SECTION I.
THE ENVIRONMENT OF SPACE

Chapter 1. The Solar System

Objectives: Upon completion of this chapter you will be able to state distances of objects within the solar system in terms of light-time, describe the sun as a typical star, relate its share of the mass within the solar system, and compare the terrestrial and jovian planets. You will be able to distinguish between inferior and superior planets, describe asteroids, comets, and the Oort cloud. You will be able to describe magnetic fields, particle and radiation environments in planetary vicinities and interplanetary space.

The solar system has been a topic of study from the beginning of history. For nearly all that time, people have had to rely on long-range and indirect measurements of its objects. At first, almost all observations were based on visible light and, later, on radio waves received here on Earth from the objects under investigation. However, with the emergence of space flight, instruments can be sent to many solar system objects to measure their physical properties and dynamics directly and at close range. With the data collected from these measurements, knowledge of the solar system is advancing at an unprecedented rate.

The solar system consists of an average star we call the sun, the planets Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto. It includes the satellites of the planets, numerous comets, asteroids, meteoroids, and the interplanetary medium. The sun is the richest source of electromagnetic energy in the solar system. The sun's nearest known stellar neighbor is a red dwarf star called Proxima Centauri, at a distance of 4.3 light years away (a light year is the distance light travels in a year, at the rate of 299,792 km per second). The whole solar system, together with the local stars visible on a clear night, orbits the center of our home galaxy, a spiral disk of 200 billion stars we call the Milky Way. The Milky Way has two small galaxies orbiting it nearby, which are visible from the southern hemisphere. They are called the Large Magellanic Cloud and the Small Magellanic Cloud. Our galaxy, one of billions of galaxies known, is travelling through intergalactic space. On a cosmic scale, all galaxies are receding from each other. Galaxies relatively close together may exhibit motion toward or away from each other on a local scale.

The planets, most of the satellites of the planets, and the asteroids revolve around the sun in the same direction, in nearly circular orbits. The sun and planets rotate on their axes. The planets orbit the sun in or near the same plane, called the ecliptic. Pluto is a special case in that its orbit is the most highly inclined (17 degrees) and the most highly elliptical of all the planets. Because of this, for part of its orbit, Pluto is closer to the sun than is Neptune.

Distances Within the Solar System

The most common unit of measurement for distances within the solar system is the astronomical unit (AU). One AU equals the mean distance from the sun to Earth, about 150,000,000 km. JPL refined the precise value of the AU in the 1960s using radar echoes from Venus, since spacecraft navigation depended on its accuracy. Another way to indicate distances within the solar system is terms of light time, which is the distance light travels in a unit of time at the rate of 299,792 km per second. Distances within the solar system, while vast compared to our travels on Earth's surface, are comparatively small-scale in astronomical terms. For reference, Proxima Centauri, the nearest star at 4 light years away, is about 250,000 AU distant from the sun.

Light Time	Approximate Distance	Example
1 second	299,792 km	~ 0.75 Earth-Moon dist.
1 minute	18,000,000 km	0.125 AU
8.3 minutes	150,000,000 km	Earth-Sun dist. (1 AU)
1 hour	1,000,000,000 km	~ 1.5 x Sun-Jupiter dist.
4 years	(Included for reference)	Distance to nearest star

The Sun

The sun is best characterized as a typical star. The sun dominates the gravitational field of the solar system; it contains 99.85% of the solar system's mass. The planets, which condensed out of the same disk of material that formed the sun, contain only 0.135% of the mass of the solar system. Satellites of the planets, comets, asteroids, meteoroids, and the interplanetary medium constitute the remaining fraction. Even though the planets make up a small portion of the solar system's mass, they retain the vast majority of the solar system's angular momentum. This storehouse of momentum can be utilized by interplanetary spacecraft on so-called "gravity-assist" trajectories.

Mass Distribution Within the Solar System

99.85%	Sun
0.135%	Planets
Remainder	Comets Satellites Minor Planets Meteoroids Interplanetary Medium

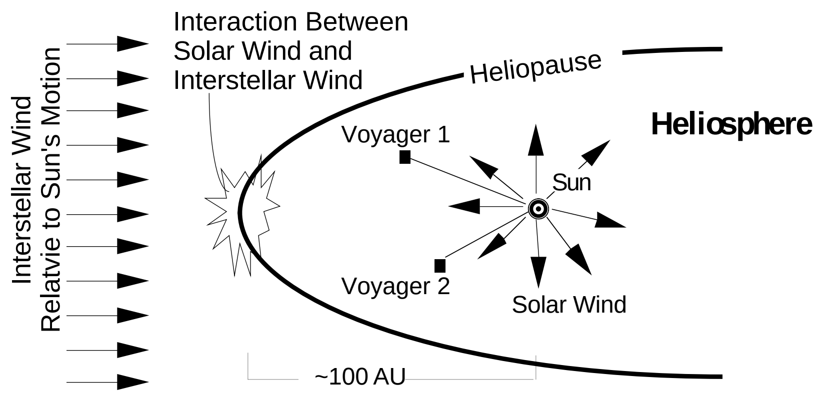
The gravity of the sun creates extreme pressures and temperatures within itself, sustaining a thermonuclear reaction fusing hydrogen nuclei and producing helium nuclei. This reaction yields tremendous amounts of energy, causing the material of the sun to be plasma and gas. These thermonuclear reactions began about 5×10^9 years ago in the sun, and will probably continue for another 5×10^9 years. The sun has no distinct surface. The apparent surface of the sun is optical only and has no discrete physical boundary.

The sun rotates once on its axis within a period of approximately 28 days at its equator. Because the sun is a gaseous body, rotation speed varies with latitude, being slower at higher latitudes.

The sun has strong magnetic fields that are associated with sunspots. The solar magnetic field is not uniform and is very dynamic. Solar magnetic field variations and dynamics are targets of major interest in the exploration of the solar system.

Interplanetary Space

Nearly all the solar system by volume appears to be an empty void. Far from being nothingness, this vacuum of "space" comprises the interplanetary medium. It includes various forms of electromagnetic radiation and at least two material components: interplanetary dust and interplanetary gas. Interplanetary dust consists of microscopic solid particles. Interplanetary gas is a tenuous flow of gas and charged particles, mostly protons and electrons—plasma—which stream from the sun, called the solar wind.



The solar wind can be measured by spacecraft, and it has a large effect on comet tails. It also has a measurable effect on the motion of spacecraft. The speed of the solar wind is about 400 km per second in the vicinity of Earth's orbit. The speed approximately doubles at high solar latitudes. The point at which the solar wind meets the interstellar medium, which is the "solar" wind from other stars, is called the heliopause. It is a boundary theorized to be roughly circular or teardrop-shaped, marking the edge of the sun's influence perhaps 100 AU from the sun. The space within the boundary of the heliopause, containing the sun and solar system, is referred to as the heliosphere.

