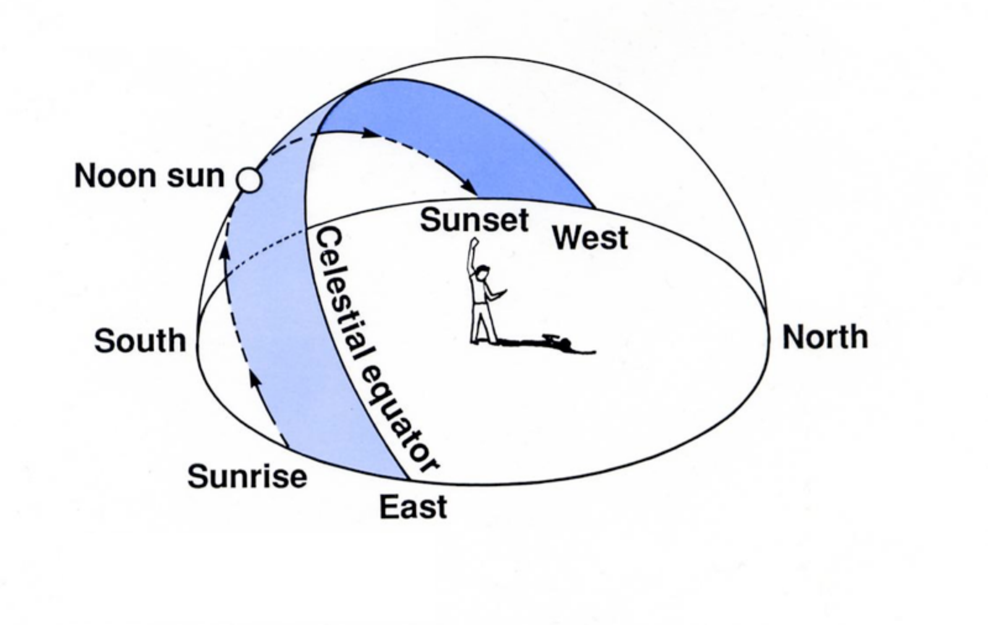


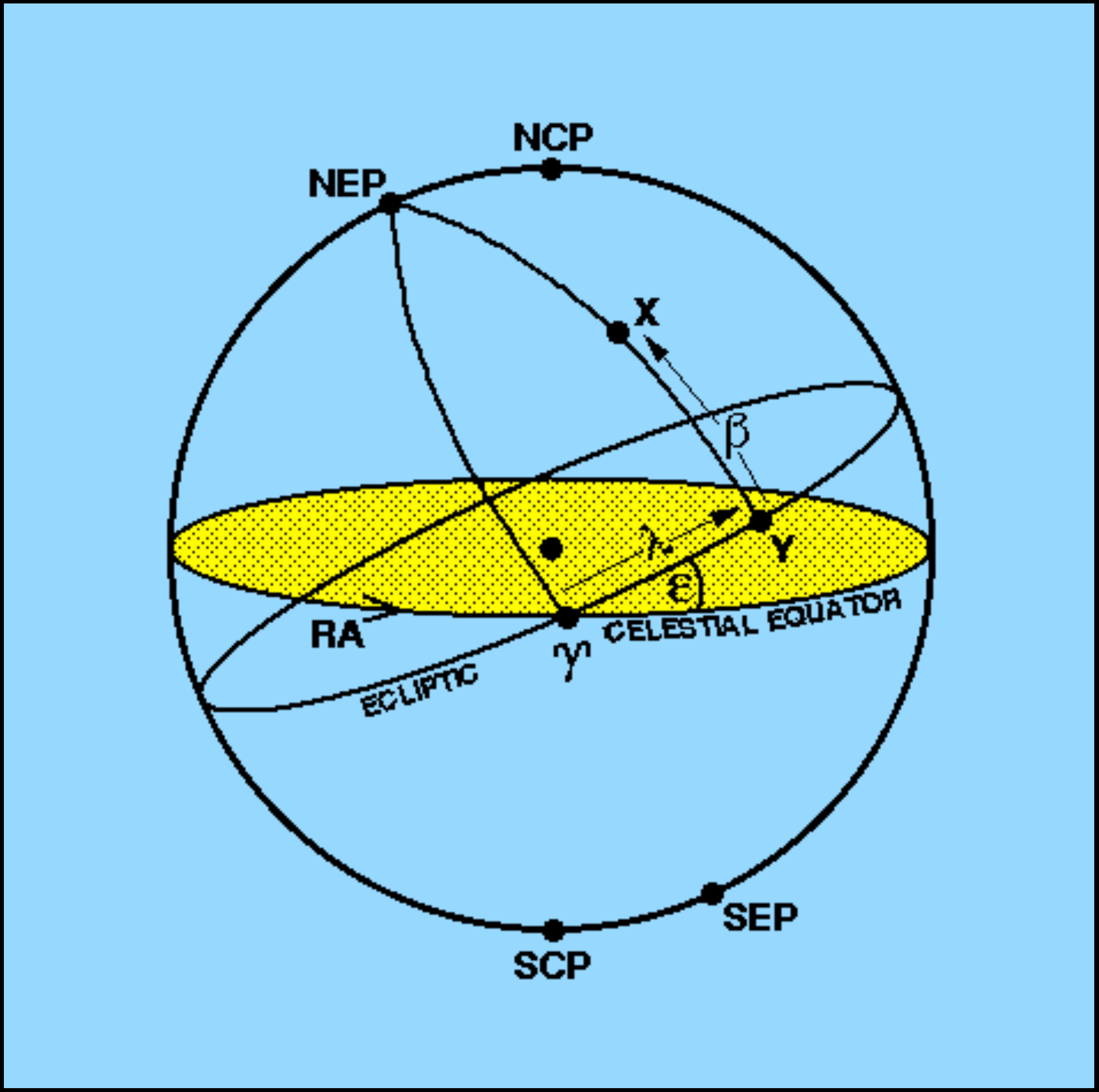


Paths of the Sun at summer and winter solstice

Seeds, Horizons, 3rd ed., Fig. 3-5; Foundations of Astronomy, 1990 ed., Fig. 2-15

Celestial Coordinates: The Ecliptic

Ecliptic coordinates, ecliptic longitude and latitude



Observer's coordinates and celestial coordinates

Examples relating observer's coordinates (altitude) with celestial coordinates (declination) for various latitudes on Earth. We consider only maximum altitudes.

Observer's Latitude	Altitude of North Celestial Pole (Az.=0)	Altitude of South Celestial Pole (Az.=180)	Altitude of Celestial Equator (Az.= 0 or 180)	Declination of North horizon	Declination of South horizon	Declination of Zenith
0 (Ecuador)	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
30 (Caribbean)	[redacted]	[redacted]	[redacted]	([redacted]es [redacted]	[redacted]	[redacted]
60 (Canada)	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
90 (North Pole)	[redacted]	[redacted]	(i.e[redacted]uals ce[redacted]or)	[redacted]	[redacted]	[redacted]

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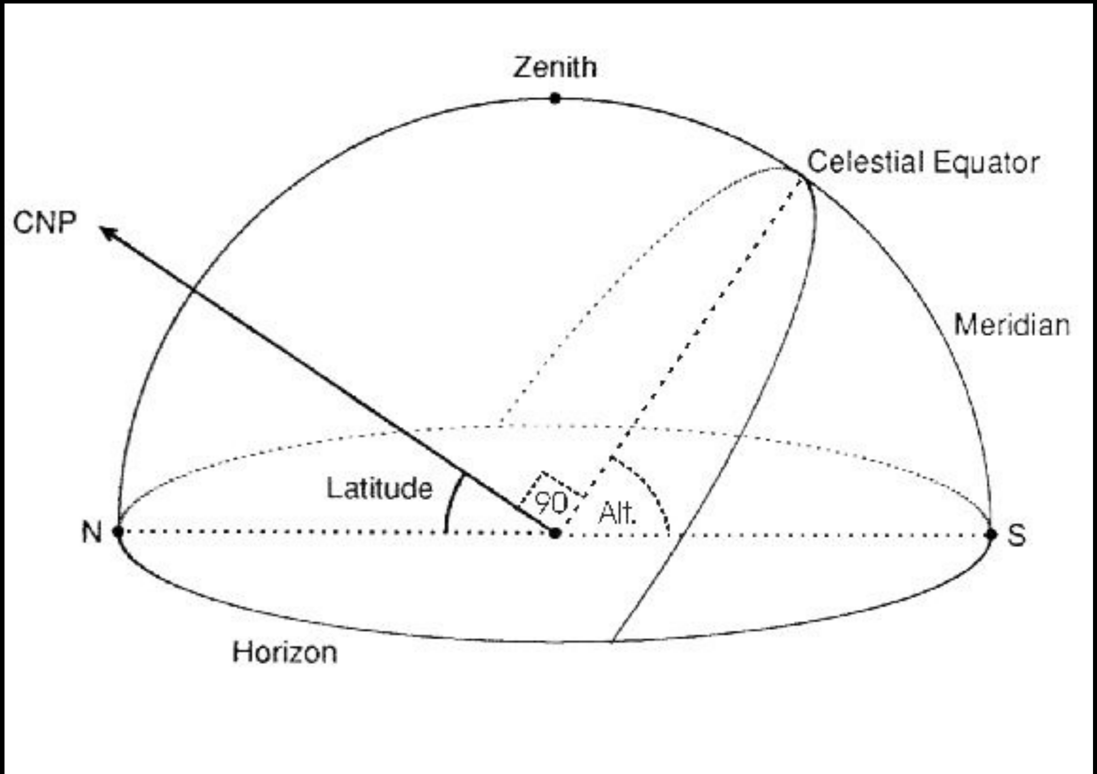
Observer's coordinates and celestial coordinates

Formulae that seem obvious from looking at the table:

- altitude of NCP = observer's latitude
- altitude of SCP = -(observer's latitude)
- max. altitude of celestial equator = 90 - (observer's latitude)
- Dec. of north horizon = 90 - (observer's latitude)
- Dec. of south horizon = -90 + (observer's latitude)
- Dec. of zenith = observer's latitude

- This works south of the equator also, but you have to switch all of the "norths" with the "souths".

The latitude/declination/altitude correspondences are always true, but longitude / right ascension correspondences depend on the hour of the day and also the season.



