Chapter 7

Mapping the Sky

Objectives: When you have completed this chapter, you will be able to describe the terrestrial coordinate system; define and describe the relationship among the terms commonly used in the "horizon" coordinate system, the "equatorial" coordinate system, the "ecliptic" coordinate system, and the "galactic" coordinate system; and describe the difference between an azimuth-elevation antenna and hour angle-declination antenna.

In order to explore the universe, coordinates must be developed to consistently identify the locations of the observer and of the objects being observed in the sky.

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 have 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.

Earth's Coordinate System

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, the GAVRT is located at 116.805 degrees, or 116 degrees, 48 minutes, 18 seconds of arc westward of the prime meridian: 116deg. 48' 18" W.

The starting point for measuring north-south locations on Earth is the equator (the equator is the imaginary circle around the 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 the Earth. The GAVRT is located at 35.300 degrees, or 35 degrees, 18 minutes of arc north of the equator: 35deg. 18' 00" N.

Terrestrial Coordinates
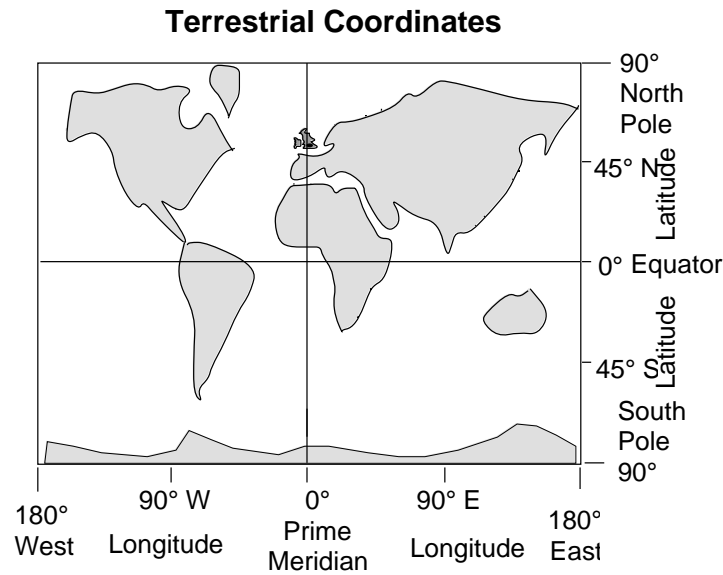

Revolution of Earth

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 adds up to about an extra day every fourth year, which is designated a leap year, with the extra day added as February 29th.

Solar vs. Sidereal Day

The 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. Earth's rotation period relative to the other stars (sidereal time) is 3 minutes 56.55 seconds shorter than the mean solar day.

The following figure explains this apparent discrepancy. Suppose the day starts when Earth's orbital position is at A and the Sun on the meridian (that is, directly above the local southern horizon) of an observer at point O on Earth's surface. When Earth has completed one rotation with respect to the distant stars (C), the Sun will not yet have advanced to the meridian for the observer at point O due to the movement of Earth along its orbit about the sun from A to B. To complete a solar day, Earth must rotate an additional 1/365 of a full turn, which takes nearly 4 minutes. Thus the solar day is about 4 minutes longer than the sidereal day. Therefore, a clock geared to sidereal time, in the space of one year, falls behind a regular clock by an amount equal to about one solar day (24 hours).