The solar magnetic field extends outward into interplanetary space; it can be measured on Earth and by spacecraft. The solar magnetic field is the dominating magnetic field throughout the interplanetary regions of the solar system, except in the immediate environment of planets which have their own magnetic fields.

Recap

1. The whole solar system, together with the local stars visible on a clear night, orbits the center of our home _____________________ .
2. The planets, most of the satellites of the planets, and asteroids revolve around the sun in the same direction and nearly in the same _________________ .
3. One AU equals the mean distance from the ________ to the ______________ .
4. The sun is best characterized as a __________________ _______________ .
5. The gravity of the sun creates extreme pressures and temperatures within itself, sustaining a __________________ reaction .
6. The Astronomical Unit is abbreviated _______________ .
7. Even though the planets make up a small portion of the solar system's mass, they retain the vast majority of the solar system's __________________ _____________________.

1. galaxy 2. plane 3. sun...Earth 4. typical star 5. thermonuclear 6. AU 7. angular momentum

The Terrestrial Planets

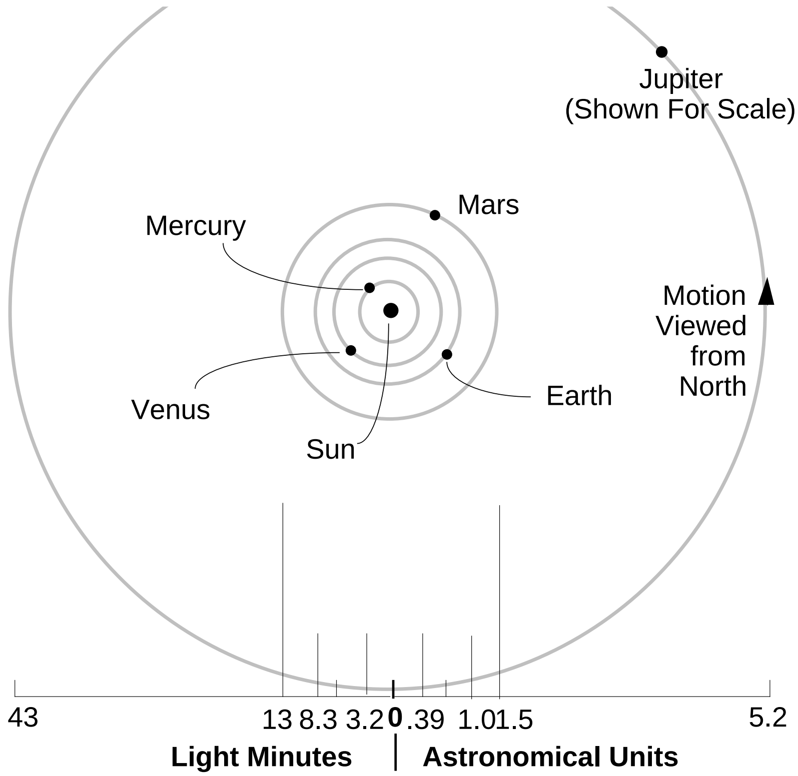
The terrestrial planets are Mercury, Venus, Earth, and Mars, and are called terrestrial because they have a compact, rocky surface like Earth's terra firma. The terrestrial planets are the four innermost planets in the solar system.

Light minutes are often used to express distances within the region of the terrestrial planets, useful because they indicate the time required for radio communication with spacecraft at their distances.

Of the terrestrial planets, Venus, Earth, and Mars have significant atmospheres. The gases present in a planetary atmosphere are related to a planet's size, mass, temperature, how the planet was formed, and whether life is present. The temperature of gases may cause their molecules or atoms to achieve velocities that escape the planet's gravitational field.

Earth is the most massive of the terrestrial planets. The ratios of mass for the terrestrial planets with respect to Earth (100%) is: Venus, 82%; Mars, 11%; and Mercury, 5%. In terms of Earth's radius, Venus is only slightly smaller, Mars is about 50% of Earth's, and Mercury's radius is only 40% of Earth's. In terms of Earth's 24-hour days, Mercury rotates on its axis in 59 days, Venus in 243 days, and Mars every 1.03 days. The slow rotation of Venus is retrograde, opposite the normal rotation of the planets.

Mean Distances Of The Terrestrial Planets From The Sun
(Orbits drawn approximately to scale)



Terrestrial Planetary Data (Approximate)

	Mercury	**Venus**	**Earth**	**Mars**
Mean distance from sun	0.39 AU	0.72 AU	1.0 AU	1.5 AU
Light minutes from sun	3.2	6.0	8.3	12.7
Mass in terms of Earth’s	0.05	0.82	1.00	0.11
Radius in terms of Earth’s	0.38	0.95	1.00	0.53
Rotation period Earth days	59	243 (retrograde)	1.00	1.03
Natural satellites	0	0	1	2

None of the terrestrial planets have rings. Earth does have a layer of rapidly moving charged particles known as the Van Allen belt, which is trapped by Earth's magnetic field in a doughnut-shaped region surrounding the equator. Of the terrestrial planets, Earth and Mars have natural satellites, Mercury and Venus do not.

The Jovian Planets

Jupiter, Saturn, Uranus, and Neptune are known as the jovian (Jupiter-like) planets, because they are all gigantic compared with Earth, and they have a gaseous nature like Jupiter's. The jovian planets are also referred to as the "gas giants," although some or all of them may have small solid cores.

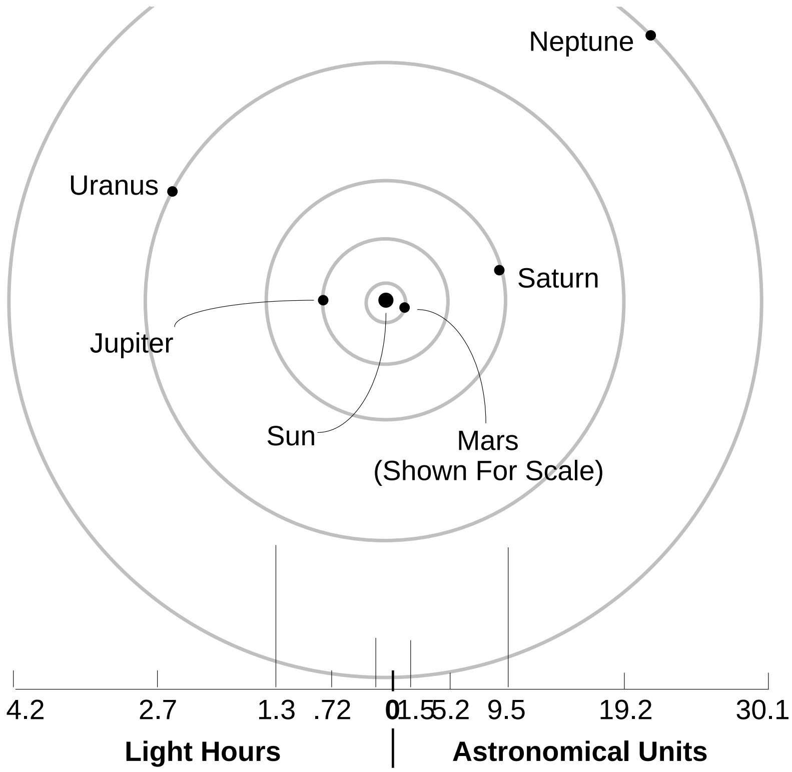
Jupiter is about 43 light minutes from the sun (add or subtract up to 8.3 minutes to determine light time to Earth); Saturn about 1 hour 20 minutes, Uranus about 2 hours 40 minutes, and Neptune about 4 hours 10 minutes from the sun. By comparison, Pluto, when at its farthest point in orbit, is 5 hours 31 minutes light time from the sun.