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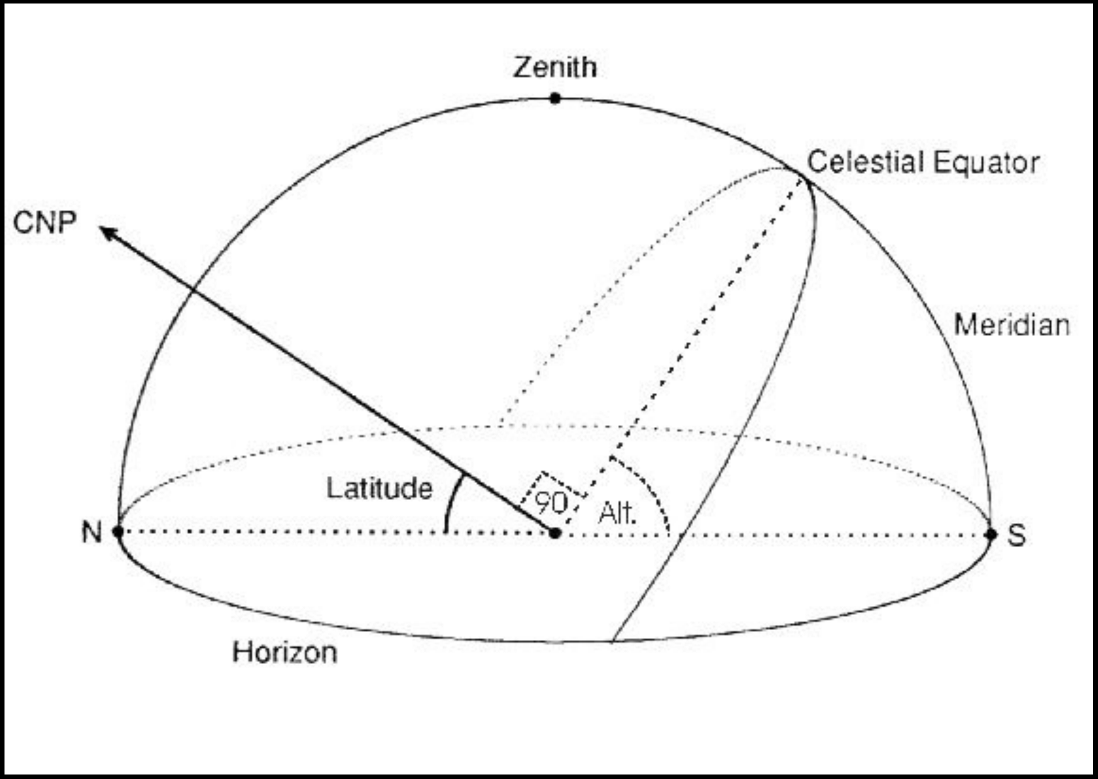
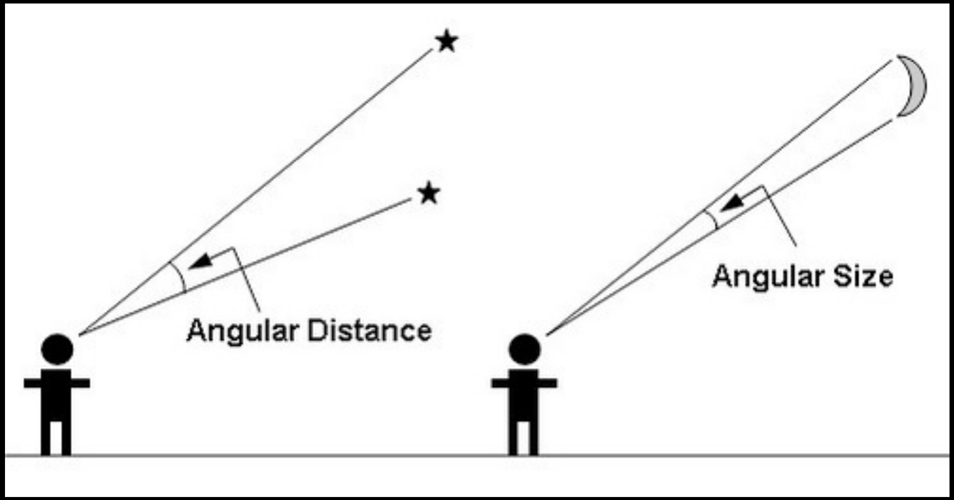


Scales and Angular Measurement

The apparent sizes of and distances between objects are described with **angular measurement**.



The system of angular measurement used by astronomers is based on divisions of the circle. The circle is divided into 360 degrees. Degrees are divided into 60 minutes of arc, or arc minutes, and each minute is divided into 60 arc seconds.

1° => 60' => 3600"

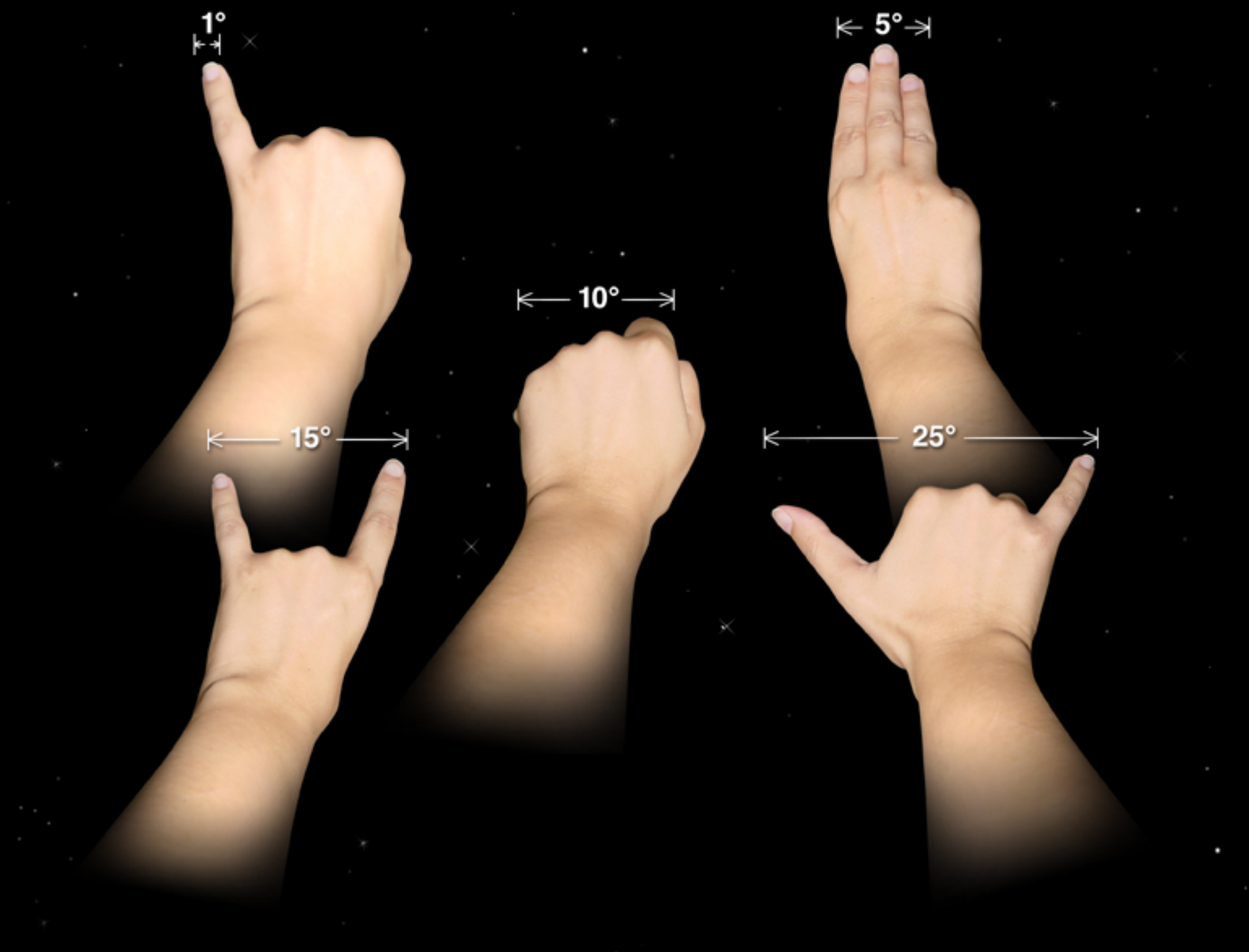
Because the Earth rotates it is possible to express longitude and R.A. in time or angular units:

360° => 24 hours
15° => 1 hour
1° => 4 minutes
1' => 4 seconds
1" => 1/15 of a second

24 hours => 360°
1 minute => 15'
1 second => 15"

Scales and Angular Measurement

In the field, angular distance on the sky can be estimated using your hands for reference



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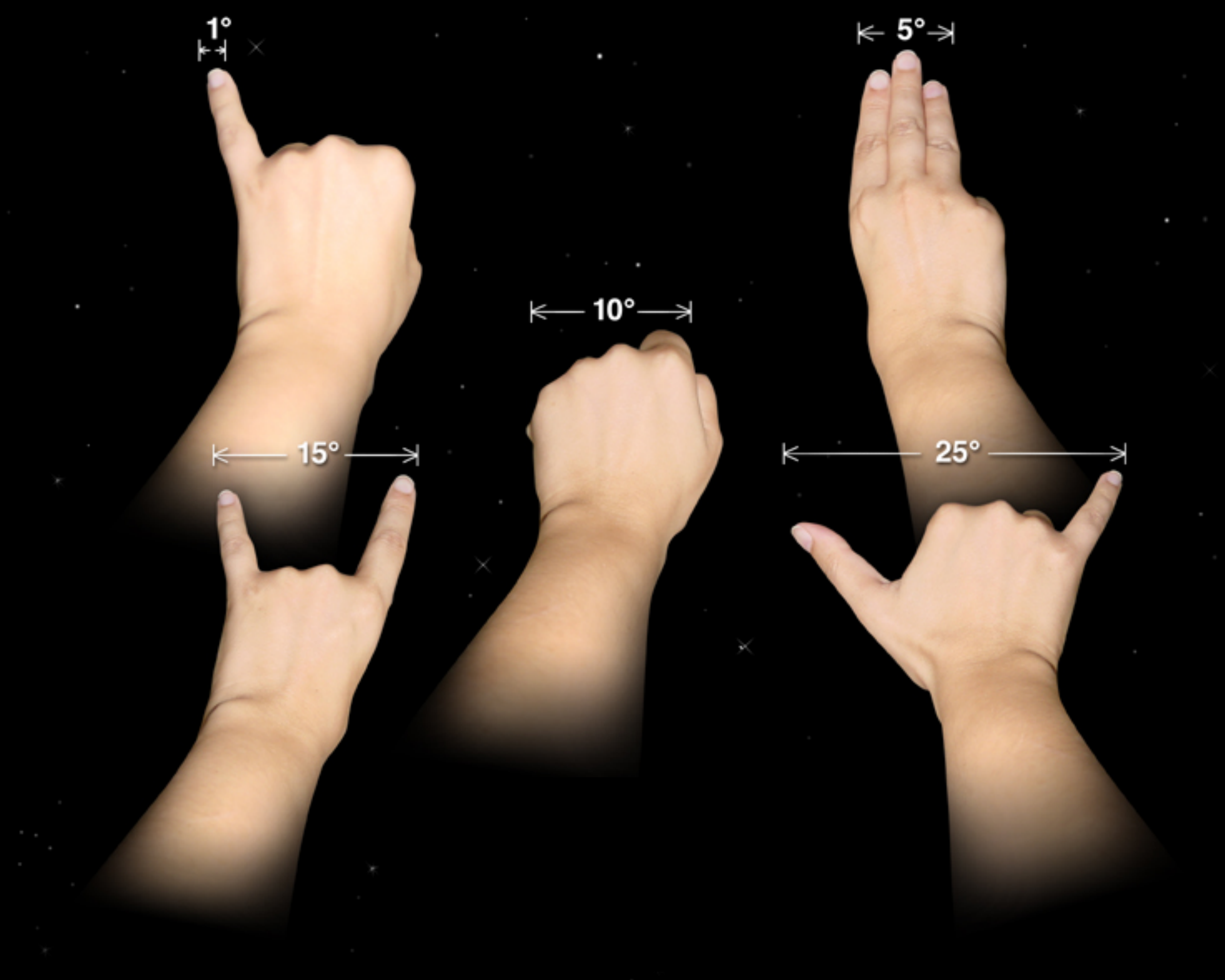