Solar Day vs. Sidereal Day

C

C

To remote point
on celestial sphere

Sun

1°

1°

O

O

B

A
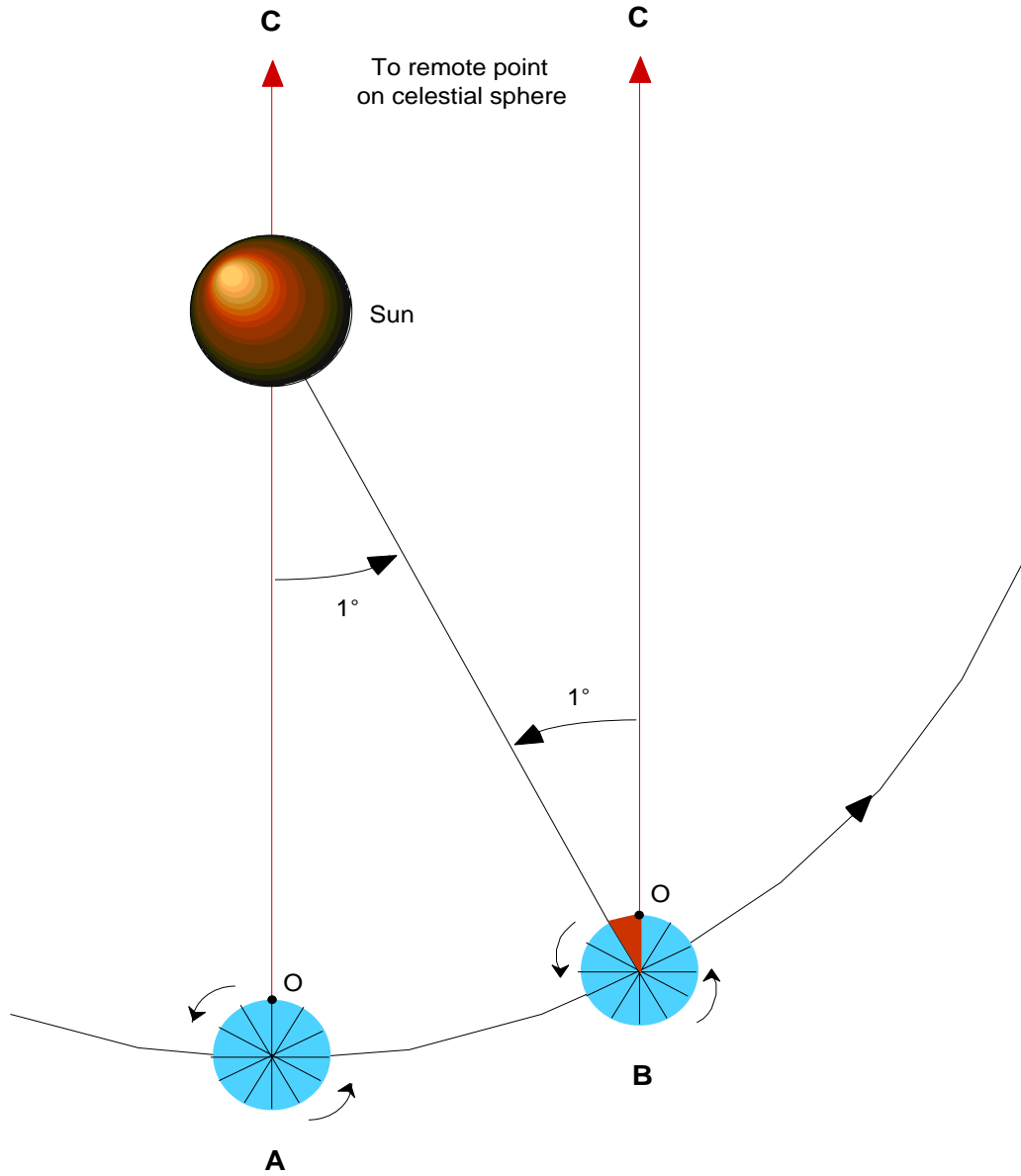
Precession of the Earth Axis

Like a spinning top with a slow wobble, Earth's axis slowly wobbles, or *precesses*, relative to its orbital plane. 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.