Jupiter is 318 times more massive than Earth. Its radius is 11 times Earth's. Jupiter emits electromagnetic energy from a vast number of charged atomic particles spiraling through the planet's magnetic field—its magnetosphere. Jupiter's magnetic field is 20 to 30 times stronger than Earth's. Jupiter has a single equatorial ring made up of particles probably less than 10 microns in diameter— about the size of cigarette smoke particles.

Jupiter has many satellites. Each of the four Galilean satellites, so named because Galileo Galilei (1564-1642) discovered them when he turned his telescope toward Jupiter, exhibits great diversity from the other. Io, the closest Galilean satellite to Jupiter, has active volcanoes, driven by the heat resulting from tidal forces (discussed further in Chapter 3) which flex its crust. Volcanoes are resurfacing the body continuously in the present time. They can now be monitored by Earth-based telescopes. Ganymede has mountains, valleys, craters, and lava flows. Its ancient surface resembles Earth's moon. Callisto is pocked all over with impact craters, revealing the fact that its surface has not changed since the early days of its formation. Europa is covered with an extremely smooth shell of water ice. There may be an ocean of liquid water below the shell, warmed by the same forces that heat Io's volcanoes! (Could life exist there?) Saturn's largest moon, Titan, has a hazy nitrogen atmosphere about as dense as Earth's. All of Uranus's 5 largest moons have extremely different characteristics. The surface of Miranda, the smallest, shows evidence of extensive geologic activity. Umbriel's surface is dark, Titania and Umbriel have trenches and faults, and Oberon's impact craters show bright rays similar to those on Callisto. Neptune's moon Triton is partly covered with nitrogen ice and snow, with active geysers.

Saturn, Uranus, and Neptune all have rings made up of myriad particles of ice, ranging in size from sand to boulders. Jupiter has a thick ring of fine dust, which can be detected at close range in visible light, and from Earth in the infrared. Each particle within a ring is an individual satellite in its own right. When two satellites occupy orbits very close to each other within a ring system, one orbiting farther from the planet than a ring, and the other one orbiting closer to the planet than that ring, they perform like sheep dogs and "flock" the particles between their orbits into a narrow ring, by gravitationally interacting with the ring particles. Thus these satellites are called shepherd moons.

Mean Distances Of The Jovian Planets From The Sun
(Orbits drawn approximately to scale.
Pluto omitted to accommodate scale)

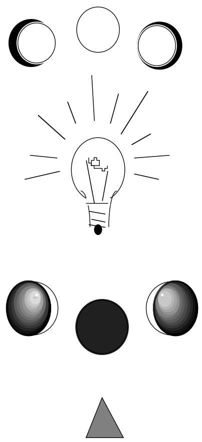


Jovian Planetary Data (Approximate)

	Jupiter	**Saturn**	**Uranus**	**Neptune**
Mean distance from sun	5.2 AU	9.5 AU	19.2 AU	30.1 AU
Light hours from sun	0.72	1.3	2.7	4.2
Mass in terms of Earth's	318	95	15	17
Radius in terms of Earth's	11	9	4	4
Rotation period in hours	9.8	10.7	17.2	16.1
Known natural satellites (1995)	16	18	15	8
Rings	Dust	Extensive system	Thin, dark	Broken ring arcs

Inferior and Superior Planets

Mercury and Venus are referred to as inferior planets because their orbits are closer to the sun than is Earth's orbit. Likewise, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto are known as superior planets because their orbits are farther from the sun than is Earth's. Viewed from Earth, Venus and Mercury go through phases of illumination like Earth's moon does. To visualize phases, in a dark room hold a tennis ball up in front of a light bulb, blocking out the bulb from your view (the tennis ball is now in inferior conjunction with the bulb, and occulting it). The unlighted side of the ball that you see is in the new phase, like a new moon. Move the ball slightly off to one side. Watch a bright crescent appear on the ball. Since the ball can be located between you and the bulb, it can be called an inferior ball. You can see that if the ball were directly across on the other side of the light bulb from you (at superior conjunction), one whole side would be fully illuminated: the full phase. Now swivel around 180° placing your back to the light. Hold the ball out in front of you (it is now a superior ball). Notice its full or near-full phase. Since the superior planets never come between Earth and the sun, they always show a nearly full phase when viewed from Earth. Viewed from superior planets, Earth goes through phases. Superior planets can be seen as crescents only from the vantage point of a spacecraft that is beyond them.