The Sun and the moon have angular diameters of about 0.5° or 30'

The Sun is 400 times larger than the moon. It is also 400 times more distant, so it appears to be the same size as the full moon; that is, it has the same angular size.

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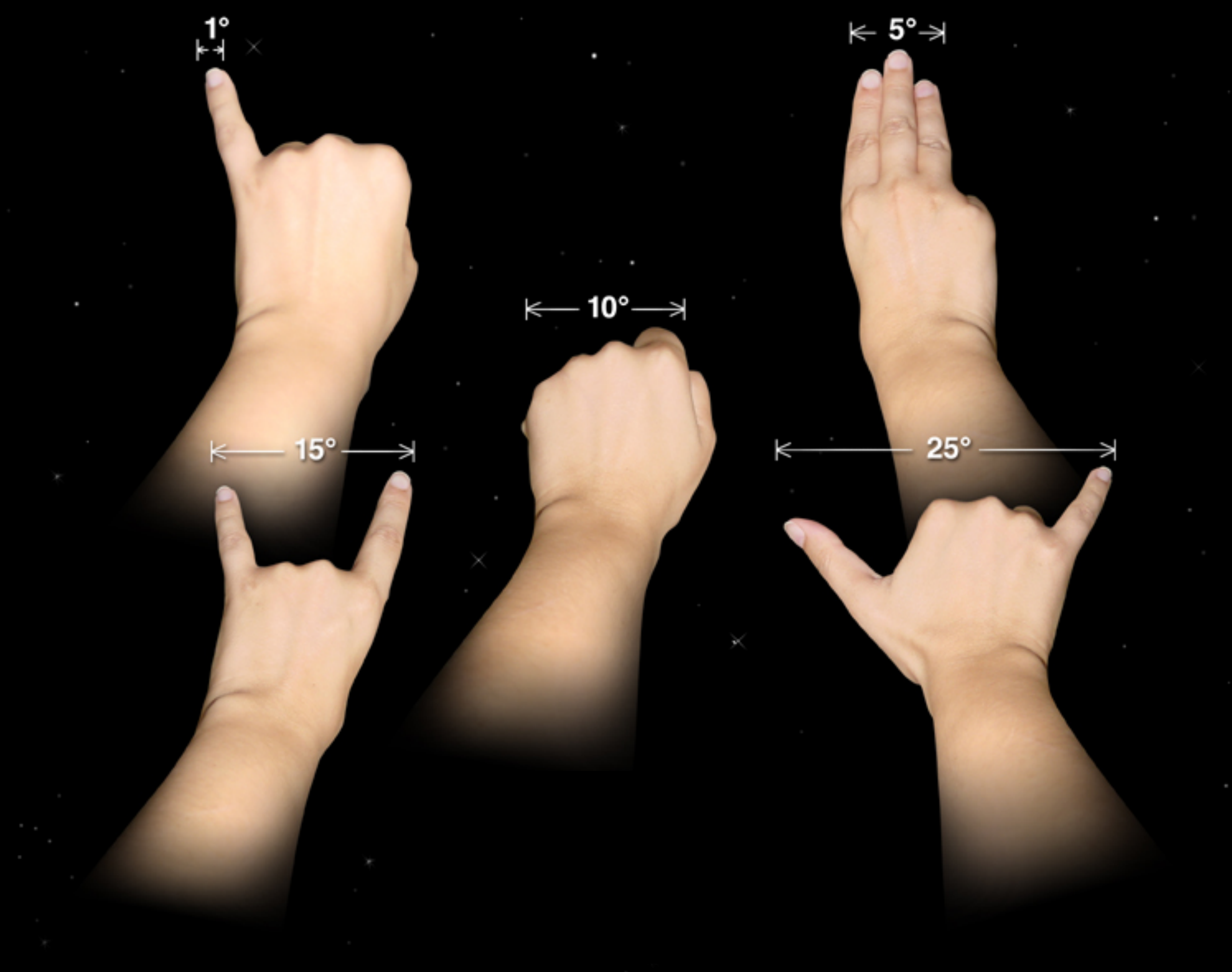

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The Sun is 400 times larger than the moon. It is also 400 times more distant, so it appears to be the same size as the full moon; that is, it has the same angular size.

People with keen eyesight can distinguish objects that are about an arc minute in diameter.

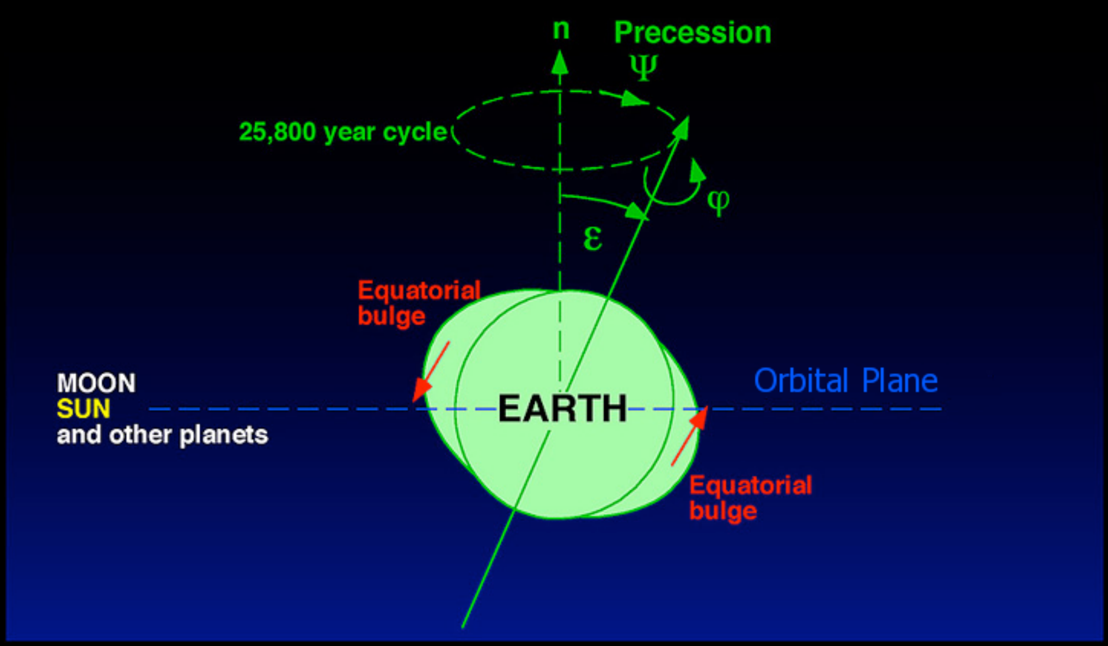
Precession

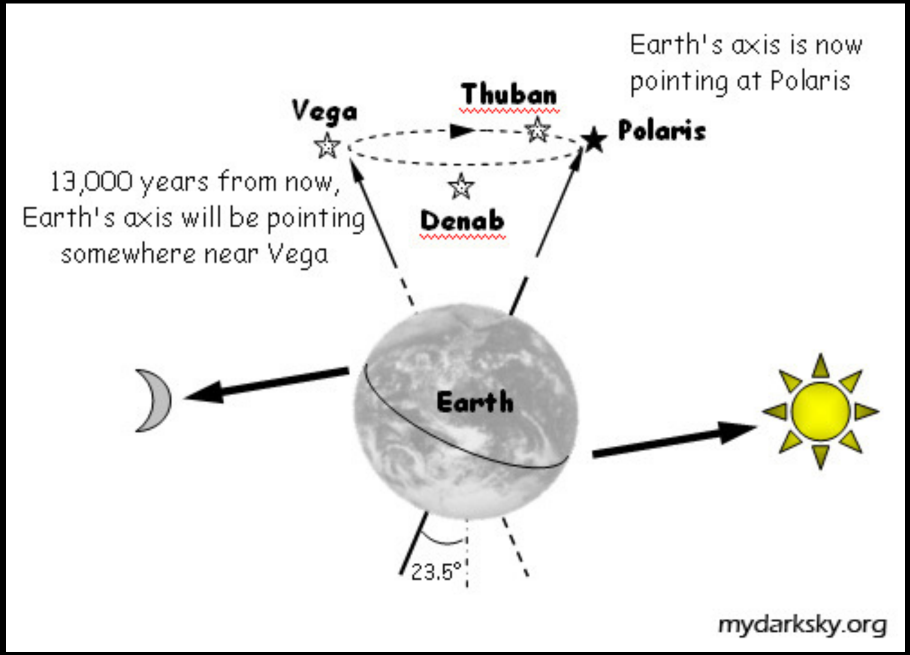
The R.A. and Dec. of celestial objects very inconveniently change with time.