Precession of the Earth

Precession of the Earth's Axis Every 26,000 Years

23 1/2°

Rotation of the Earth on Its Axis Every 24 Hours
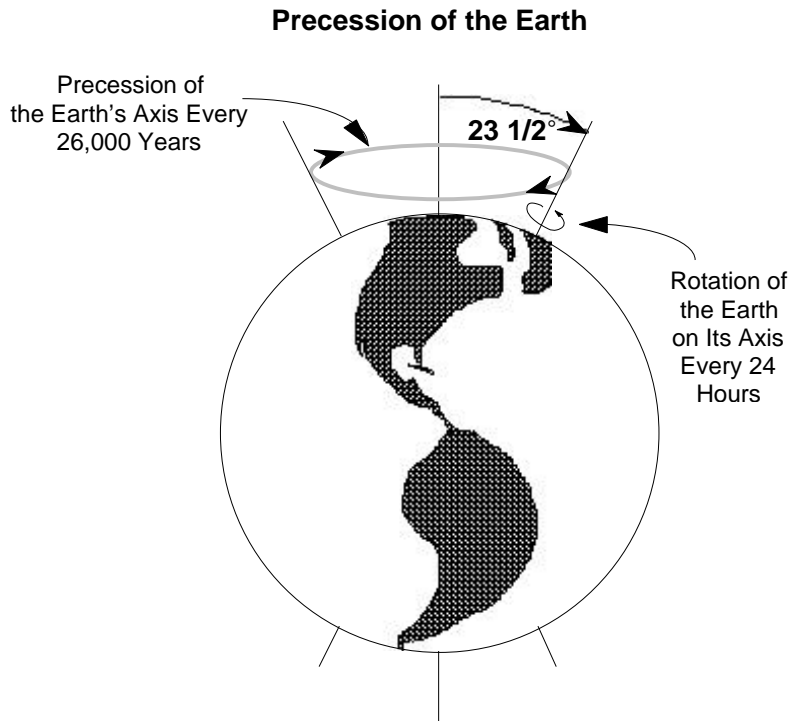
Astronomical Coordinate Systems

Mapping locations on Earth is easy because, except for an occasional earthquake and the slow glide of the tectonic plates, things stay put on Earth's surface. But in the sky, things are moving, and of course we are constantly moving with respect to the sky. Therefore, coordinate systems for locating objects in the sky have to take all this movement into account. Several systems have been devised to describe positions of celestial objects relative to Earth. The choice of which one to use depends on what you are observing and how.

Horizon Coordinate System

The horizon is defined as the dividing line between the Earth and the sky, as seen by an observer on the ground. In the *horizon coordinate system* the *astronomical horizon* is the hypothetical interface between Earth and sky, as would be seen by the observer if the surrounding terrain were perfectly flat (as out on a calm ocean).