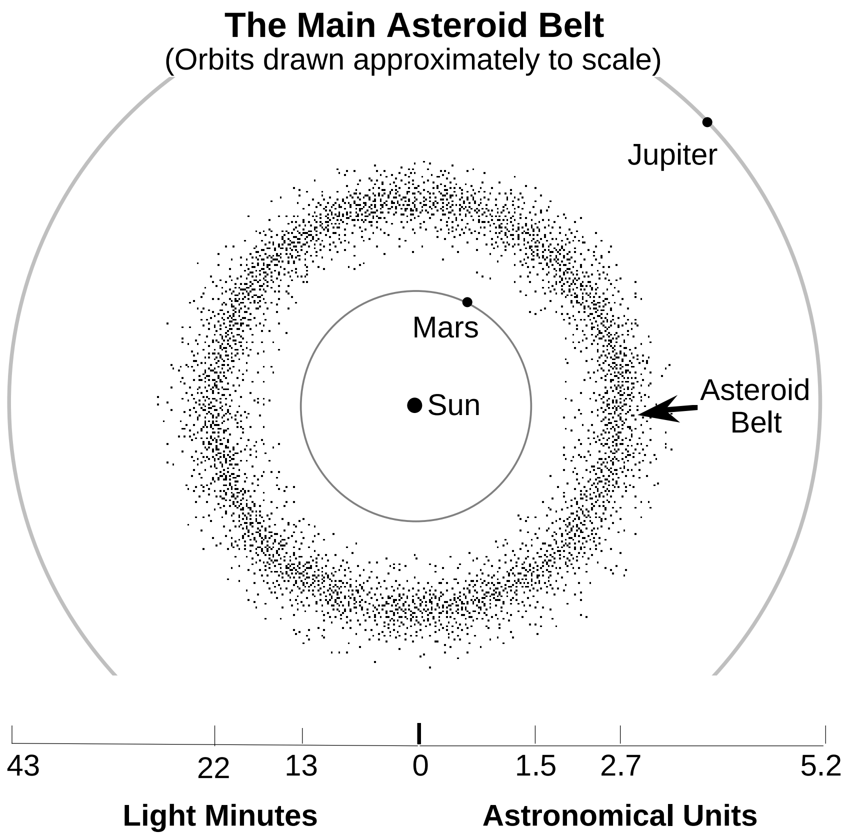
Recap

1. The terrestrial planets are... called terrestrial because they have a compact, ___________________ surface like Earth's...
2. ...a layer of rapidly moving charged particles known as the __________ ____________ belt is trapped by Earth's magnetic field.
3. Jupiter, Saturn, Uranus, and Neptune are known as the jovian planets because they are all gigantic... and have a __________________ nature like Jupiter's.
4. Jupiter emits electromagnetic energy from a vast number of charged atomic particles spiraling through the _______________ _________________ associated with the planet...
5. Jupiter has satellites ... of great diversity. Io, the closest Galilean satellite to Jupiter, has active _______________ .
6. Mars, Jupiter, Saturn, Uranus, and Neptune, and Pluto are known as ____________________ planets because their orbits are further from the sun than is Earth's.

1. rocky 2. Van Allen 3. gaseous 4. magnetic field 5. volcanoes 6. superior

Asteroids

Asteroids, also called minor planets, are rocky objects in orbit around the sun. Most asteroids orbit the sun between Mars and Jupiter, moving in the same direction as the planets. Asteroids range in size from Ceres, which has a diameter of about 1000 km, down to the size of pebbles. Sixteen asteroids have a diameter of 240 km or greater. Some asteroids, called Apollo Asteroids, cross the orbit of Earth. It has been estimated that there are around 1000 Earth-crossing asteroids with a diameter of a kilometer or more.

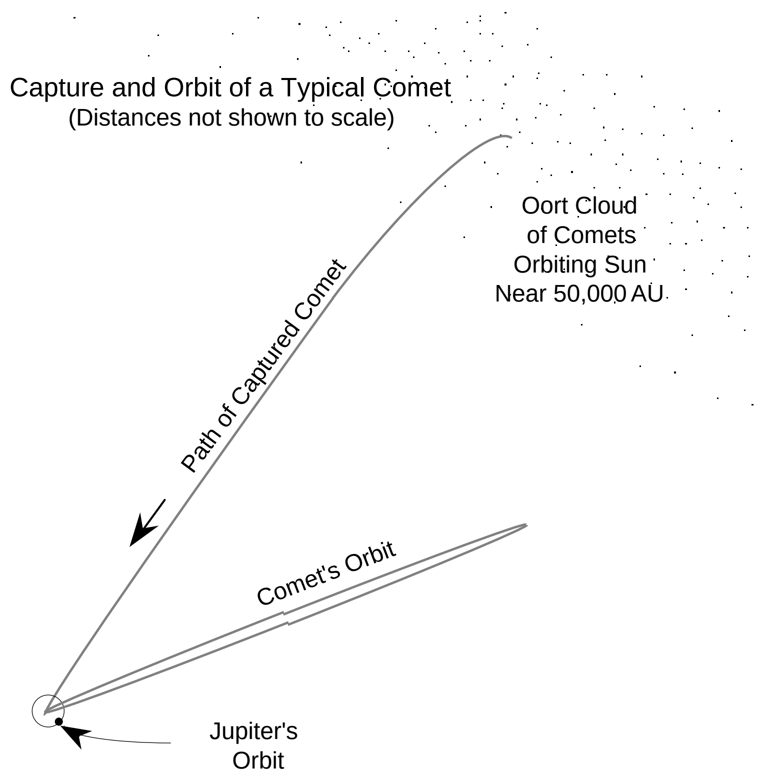


Comets

Most comets are believed to be composed of rocky material and water ice. A few have highly elliptical orbits that bring them very close to the sun and swing them deeply into space, often beyond the orbit of Pluto.

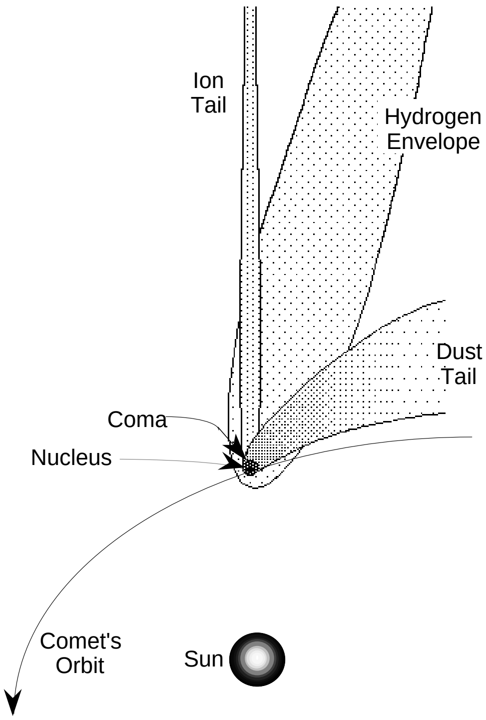
The most widely accepted theory of the origin of comets is that there is a huge cloud of comets called the Oort Cloud (after the Dutch Astronomer Jan H. Oort who proposed the theory), of perhaps 10^{11} comets orbiting the sun at a distance of about 50,000 AU (just under a light year). These comets are near the boundary between the gravitational forces of the sun and the gravitational forces of other stars with which the sun comes into interstellar proximity every several thousand years. According to the theory, these stellar passings perturb the orbits of the comets within the Oort cloud. As a result, some comets may be captured by the visiting star, some may be lost to interstellar space, and some may begin to “fall” toward the sun. Actually, the comet is still in orbit around the sun as it “falls.” However, the orbit has been modified from a relatively circular orbit to an extremely elliptical one. These are the comets we observe.