The direction in which the Earth's axis points is changing, owing to tidal pull on the not quite spherical Earth => **Precession**

An **epoch** must be stated in respect of all R.A. and Dec. coordinates. Standard **epochs** for catalogues of objects were B1900, B1950 and **J2000**.

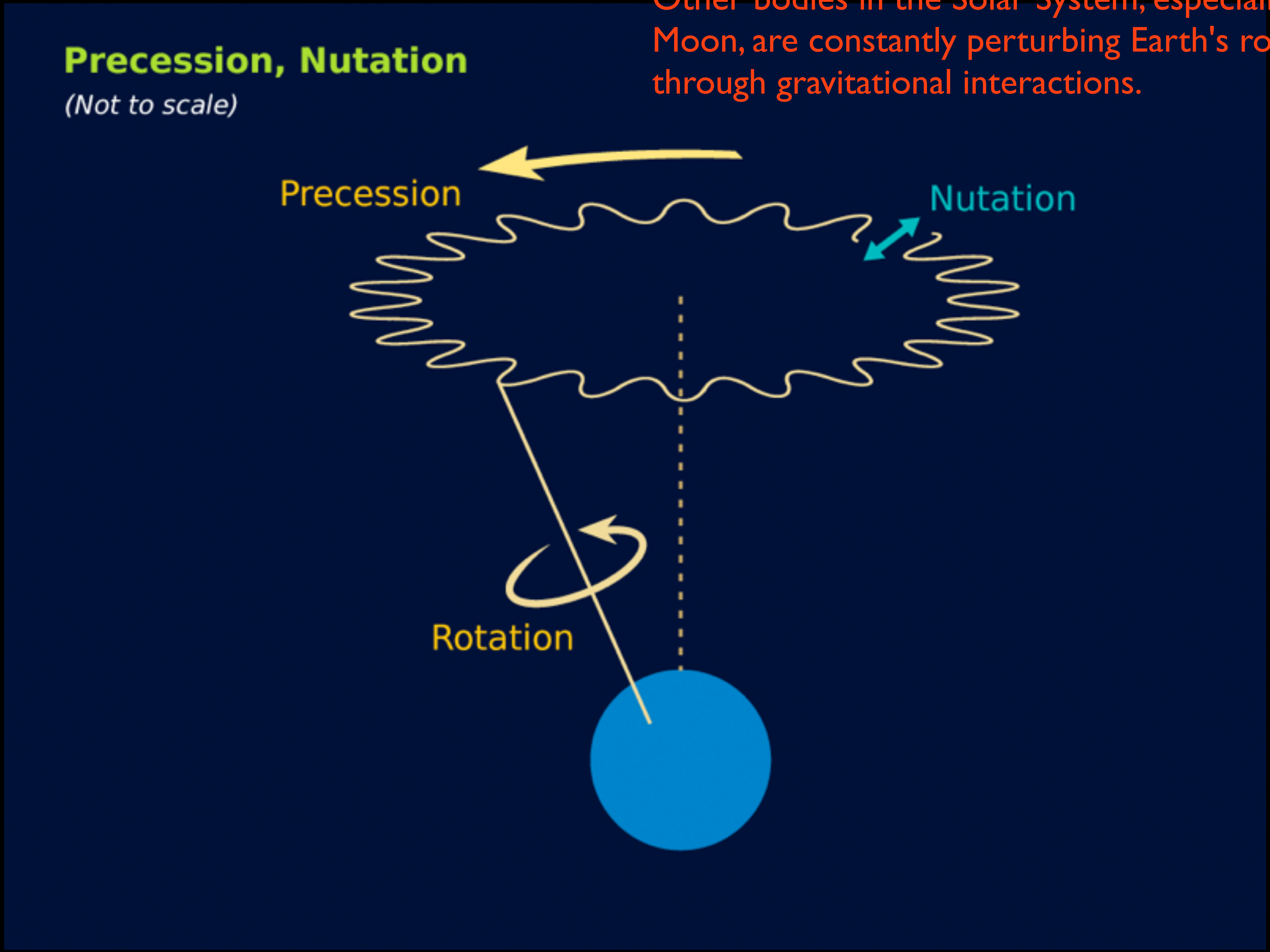
To get the current position of coordinates of an object in order to observe it, its coordinates must be **precessed** from the catalogue epoch to the date and time of observation.



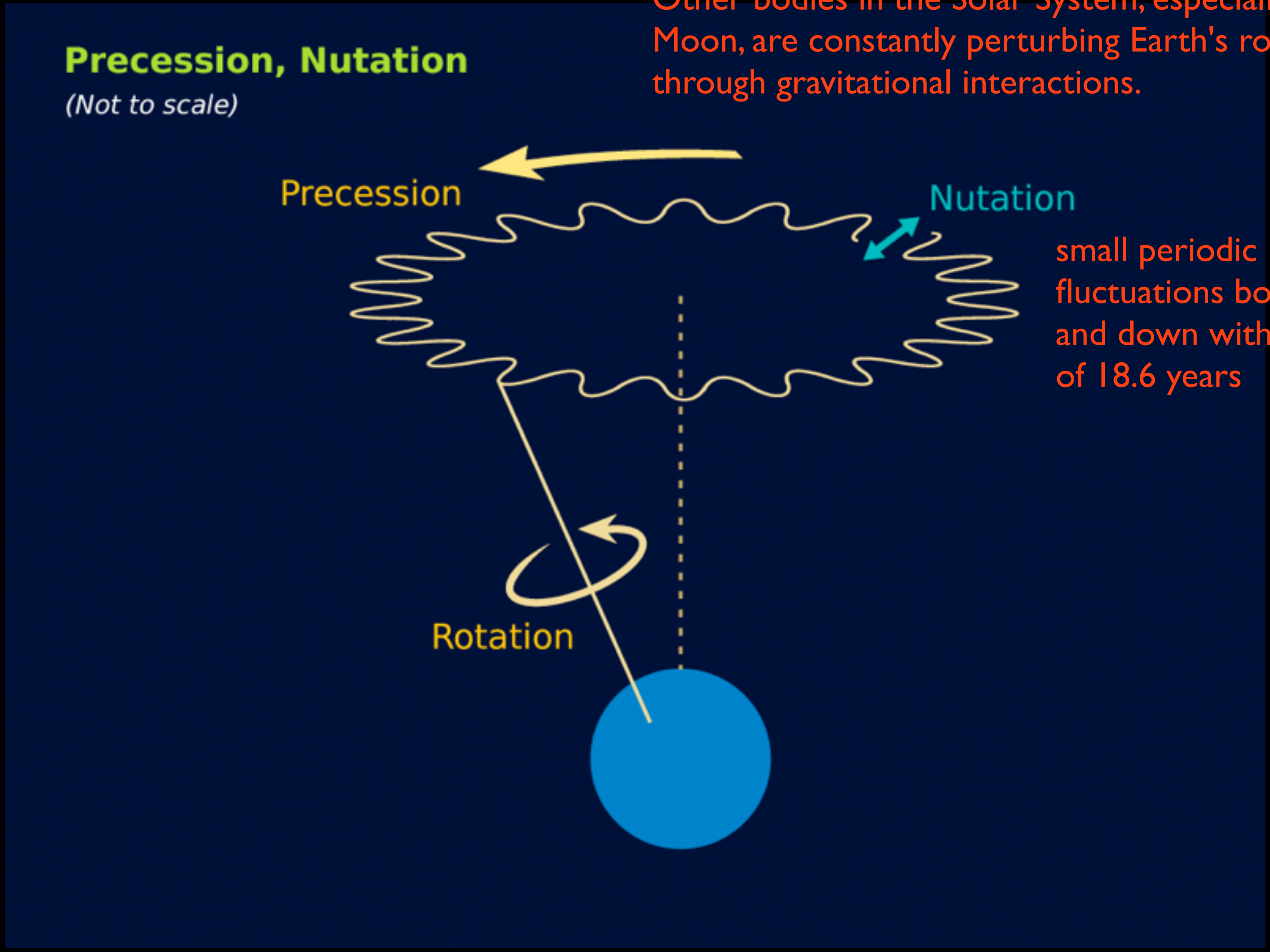


Precession, Nutation and Rotation

Other bodies in the Solar System, especially the Moon, are constantly perturbing Earth's rotation through gravitational interactions.



Precession, Nutation and Rotation



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small periodic fluctuations bobs up and down with a period of 18.6 years

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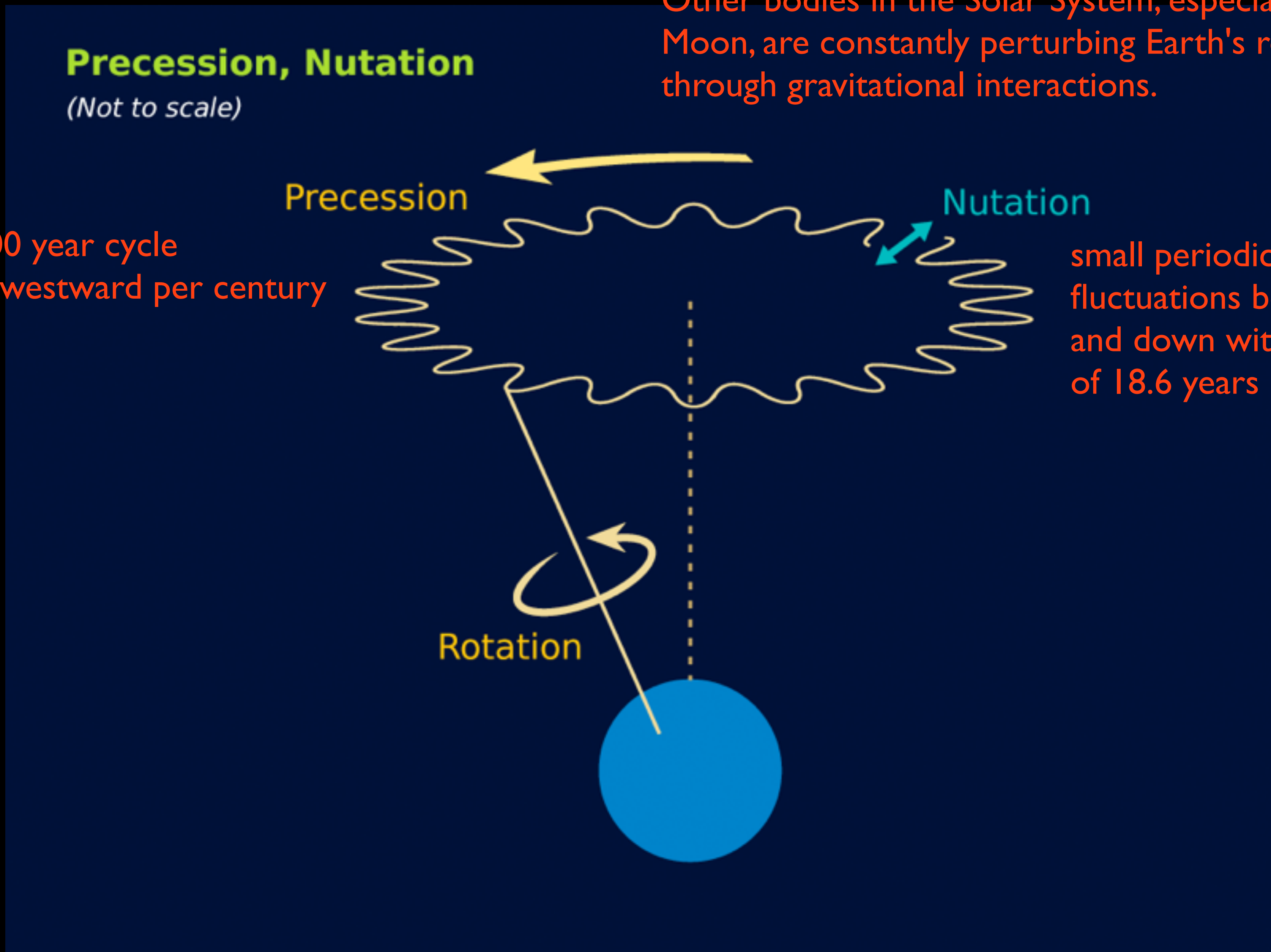