Referring to the drawing below, *zenith* is the point straight overhead, perpendicular to the horizon plane, and *nadir* is the point directly under the observer. A vertical circle through an object in the sky and the zenith is the *object circle*. The coordinates of the object are given by the *azimuth*, which is the horizontal angle from north clockwise to the object circle, and the altitude or *elevation* angle, which is measured upward from the horizon to the object. The great circle through the north and south points on the horizon and the zenith is called the *meridian*.
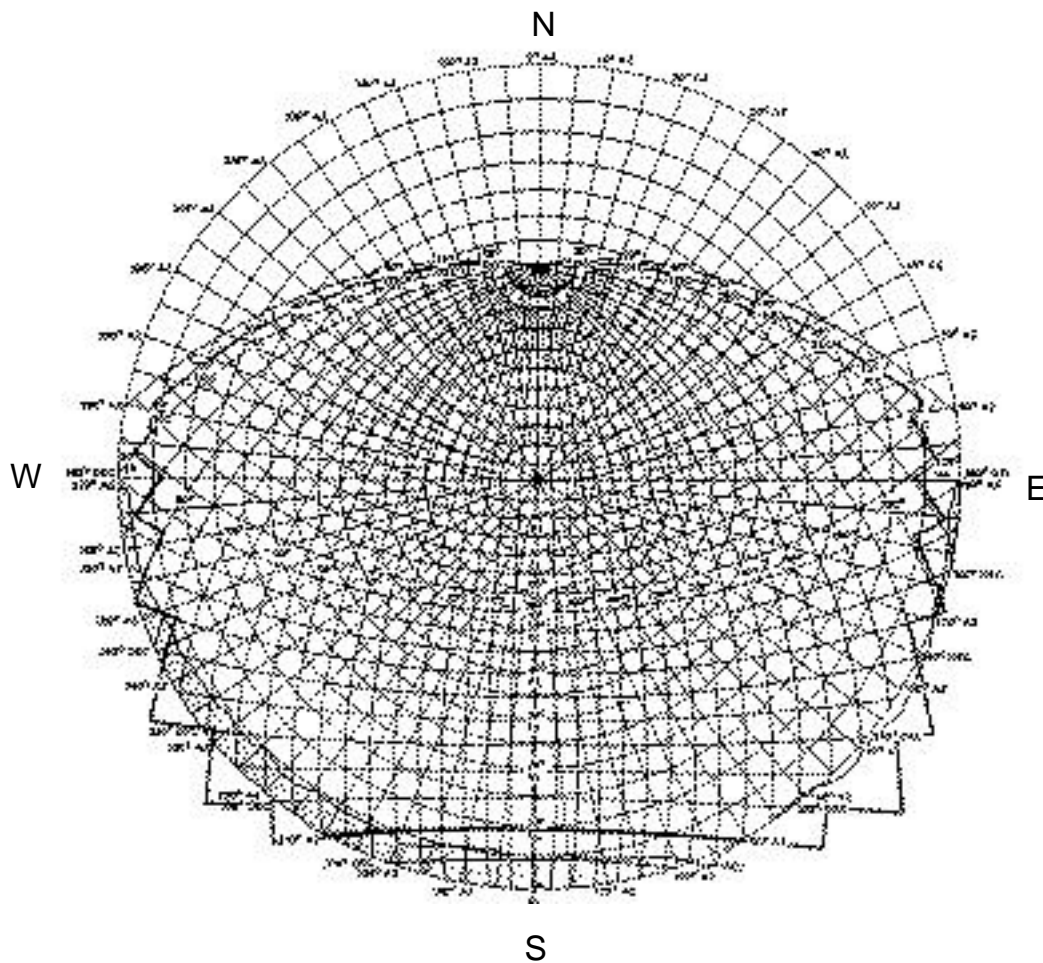
Horizon Coordinate System
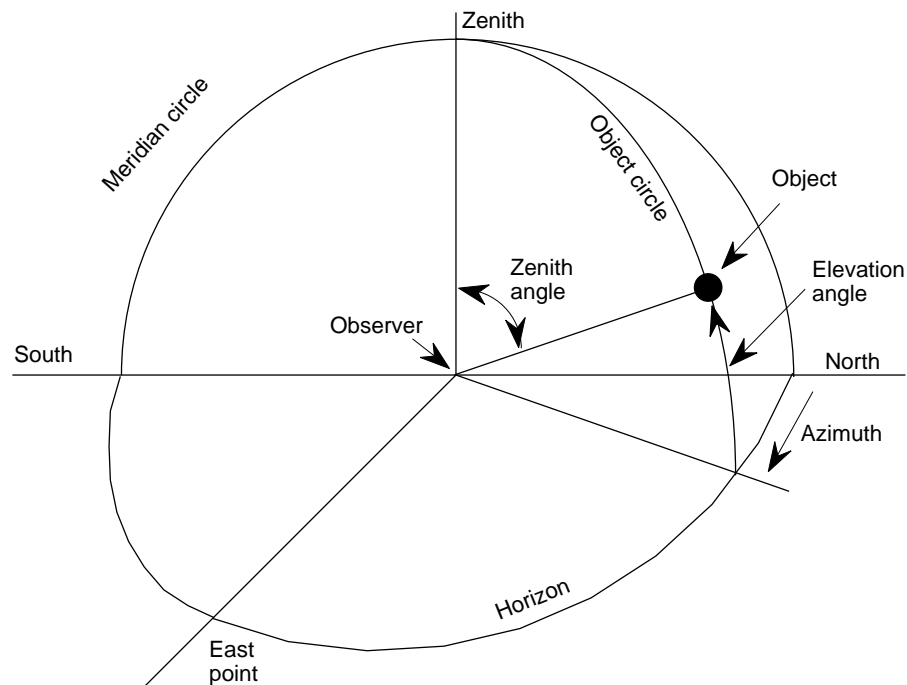
A *horizon mask* is a diagram that maps in silhouette the horizon in 360° of azimuth as actually seen by the observer, including hills, valleys, mountains, buildings, trees, and anything else that would hide from view any part of the sky that would be visible if the terrain were perfectly flat. A horizon mask for the GAVRT is shown on the next page.