A comet entering our planetary system may come under the gravitational influence of the planets as it comes within about 30 AU, especially Jupiter which is at about 5 AU, and its path may be perturbed again. A comet may be accelerated onto a hyperbolic (open) curve, which will cause it to leave the solar system. Unlike the planets that have orbits in nearly the same plane, comet orbits are oriented randomly in space. Comets have been known to break up on closest approach to the sun. Discovered early in 1993, comet Shoemaker-Levy 9 had broken up apparently because of its close passage to Jupiter. It had been captured into orbit about Jupiter and would collide with the planet in July of 1994. The spectacular collision was widely observed.



Comet structures are diverse and very dynamic, but they all develop a surrounding cloud of diffuse material, called a coma, that usually grows in size and brightness as the comet approaches the sun. The dense, inner coma often appears pointlike, but the actual nucleus is rarely seen from Earth because it is too small and dim. The coma and the nucleus together constitute the head of the comet.

Components of Comet



As many comets approach the sun they develop enormous tails of luminous material that extend for millions of kilometers from the head, away from the sun. When far from the sun, the nucleus is very cold and its material is frozen solid within the nucleus. In this state comets are sometimes referred to as a “dirty iceberg” or “dirty snowball,” since over half of their material is ice. When a comet approaches within a few AU of the sun, the surface of the nucleus begins to warm, and volatiles evaporate. The evaporated molecules boil off and carry small solid particles with them, forming the comet’s coma of gas and dust.

When the nucleus is frozen, it can be seen only by reflected sunlight. However, when a coma develops, dust reflects still more sunlight, and gas in the coma absorbs ultraviolet radiation and begins to fluoresce. At about 5 AU from the sun, fluorescence usually becomes more intense than reflected light.

As the comet absorbs ultraviolet light, chemical processes release hydrogen, which escapes the comet’s gravity, and forms a hydrogen envelope. This envelope cannot be seen from Earth because its light is absorbed by our atmosphere, but it has been detected by spacecraft.

The sun’s radiation pressure and solar wind accelerate materials away from the comet’s head at differing velocities according to the size and mass of the materials. Thus, relatively massive dust tails are accelerated slowly and tend to be curved. The ion tail is much less massive, and is accelerated so greatly that it appears as a nearly straight line extending away from the comet opposite the sun.

Each time a comet visits the sun, it loses some of its volatiles. Eventually, it becomes just another rocky mass in the solar system. For this reason, comets are said to be short-lived, on a cosmological time scale. Many scientists believe that some asteroids are extinct comet nuclei, comets that have lost all of their volatiles.

Meteoroids

Meteoroids are small, often microscopic, solid particles that are in orbit around the sun. We see meteoroids as bright meteors when they enter Earth's atmosphere at high speed as they burn up from frictional heat. Any part of a meteor that reaches the ground is called a meteorite. As volatiles boil off from comets they carry small solid particles with them. Particles released from comets in this way become a source for meteoroids, causing meteor showers as Earth passes through them. Meteoroids also come from the asteroid belt.

Recap

1. Asteroids, also called minor planets, are ____________ objects in orbit around the sun.
2. Most asteroids orbit the sun between _____________ and _______________ .
3. ...stellar passings perturb the orbits of the comets within the _________________ cloud.
4. Unlike the planets that have orbits in nearly the same plane, comets are oriented ___________________ in space.
5. ...when a coma develops, dust reflects still more sunlight, and gas in the coma absorbs ultraviolet radiation and begins to ____________________ .
6. Meteoroids are small (often microscopic) solid particles that are in orbit around the ____________ .

1. rocky 2. Mars and Jupiter 3. Oort 4. randomly 5. fluoresce 6. sun

Chapter 2. Earth and its Reference Systems

Objectives: Upon completion of this chapter you will be able to describe the system of terrestrial coordinates, the rotation of Earth, precession, and the revolution of Earth about the sun. You will be able to describe how the locations of celestial objects are stated in the coordinate systems of the celestial sphere. You will be able to describe various conventions of timekeeping.

In order to explore the solar system, coordinates must be developed to consistently identify the locations of the observer, of the natural objects in the solar system, and of any spacecraft traversing interplanetary space or orbiting a planet.

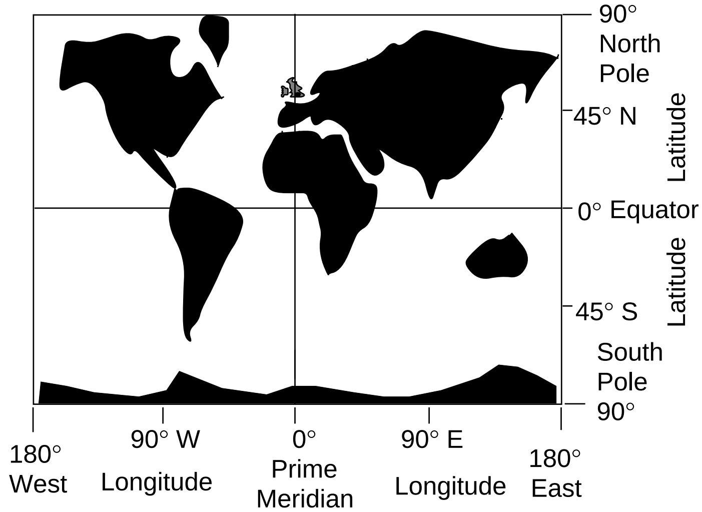
Because space is observed from Earth, Earth's coordinate system must be established before space can be mapped. Earth rotates on its axis daily and revolves around the sun annually. These two facts greatly complicated the history of observing space. However, once known, accurate maps of Earth could be made using stars as reference points, since most of the stars' angular movements in relationship to each other are not readily noticeable during a human lifetime. Although the stars do move with respect to each other, this movement is observable for only a few close stars, using instruments and techniques of great precision and sensitivity (historically, the starry sky has been called "the firmament").

Terrestrial Coordinates

A great circle is an imaginary circle on the surface of a sphere whose center is at the center of the sphere. The equator is a great circle. Great circles that pass through both the north and south poles are called meridians, or lines of longitude. For any point on the surface of Earth a meridian can be defined. The prime meridian, the starting point measuring the east-west locations of other meridians, marks the site of the old Royal Observatory in Greenwich, England. Longitude is expressed in degrees, minutes, and seconds of arc from 0 to 180 degrees eastward or westward from the prime meridian. For example, downtown Pasadena is located at 118 degrees, 8 minutes, 41 seconds of arc westward of the prime meridian: 118° 8' 41" W.

The starting point for measuring north-south locations on Earth is the equator (the equator is the imaginary circle around Earth which is everywhere equidistant from the poles). Circles in parallel planes to that of the equator define north-south measurements called parallels, or lines of latitude. Latitude is also expressed in degrees, minutes, and seconds of the arc subtended from the center of Earth. Downtown Pasadena is located at 34 degrees, 08 minutes, 44 seconds of arc north of the equator: 34° 08' 44" N.