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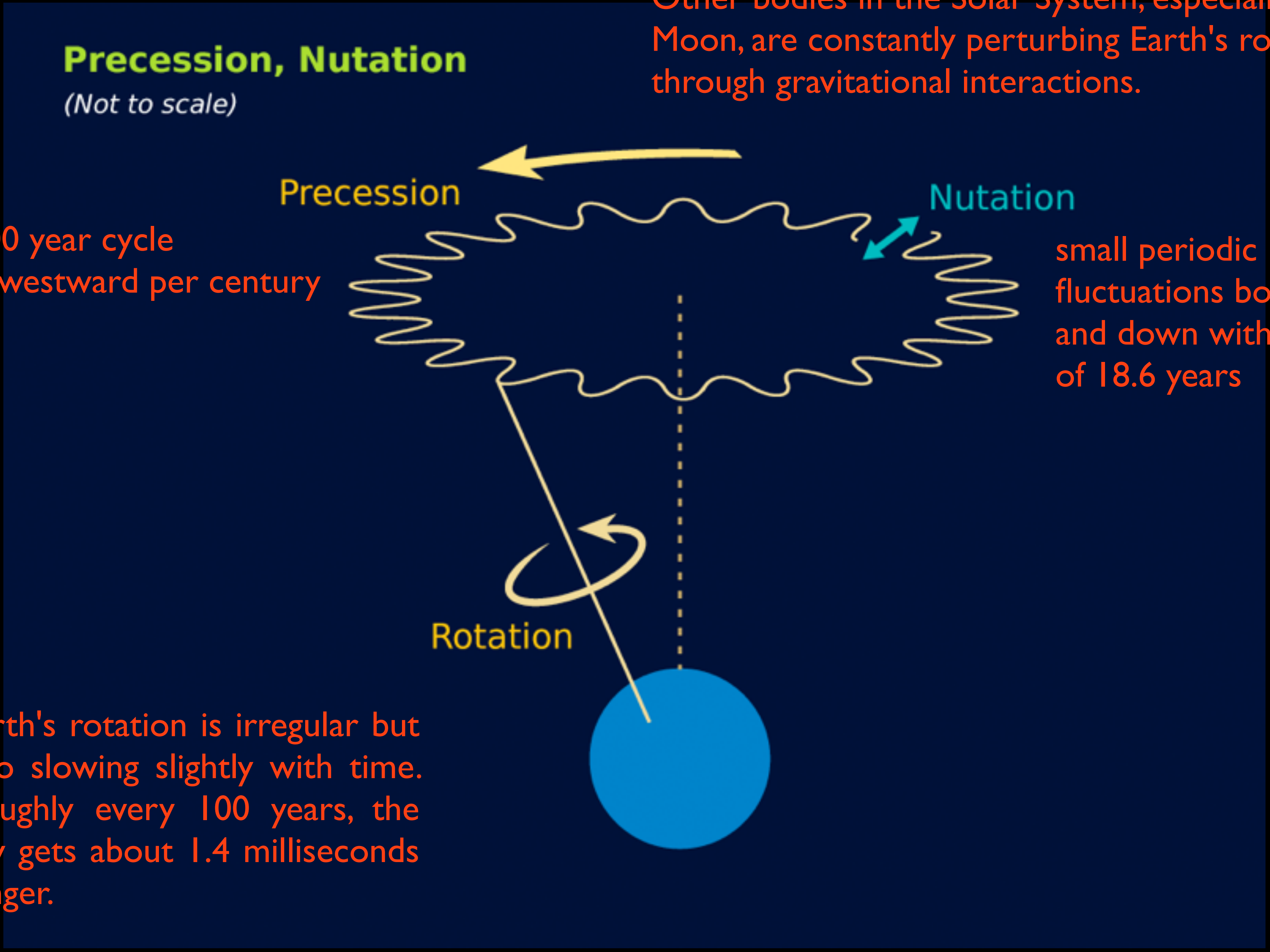


small periodic fluctuations bobs up and down with a period of 18.6 years

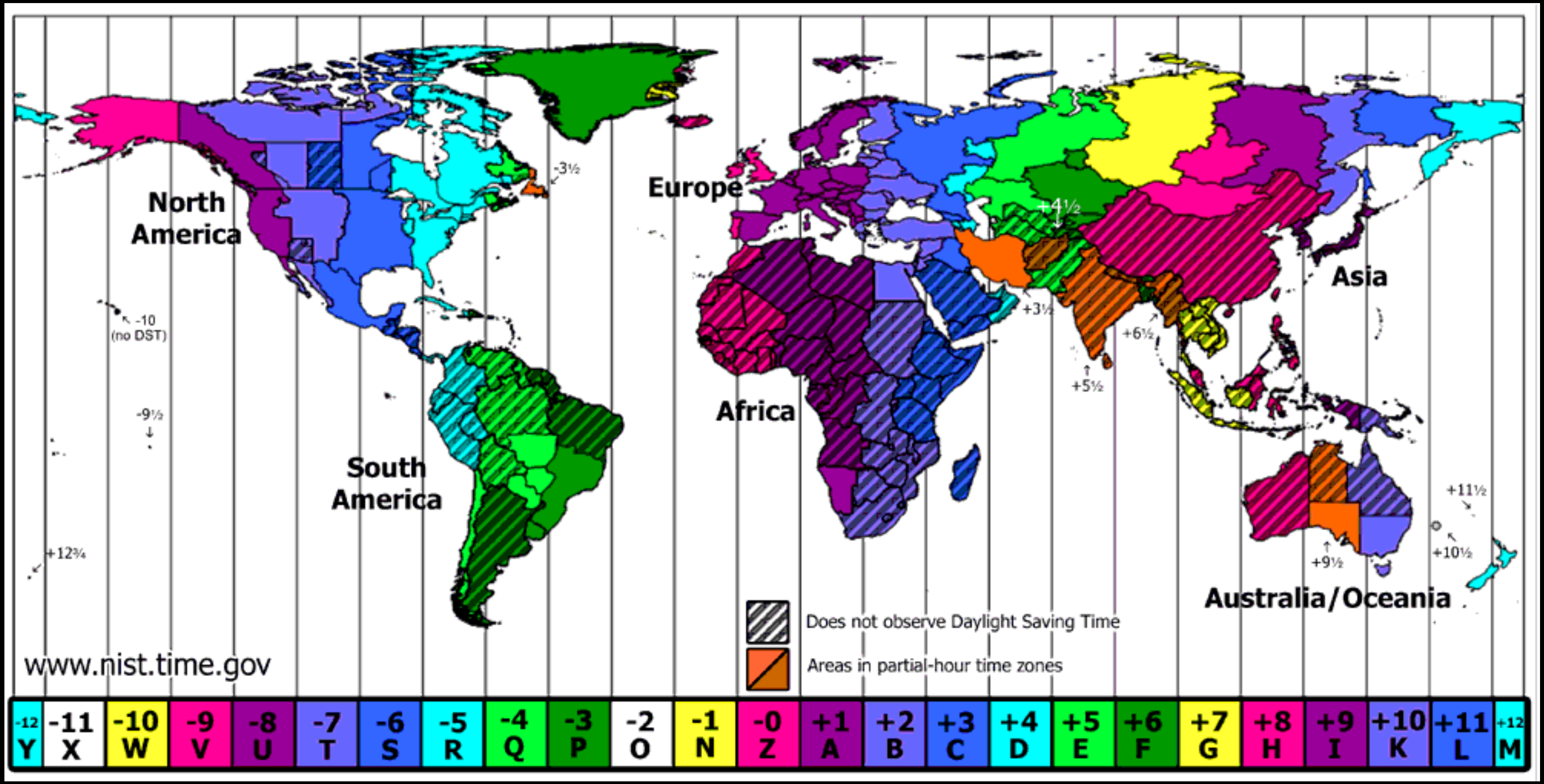
Earth's rotation is irregular but also slowing slightly with time. Roughly every 100 years, the day gets about 1.4 milliseconds longer.

Time

Universal Time Coordinated (UTC) is the common time standard across the world and is kept using highly precise atomic clocks.

The world is divided into Time Zones => 15° change in longitude is equal to an hour's change in time.
Greenwich Mean Time (GMT) => time zone that corresponds to UTC.