In the horizon system, the coordinates of an object in the sky change throughout the day with Earth's rotation. While the azimuth and elevation angles are convenient for positioning a radio telescope antenna that rotates around horizontal and vertical axes (AZ-EL mounted), they are not so convenient for specifying the position of a celestial object. Better for this purpose are systems using fixed coordinates, such as the equatorial coordinate system.
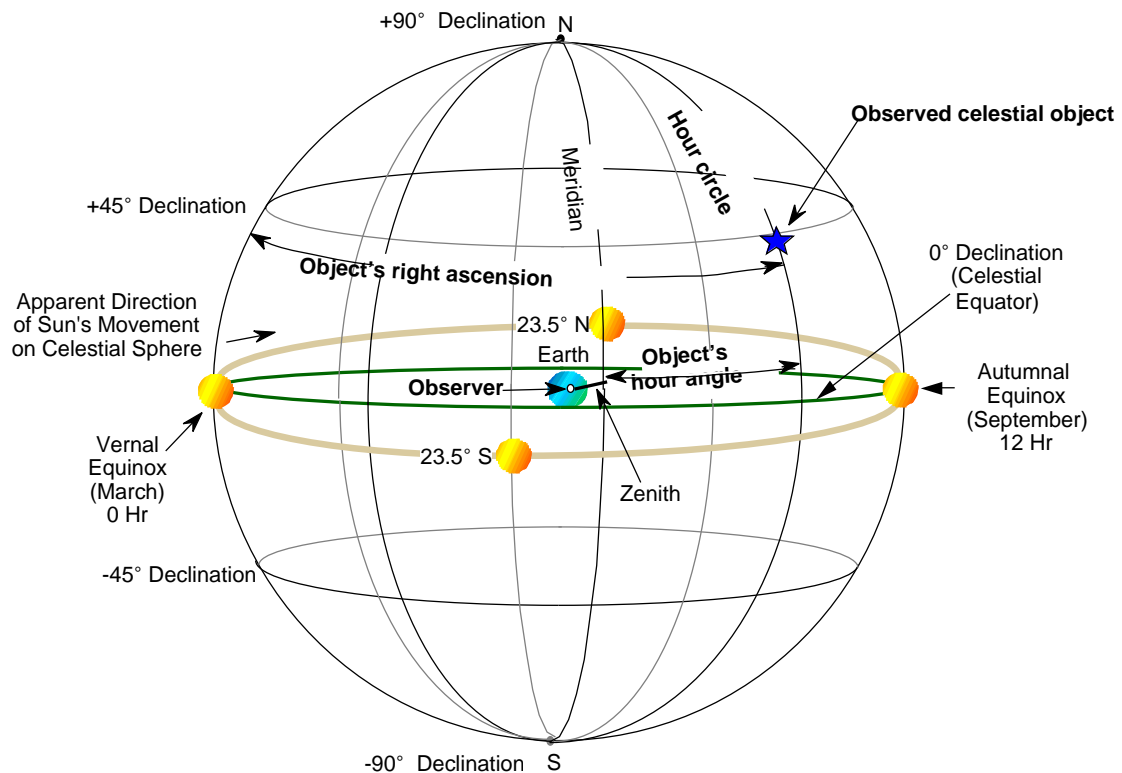
Horizon Mask for the Goldstone-Apple Valley Radio Telescope

Equatorial Coordinate System

In the *equatorial coordinate system*, Earth's equator is the plane of reference. Earth's axis of rotation points to the north and south *celestial poles*. The *celestial sphere* is as large as the known universe, and Earth is at the center of this sphere. The celestial poles do not move as Earth rotates. For an observer standing at Earth's equator, the celestial poles are on opposite horizons at exactly the north and south points, and the *celestial equator* passes overhead going exactly from the east to west horizon.