Terrestrial Coordinates



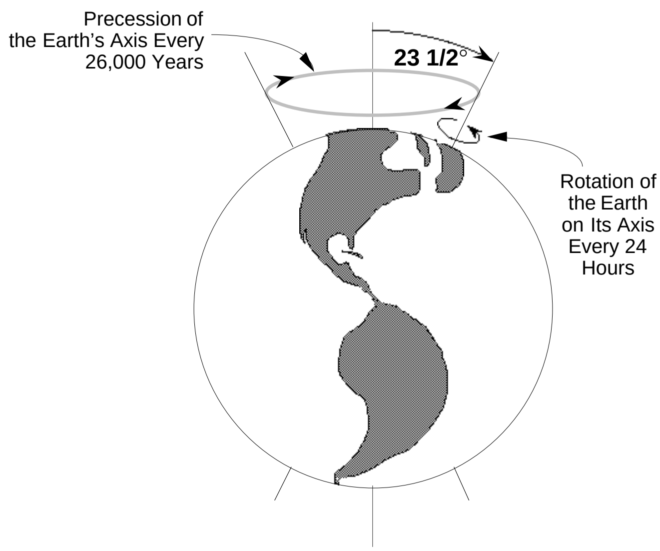
Rotation of Earth

Earth rotates on its axis relative to the sun every 24.0 hours mean solar time, with an inclination of 23.5 degrees from the plane of its orbit around the sun. Mean solar time represents an average of the variations caused by Earth's non-circular orbit. Its rotation relative to the other stars (sidereal time) is 3 minutes 56.55 seconds shorter than the mean solar day, the equivalent of one solar day per year. Forces associated with the rotation of Earth cause it to be slightly oblate, displaying a bulge (oblateness) at the equator.

Precession of the Earth Axis

The moon's gravity, primarily, and to a lesser degree the sun's gravity, acting on Earth's oblateness tries to move Earth's axis perpendicular to the plane of Earth's orbit. However, due to gyroscopic action, Earth's poles do not "right themselves" to a position perpendicular to the orbital plane. Instead, they precess at 90 degrees to the force applied. This precession causes the axis of Earth to describe a circle having a 23.5 degree radius relative to a fixed point in space over about 26,000 years, a slow wobble reminiscent of the axis of a spinning top swinging around.

Precession of the Earth



Revolution of Earth

Earth revolves around the sun in 365 days, 6 hours, 9 minutes with reference to the stars. Its mean orbital speed is about 100,000 km per hour. The 6 hours, 9 minutes add up to about an extra day every fourth year, which is designated a leap year, with the extra day added as February 29th. Earth's orbit is elliptical and reaches its closest approach to the sun (perihelion) on about January fourth of each year.

Recap

1. Most of the stars' movements in relationship to each other are not readily noticeable during a ___________________ ______________________ .
2. Longitude is expressed in degrees, minutes, and seconds of arc from 0 to 180 degrees eastward or westward from the _______________ _________________ .
3. North-south measurements on the surface of Earth are called _____________________ , or lines of ________________ .
4. Forces associated with the _______________ of Earth cause it to be slightly oblate.
5. Precession causes the axis of Earth to describe a circle having a _______ - degree radius over a period of about ____________________ years.
6. Earth's orbit is _______________________ (in shape).

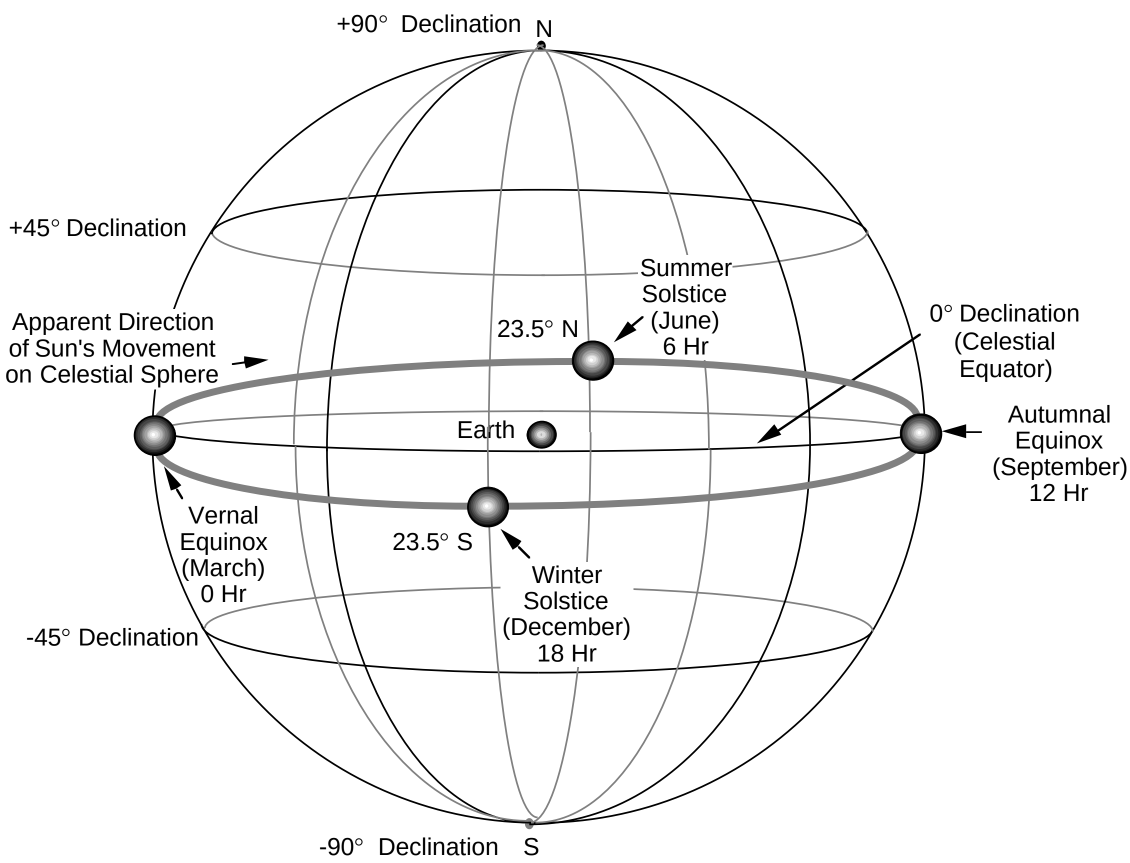
1. human lifetime 2. prime meridian 3. parallels...latitude 4. rotation 5. 23.5 ... 26,000 6. elliptical

The Celestial Sphere

To establish a consistent coordinate system for the sky, a celestial sphere has been conceived. The center of the celestial sphere is the center of Earth. The celestial sphere has an imaginary radius larger than the distance to the farthest observable object in the sky. The extended rotational axis of Earth intersects the north and south poles of the celestial sphere.