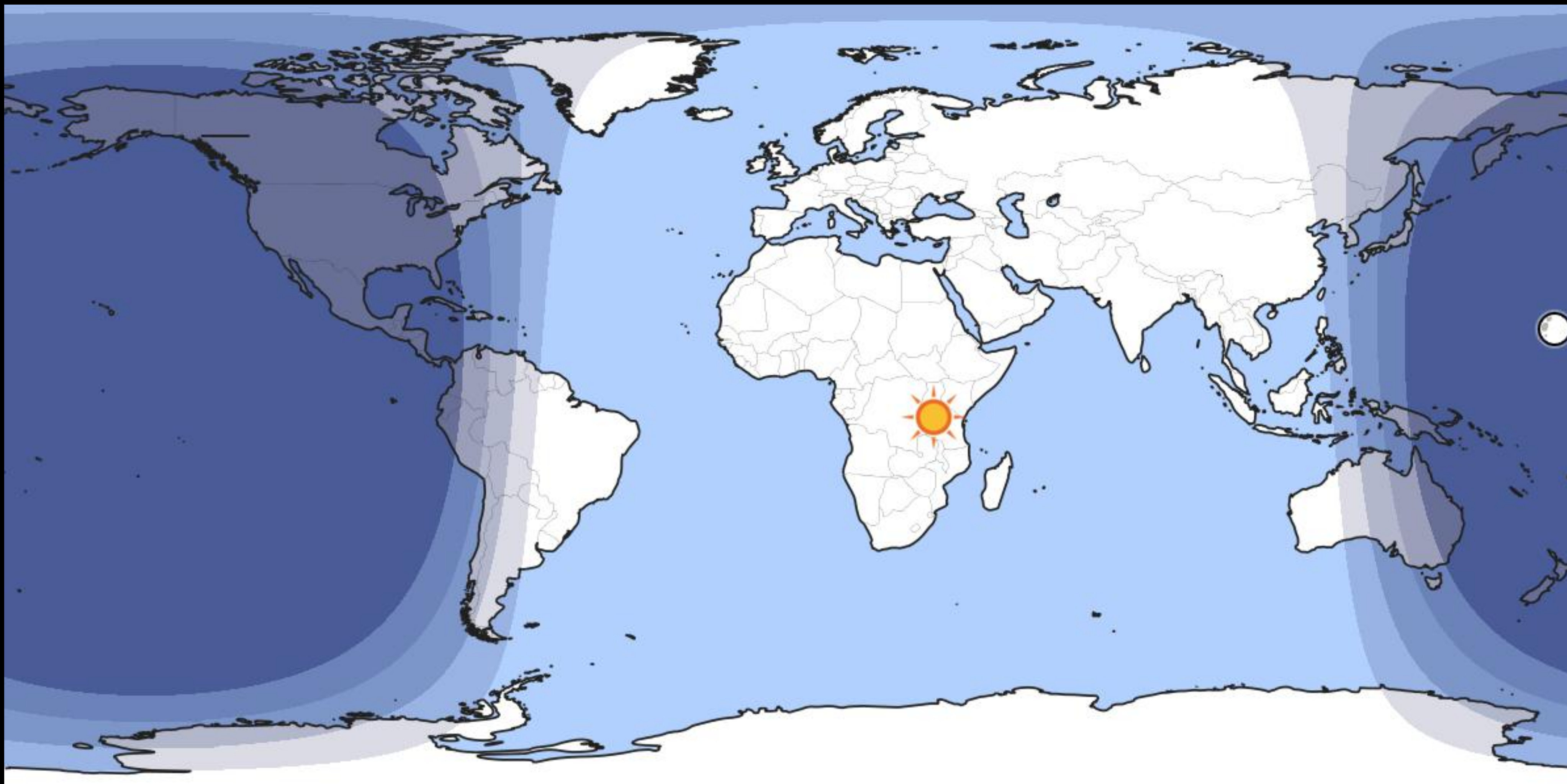
South Africa is roughly 30° east of Greenwich, and so South African Standard Time (SAST) is set to be 2 hours ahead of UTC.



Time

6:05 AM
8:27 PM
San Francisco, CA, United States
Tuesday, July 22, 2014
Jan 1
Dec 31
5:24 AM
12:00 AM
11:59 PM

Time



Perfect Time' ing

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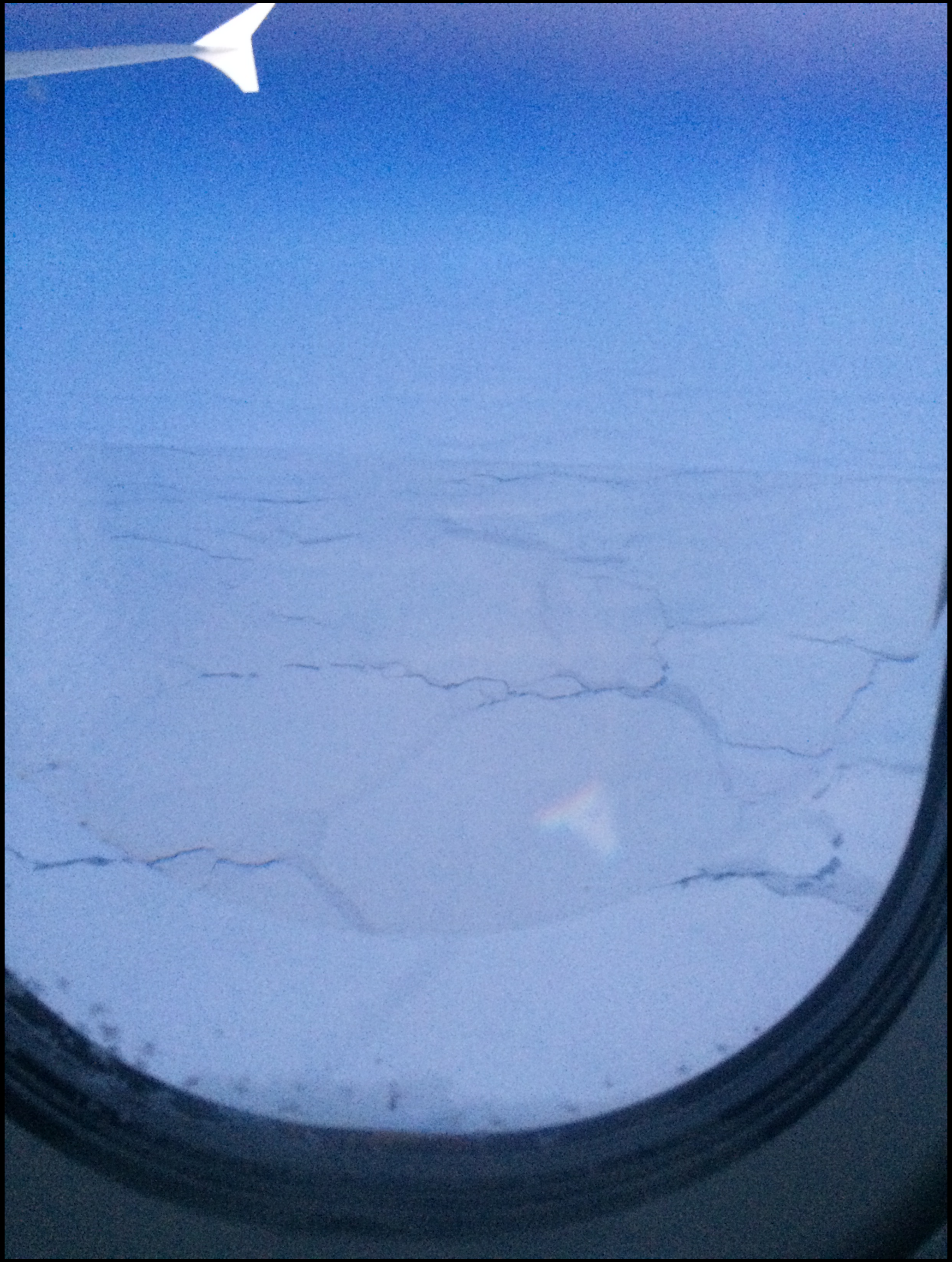