Equatorial Coordinate System

+90° Declination N

Observed celestial object

Hour circle

Meridian

+45° Declination

Object's right ascension

0° Declination
(Celestial
Equator)

Apparent Direction
of Sun's Movement
on Celestial Sphere

23.5° N

Earth

**Object's
hour angle**

Observer

Autumnal
Equinox
(September)
12 Hr

Vernal
Equinox
(March)
0 Hr

23.5° S

Zenith

-45° Declination

-90° Declination S

To describe an object's location in the sky, we imagine a great circle through the celestial poles and the object and call this the object's *hour circle*. Where the sun in its path crosses the celestial equator each year around March 21 is called the *vernal equinox*, and it is this line that is the reference for the east-west coordinate of the object. Because Earth's axis is inclined 23.5˚ to the plane of its orbit around the sun, objects in the solar system (such as the planets and, from our perspective, the sun) move across the celestial sphere not along the equator, but rather in their own orbits, most of which are in nearly the same plane as Earth's orbit. This imaginary path of the sun's apparent motion, called the ecliptic, is a curving line that runs around the sphere ranging between 23.5˚ north and 23.5˚ south. The constellations of the zodiac all lie on the ecliptic. The object's elevation above the celestial equator is called *declination*.

The coordinates of the object, then, are given by its *declination* and its *right ascension* or hour angle between the object's hour circle and the vernal equinox. Declination is expressed in degrees (0° to +90° if north of the equator, 0° to -90° if south of the equator). Right ascension is expressed either in degrees (0° to 360° measured eastward from the vernal equinox) or, more commonly, in hours, minutes, and seconds of time (0 to 24 hours).

Declination and right ascension are absolute coordinates regardless of the observer's location on Earth or the time of observation. The only exception is due to the slight 26,000-year cyclic change in the equatorial coordinates because of the precession of Earth's axis. 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. For example, in the time of ancient Rome, the vernal equinox was located in the constellation of Aries. It is now moving into the constellation of Aquarius.

Precessional Path of the North Celestial Pole
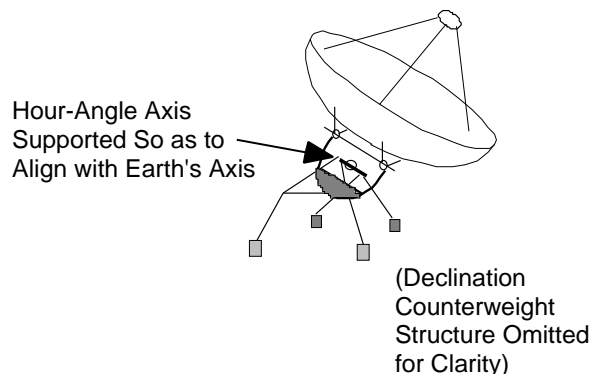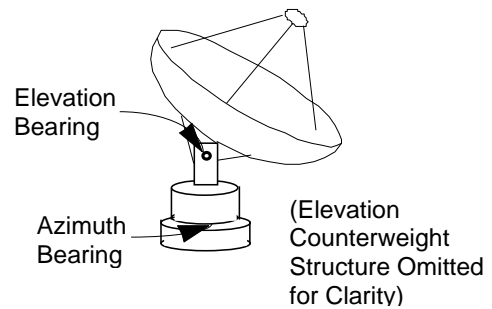(Earth's Axis Projected on the Northern Sky)
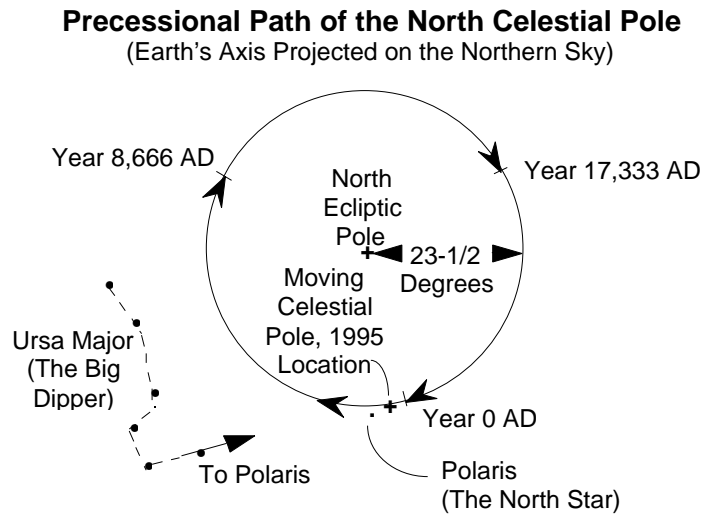
For this reason, sky almanacs identify the date and time of the instant used as the date of reference, or *epoch*, and provide equations for updating data based on the almanac to the current date. Epochs are named in 50-year increments. The 1950 epoch, for example, gives the coordinates precisely as they were on January 1, 1950.