The direction to any star or other object can be plotted in two dimensions on the inside of this sphere. The apparent constancy of observed stellar positions allows the preparation of long-lived sky almanacs that identify the direction on the celestial sphere to the observable stars. The apparent direction to the sun, moon, planets, spacecraft, or any object in our solar system can also be plotted on the inside of the celestial sphere. However, these objects all move fairly rapidly in apparent angular distance with respect to the “stationary” stars plotted on the celestial sphere, causing their plots to need regular updating.

A coordinate system analogous to Earth’s latitude and longitude has been devised for the celestial sphere to designate positions on the sphere.

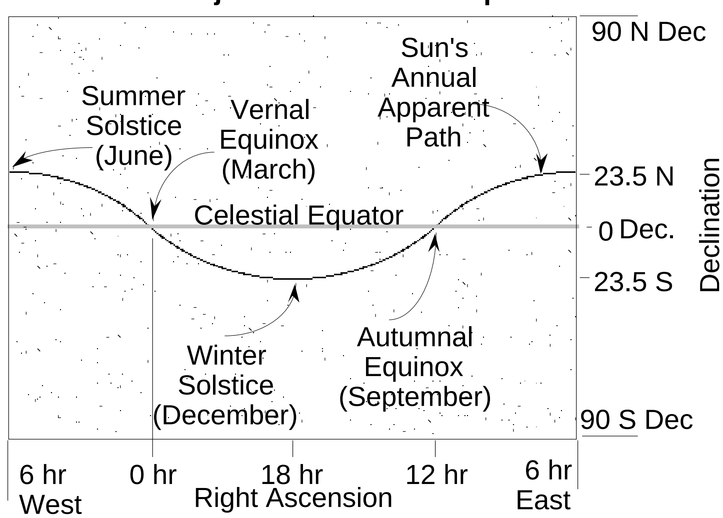


Right Ascension, Declination, and Related Terms

Right ascension (RA) is angular distance measured in hours, minutes, and seconds of the 24-hour circle along the celestial equator eastward from the vernal equinox. The vernal equinox is that point of the celestial sphere where the sun's path crosses the celestial equator going from south to north each year. Declination (DEC) is angular distance measured in degrees north or south of the celestial equator (+90 to -90 degrees). Zenith is imagined as a point straight up from any point on the surface of Earth. Observer's Meridian is an arc on the celestial sphere extending from the north to the south celestial poles that passes through the observer's zenith. The Nadir is the direction opposite the zenith: for example, straight down from a spacecraft to the center of the planet.

Hour angle (HA) is the angular distance measured westward along the celestial equator from the zenith crossing. In effect, HA represents the RA for a particular location and time of day.

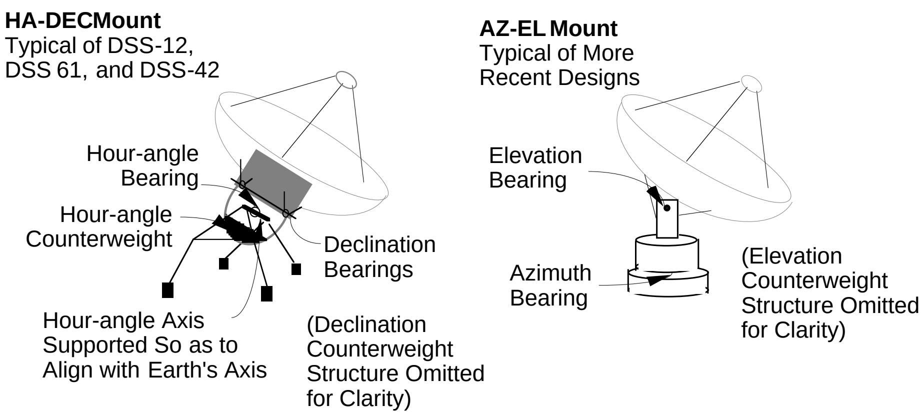
Mercator Projection of Celestial Sphere



RA, HA and DEC are references within a system based on Earth's equator and poles. There is a simpler system, which uses the local horizon as its reference. Its measurements are elevation (or altitude), EL (or ALT), in degrees above the horizontal, and azimuth (AZ), in degrees clockwise around the horizon from true north. In such a system East is 90° AZ, and halfway up in EL or ALT would be 45°. AZ-EL and ALT-AZ are simply different names within the same reference system.

Telescopes, radio telescopes, and JPL's Deep Space Station antennas are designed with mountings that are engineered to take best advantage of either the HA-DEC coordinate system or the AZ-EL (ALT-AZ) system.

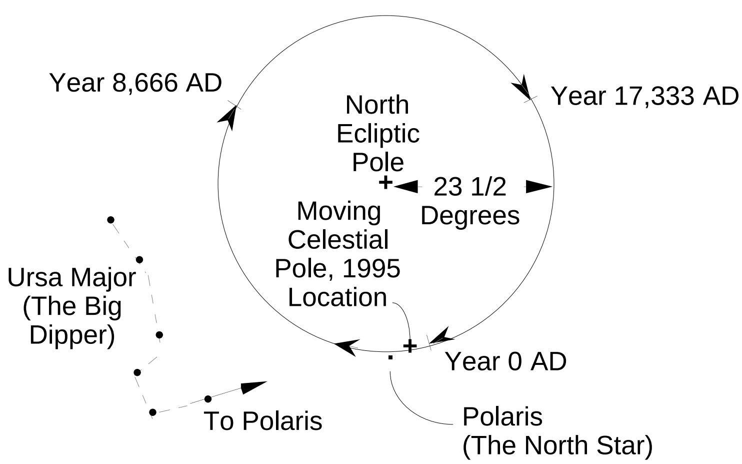
In a HA-DEC system, the HA axis is parallel to Earth's rotational axis. Thus the mounting built for a telescope near the equator would appear different from one built for use in high latitudes. ALT-AZ or AZ-EL systems would appear the same no matter where on Earth they are being used.



HA-DEC antenna mounting systems require an asymmetrical structural design unsuited to the support of very heavy structures. Their advantage is that motion is required mostly in only one axis to track an object as Earth rotates, although this advantage has largely been obviated by the use of digital computers that can drive both axes of AZ-EL systems properly while they track.

Because of the precession of the poles over 26,000 years, all the stars appear to shift over time, and sky almanacs must be occasionally updated. Precession causes the stars to appear to shift west to east at the rate of .01 degree (360 degrees/ 26,000 years) with respect to the vernal equinox each year. Sky almanacs identify the date and time of the instant used as the date of reference, or epoch, when preparing the almanac, and provide equations for updating data based on the almanac to the current date.