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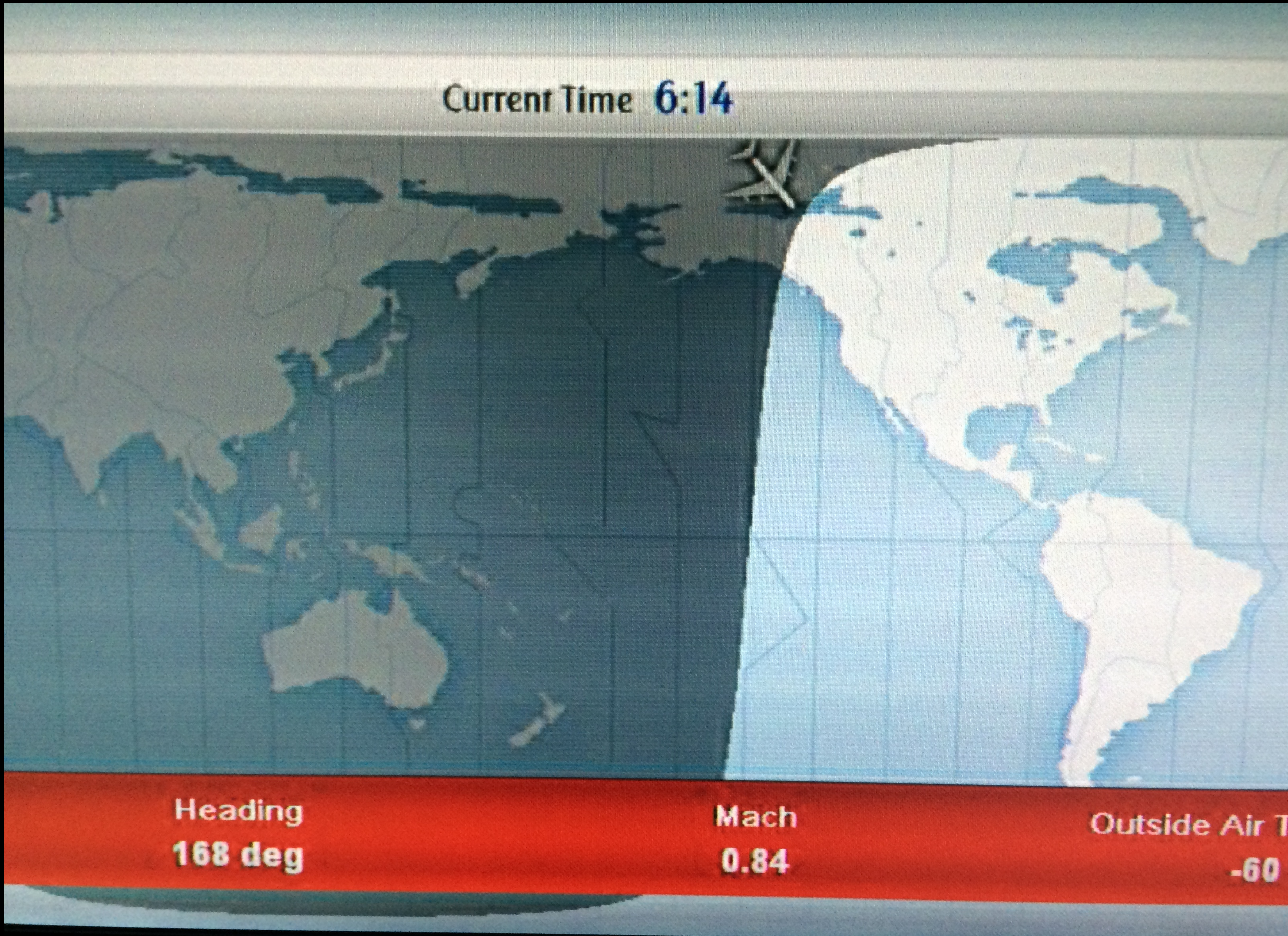
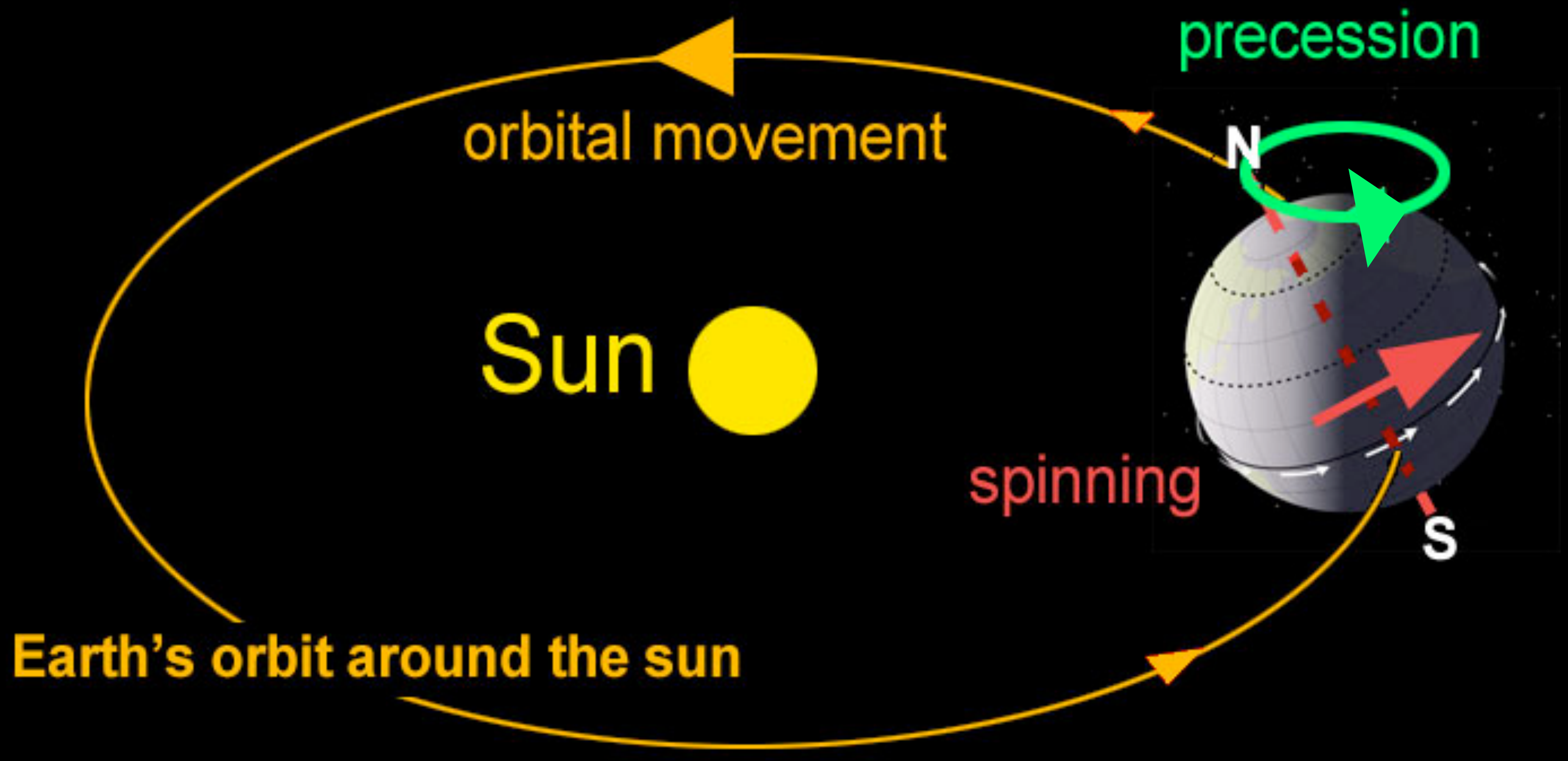


Perfect Time’ ing

Time

One **"year"** is technically the Earth's **"tropical period"** => the time that elapses between two alignments of its axis of rotation with the Sun, or 365.242 days.

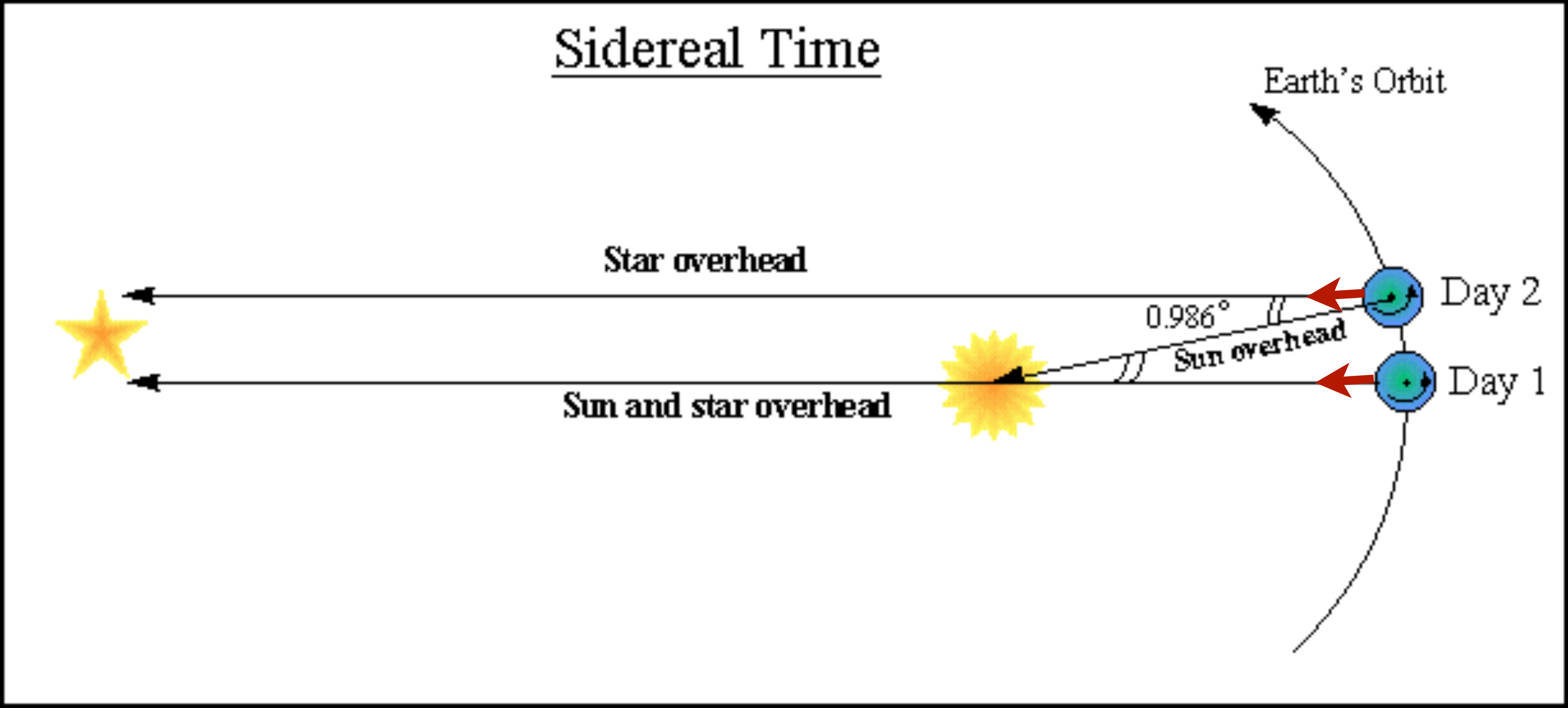
The Earth's **orbital (sidereal) period** around the Sun is 365.256 days. The 0.014 day (= 20 minutes) difference is caused by **precession.**



Time

Solar time is time measured with respect to the Sun's apparent motion in the sky, caused by the rotation of the Earth. So, our clocks measure the length of time (24 hours) required for the Earth to rotate once with respect to the Sun. This period is known as a **solar day**.

Sidereal time is time measured with respect to the apparent motion of the 'fixed' stars in the sky due to the Earth's rotation. While the Earth is rotating on its axis it is also moving along its orbit around the Sun. From our perspective, the Sun moves about one degree from west to east with respect to the 'fixed' stars.