Coordinates may also be given relative to the observer's location and time of observation. The great circle that passes through the celestial poles and the zenith is called the *meridian circle*. The angle between the object's hour circle and the meridian circle is the object's *hour angle*. The hour angle increases with time, being negative before the object's hour circle crosses the meridian and positive afterwards. Hour angle is measured either in degrees or hours, minutes, and seconds of sidereal time.

Radio telescopes are designed with mountings that are engineered to take best advantage of either the hour angle-declination (HA-DEC) coordinate system or the azimuth-elevation (AZ-EL) system (also called the altitude-elevation system, or ALT-EL). In an HA-DEC system, the HA axis is parallel to Earth's axis of rotation. In this way, since Earth is turning toward the east, the telescope is mounted to turn toward the west (backwards) on an axis exactly parallel to Earth's, thus cancelling out the east-west motion and simplifying the task of tracking objects in the sky. Thus, the mounting built for a telescope near the equator would appear different from one built for use in high latitudes. AZ-EL systems would appear the same no matter where on Earth they are being used.

HA-DEC Mount

AZ-EL Mount

Hour-Angle Axis
Supported So as to
Align with Earth's Axis

Elevation
Bearing

Azimuth
Bearing

(Declination
Counterweight
Structure Omitted
for Clarity)

(Elevation
Counterweight
Structure Omitted
for Clarity)

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. The GAVRT uses an HA-DEC mount.
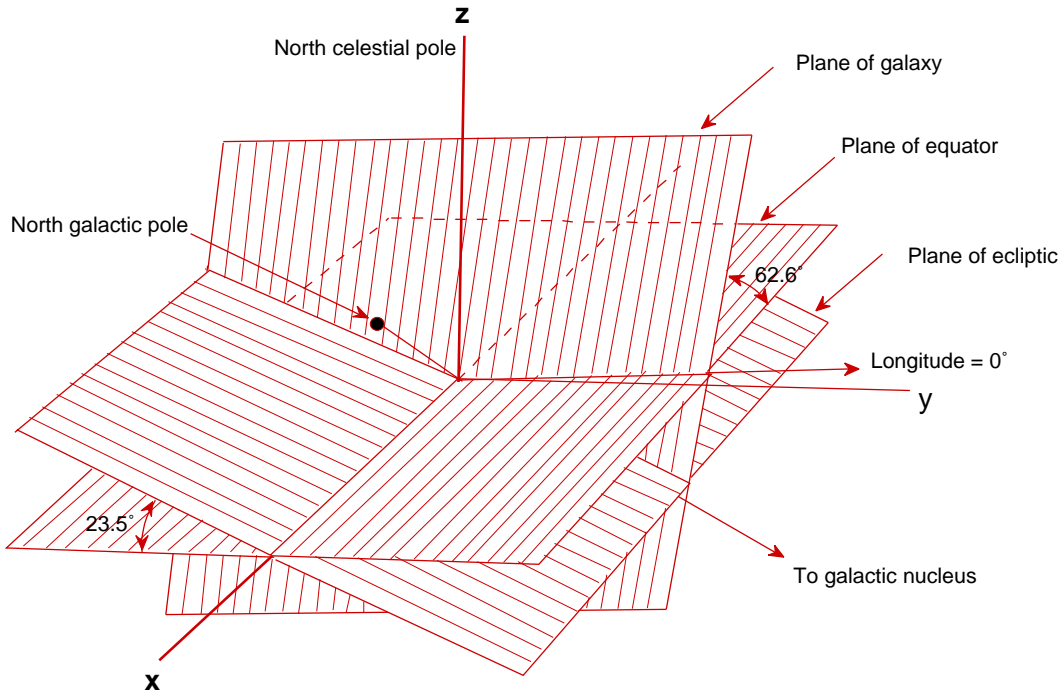
Ecliptic Coordinate System