Precessional Path of the North Celestial Pole
(Earth's Axis Projected on the Northern Sky)



At the present time in Earth's 26,000 year precession cycle, a bright star coincidentally happens to be very close (less than a degree) from the north celestial pole. This star is called Polaris, or the North Star.

Recap

1. The center of the celestial sphere is the center of the ____________________ .
2. The ______________ __________________ is the point of the celestial sphere where the sun's path crosses the celestial equator going from south to north...
3. A coordinate system analogous to Earth's longitude and latitude ... to designate positions on the celestial sphere (uses) measurements called _____________ and _______________ .
4. _________________ is the angular distance measured north or south of the celestial equator (+90 to -90°).
5. Because the precession of ... the poles ... over a period of 26,000 years, all the stars appear to move very slowly, and sky almanacs must be occasionally _________________ .

1. Earth 2. vernal equinox 3. RA ... DEC 4. DEC 5. updated

Time Conventions

Various measurements of time are used in interplanetary space flight:

Universal Time Coordinated (UTC) is the world-wide scientific standard of timekeeping. It is based upon carefully maintained atomic clocks and is kept accurate to within microseconds. The addition or subtraction of leap seconds, as necessary at two opportunities every year, keeps UTC in step with Earth's rotation. Being the most precise worldwide time system, it is used by astronomers, navigators, the Deep Space Network (DSN), and other scientific disciplines. Its reference point is Greenwich, England: when it is midnight there on Earth's prime meridian, it is midnight (00:00:00.000000) — "all balls"—UTC.

UT1, or simply UT, Universal Time, was previously called Greenwich Mean Time, GMT. It is based on the imaginary "mean sun" which averages out the effects on the length of the solar day caused by Earth's slightly non-circular orbit about the sun. UT is not updated with leap seconds as is UTC. Its reference point is also Greenwich, England: when it is noon on the prime meridian, it is noon (12:00:00) UT.

Local time is adjusted for location around Earth or other planets in time zones. On Earth, many countries adjust for standard time or daylight-savings time. Its reference point is one's immediate locality: when it is 12:00:00 noon Pacific Daylight Time (PDT) at JPL, it is 19:00:00 UTC, and 13:00:00 in Denver. Local time on another planet is conceived as the equivalent time for the height of the sun above the horizon, corresponding to the same local time on Earth. It has no bearing to the planet's rotation rate. Thus around 11:30 am or 12:30 pm at a particular location on Venus, the sun would be nearly overhead. At 5:00 pm at a particular location on Mars, the sun would be low in the west.

Earth-received time (ERT) is the UTC of an event received at a DSN station. One-way light time (OWLT) is the elapsed time it takes for light, or a radio signal, to reach a spacecraft or other body from Earth (or vice versa). Knowledge of OWLT is maintained to an accuracy of milliseconds. OWLT varies continuously as the spacecraft's distance from Earth changes. Its reference points are the center of Earth and the immediate position of a spacecraft or the center of a celestial body. Transmission time (TRM) is the UTC time of uplink from Earth.

Round-trip light time (RTLT) is the elapsed time it takes for a signal to travel from Earth, be received and immediately transmitted or reflected by a spacecraft or other body, and return to the starting point. It is roughly equal to 2 x OWLT, but not exactly, because of the different amount of distance the signal must travel on each leg due to the constant motions of both Earth and spacecraft. RTLT from here to Earth's moon is around 3 seconds, to the sun, about 17 minutes. Voyager 1's RTLT at this writing in December 1995 is over 17 hours.

Spacecraft event time (SCET) is the UTC time onboard the spacecraft. It is equal to TRM + OWLT. ERT is equal to SCET + OWLT. Spacecraft clock time (SCLK), is the value of a counter onboard a spacecraft as described in Chapter 11. SCET has a nearly-direct relationship with SCLK, although the units of measurement are different, and SCLK is not as constant and stable as the UTC-derived SCET. Tracking the exact relationship between SCLK and SCET is accomplished by analyzing telemetered SCLK values and trends with respect to UTC-derived SCET, and producing a SCLK/SCET coefficients file which tracks the gradual drift of SCLK versus SCET.

Terrestrial Time (TT) was previously called Terrestrial Dynamical Time (TDT), which replaced Ephemeris Time (ET). TT is a measurement of time defined by Earth's orbital motion. It equates to Mean Solar Time corrected for the irregularities in Earth's motions.

This excerpt from a flight project's Integrated Sequence of Events (ISOE) illustrates use of UTC, ERT, TRM, RTLT, SCET, and SCLK.

(ISOE is discussed further in Chapter 15.)

ID: 93-24 F SOE YEAR-DAY: 93-171 PRINTED ON DAY 93-168 PAGE 142
MAGELLAN MISSION OPERATIONS
SEQUENCE OF EVENTS WEEK: 24 DOY: 169-175 RTLT = 12:56.354

ITEM NO.	GND TIME DOY/HH:MM:SS	T B	EVENT - DESCRIPTION	COMMAND	DSN	SCE TIME DOY/HH:MM:SS	S/C CLOCK
02518	171/01:28:56	E	<< STAR SCANNER PULSE TST >>	7PULS		171/01:22:28	2159880:90:0
02519	171/01:28:58	E	<< STAR SCANNER PULSE TST >>	7PULS		171/01:22:30	2159881:02:0
02520	171/01:28:58	E	<< NO OPERATION >>	6NOP		171/01:22:30	2159881:02:0
02521	171/01:32:37	E	MISC,NOTE,391AG99A,, 93-171/01:26:09.131,APOAPS,GOTHER, A7931			171/01:26:09	2159884:58:0
02522	171/01:33:59	T	ACQ U/L - DSS 42 S BAND		42	171/01:40:27	
02523	171/01:34:21	E	END OF MEMORY READOUT	6MROH			
02524	171/01:34:57	E	MISSION PHASE ORB OPS S/W MODE*ATT REF HOLD	AACS		171/01:28:29	2159886:86:0
02525	171/01:35:01	E	STAR,FSTAR- << MANEUVER SPECIFICATION >>	7MNVR		171/01:28:33	2159887:00:0
02526	171/01:35:01	E	MISSION PHASE ORB OPS S/W MODE*SLEW TO ATT	AACS		171/01:28:33	2159887:00:0

Recap

1. Universal Time (UT) is the mean or average value of UTC: It is a not updated with ________________ seconds as is UTC.
2. When it is 12:00:00. noon Pacific Daylight Time (PDT) at JPL, it is ________ UTC.
3. (The abbreviation) __________ is the UTC time on board the spacecraft. It is equal to UTC + OWLT.
4. Spacecraft Clock time (SCLK) is the value of a _______________ on board a spacecraft

1. leap   2. 1900   3. SCET   4. counter