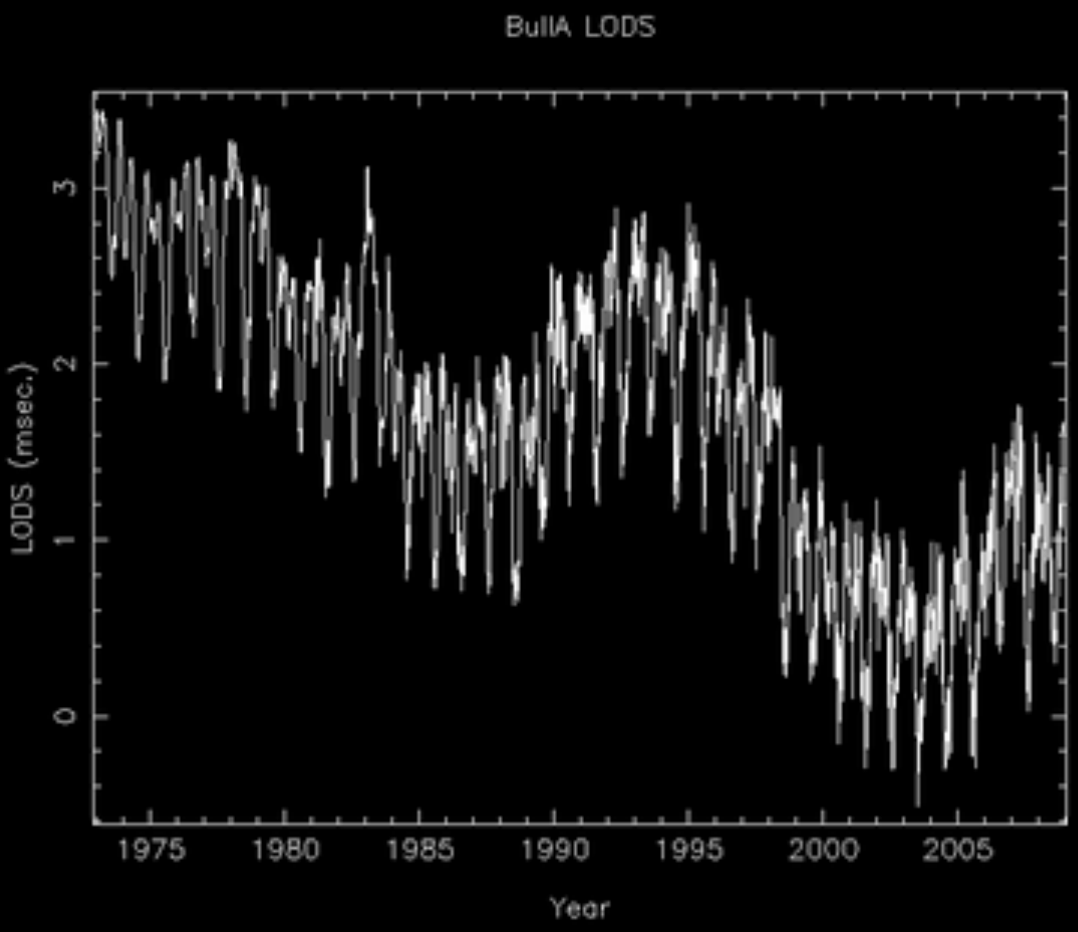
Time

According to our clocks, which are based on solar time, a given star will rise or set about four minutes earlier each day (1 degree of rotation = 4 minutes of time). For example, a star that rises at 9:00pm tonight will rise at 8:56pm tomorrow. One month later that star will rise or set 2 hours earlier. From our perspective, the stars revolve around the Earth in only 23 hours 56 minutes and 04 seconds => **sidereal day**

Time

To point our telescopes we have to make allowance for the actual, irregular period of the Earth. **UT1** is the time scale used to measure this. Leap seconds are inserted in **UTC** at intervals to keep **UTC** and **UT1** within 0.9 of a second.

Measuring the changing length of day is done by a global network of radio telescopes using quasars far out in the universe as fixed beacons. The HartRAO 26m telescope is part of this network.



The difference between the rotationally determined length of day and 24 hours of UTC time, otherwise known as the excess length of day (in milliseconds per day).

Time

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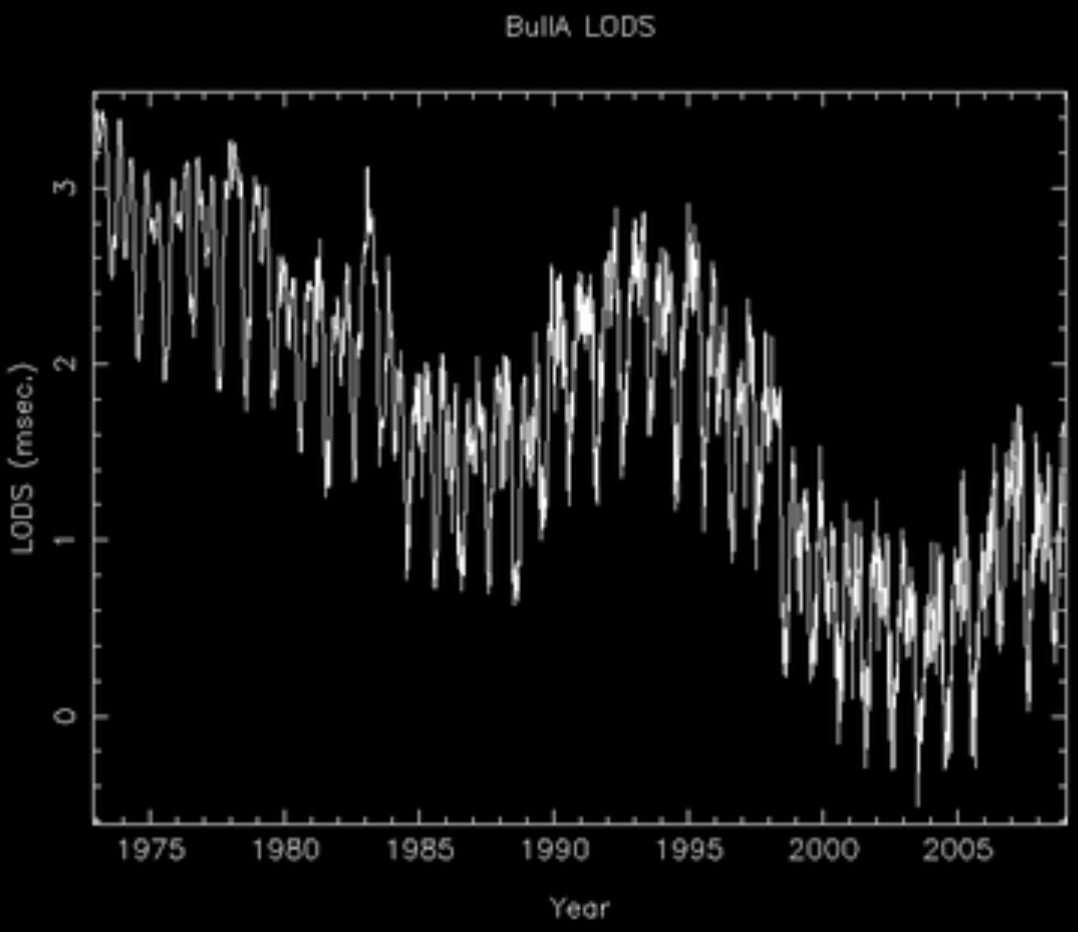

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                                   Bulletin C 52

To authorities responsible for the measurement and distribution of time


                         UTC TIME STEP
                  on the 1st of January 2017


A positive leap second will be introduced at the end of December 2016.
The sequence of dates of the UTC second markers will be:

                    2016 December 31, 23h 59m 59s
                    2016 December 31, 23h 59m 60s
                    2017 January   1,  0h  0m  0s

The difference between UTC and the International Atomic Time TAI is:

 from 2015 July 1, 0h UTC, to 2017 January 1 0h UTC   : UTC-TAI = - 36s
 from 2017 January 1, 0h UTC, until further notice    : UTC-TAI = - 37s


Leap seconds can be introduced in UTC at the end of the months of December
or June, depending on the evolution of UT1-TAI. Bulletin C is mailed every
six months, either to announce a time step in UTC or to confirm that there
will be no time step at the next possible date.
```

Using Sidereal Time

As with longitude like coordinates, a zero point has to be set for **sidereal time** => **Greenwich Mean Sidereal Time (GMST)** => it is the elapsed time since the zenith meridian transit of the vernal equinox at the Greenwich meridian.

Local Mean Sidereal Time (LMST) => current **GMST** plus the observers longitude (East longitude is positive), converted from degrees to hours.

$$\mathrm{LMST[h]} = \mathrm{GMST[h]} + \mathrm{Longitude}[^\circ] / 15$$

A small correction (< 1.15 s) for nutation is added (18.6 yr period) => **Local Apparent Sidereal Time (LAST)** = R.A. of all bodies currently crossing the observers **zenith meridian**.
(Sidereal time is some 0.0084 seconds shorter due to precession)

Hour Angle (HA) is the angle of an object east or west of the observers **zenith meridian**.

$$\mathrm{HA} = \mathrm{LST} - \mathrm{RA}$$

A negative HA => time until object crosses the zenith meridian
A positive HA => time since it has crossed the zenith meridian

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http://www.hartrao.ac.za/hart_lst.html, http://www.jgiesen.de/astro/astroJS/siderealClock/

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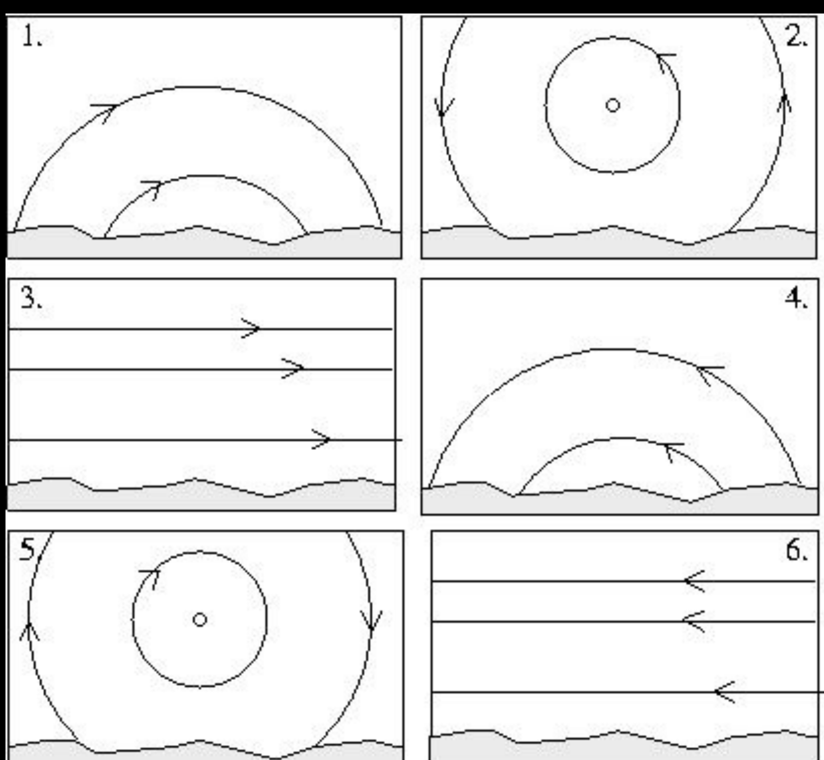
Effects of Earth’s Rotation

Stars and other celestial bodies appear to rotate around the celestial poles => move along circles of constant declination in the co-rotating equatorial system.

Stars will cross the local meridian twice a day (**transits**) => **upper and lower transits**

These events also mark the maximal and minimal altitude the objects can reach and in the observer’s sky and may both take place above or below the horizon, depending on the Dec of the object and geographical latitude of the observer.



Objects with lower transits above the horizon will never set => circumpolar.

http://www.astronomynotes.com/nakedeye/s4.htm


Thank you !!