In the ecliptic coordinate system, the reference is the plane of the ecliptic—that is, the plane formed by Earth's orbit around the sun. The orbits of the other planets in the solar system, with the except of Pluto, lie within 7° of this plane. (Pluto's orbit is inclined 17° to the ecliptic.) The coordinates of an object are given as celestial longitude, measured eastward along the ecliptic from the vernal equinox, and celestial latitude, measured north (+) or south (-) from the ecliptic. This system is handy for studying the solar system.

Galactic Coordinate System

In the galactic coordinate system, the reference is a plane through the sun parallel to the mean plane of the galaxy. By specifying the orientation of the north galactic pole in terms of its equatorial coordinates, equatorial coordinates can be converted into galactic coordinates, and vice versa, using transformation equations on a pocket calculator.

Galactic Coordinate System

z

North celestial pole

Plane of galaxy

Plane of equator

North galactic pole

Plane of ecliptic

62.6°

Longitude = 0°

y

23.5°

To galactic nucleus

x

Latitude in this system is given in degrees, + toward the north galactic pole, - toward the south galactic pole. Longitude is measured along the galactic equator to the east from the galactic center, with 0° at the intersection of the galactic equator with the celestial equator.

Recap

1. A sidereal day is approximately four minutes _____ than a solar day.

2. The period of the precession of Earth's axis is about _____ years.

3. _____ is the point directly over the observer's head.

4. In the horizon system, an object's coordinates are given in _____ for the vertical coordinate and _____ for the horizontal coordinate.

5. In the equatorial coordinate system, objects in the sky are imagined to be positioned on the inside surface of a huge celestial _____.

6. A great circle through the celestial poles and an observed object is called the object's

   _____ _____.

7. The _____ _____ is the point on the celestial sphere where the sun crosses the intersection of the celestial equator and the plane of Earth's orbit around the sun (the ecliptic).

8. In the equatorial system, an object's coordinates are given in _____ for the north-south coordinate, and _____ _____ for the east west coordinate.

9. In an hour angle-declination (HA-DEC) radio telescope antenna, the HA axis is parallel to

   _____ _____ _____.

10. Because Earth rotates on its axis once in 24 hours, a HA-DEC telescope can track a star by rotating in the _____ direction every 24 hours.

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1. shorter   2. 26,000   3. Zenith   4. elevation, azimuth   5. sphere   6. hour circle   7. vernal equinox   8. declination, right ascension   9. Earth's rotation axis   10. opposite

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For Further Study

- *Precession of Earth's axis:* Kaufmann, 26-29; Morrison et al., 70-72.

- *Sidereal time:* Kaufmann, 31; Morrison et al., 83-84.

- *Astronomical coordinate and timekeeping systems:* Morrison et al., 75-86, 651