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CELESTIAL NAVIGATION

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CHAPTER 15

NAVIGATIONAL ASTRONOMY

PRELIMINARY CONSIDERATIONS

1500. Definition

Astronomy predicts the future positions and motions of celestial bodies and seeks to understand and explain their physical properties. Navigational astronomy, dealing principally with celestial coordinates, time, and the apparent motions of celestial bodies, is the branch of astronomy most important to the navigator. The symbols commonly recognized in navigational astronomy are given in Table 1500.

Celestial Bodies

☉	Sun	☉̲ ☾̲	Lower limb
☾	Moon	⊖ ☾	Center
☿	Mercury	☉̅ ☾̅	Upper limb
♀	Venus	●	New moon
⊕	Earth	◐	Crescent moon
♂	Mars	◐	First quarter
♃	Jupiter	◐	Gibbous moon
♄	Saturn	○	Full moon
♅	Uranus	◑	Gibbous moon
♆	Neptune	◑	Last quarter
♇	Pluto	◑	Crescent moon
☆	Star		
☆-P	Star-planet altitude correction (altitude)		

Miscellaneous Symbols

y	Years	✳	Interpolation impractical
m	Months	°	Degrees
d	Days	′	Minutes of arc
h	Hours	″	Seconds of arc
m	Minutes of time	☌	Conjunction
s	Seconds of time	☍	Opposition
▬	Remains below horizon	□	Quadrature
▭	Remains above horizon	☊	Ascending node
////	Twilight all night	☋	Descending node

Signs of the Zodiac

♈	Aries (vernal equinox)	♎	Libra (autumnal equinox)
♉	Taurus	♏	Scorpius
♊	Gemini	♐	Sagittarius
♋	Cancer (summer solstice)	♑	Capricornus (winter solstice)
♌	Leo	♒	Aquarius
♍	Virgo	♓	Pisces

Table 1500. Astronomical symbols.

1501. The Celestial Sphere

Looking at the sky on a dark night, imagine that celestial bodies are located on the inner surface of a vast, earth-centered sphere. This model is useful since we are only interested in the relative positions and motions of celestial bodies on this imaginary surface. Understanding the concept of the celestial sphere is most important when discussing sight reduction in Chapter 20.

1502. Relative And Apparent Motion

Celestial bodies are in constant motion. There is no fixed position in space from which one can observe absolute motion. Since all motion is relative, the position of the observer must be noted when discussing planetary motion. From the earth we see apparent motions of celestial bodies on the celestial sphere. In considering how planets follow their orbits around the sun, we assume a hypothetical observer at some distant point in space. When discussing the rising or setting of a body on a local horizon, we must locate the observer at a particular point on the earth because the setting sun for one observer may be the rising sun for another.

Motion on the celestial sphere results from the motions in space of both the celestial body and the earth. Without special instruments, motions toward and away from the earth cannot be discerned.

1503. Astronomical Distances

Consider the celestial sphere as having an infinite radius because distances between celestial bodies are remarkably vast. The difficulty of illustrating astronomical distances is indicated by the fact that if the earth were represented by a circle one inch in diameter, the moon would be a circle one-fourth inch in diameter at a distance of 30 inches, the sun would be a circle nine feet in diameter at

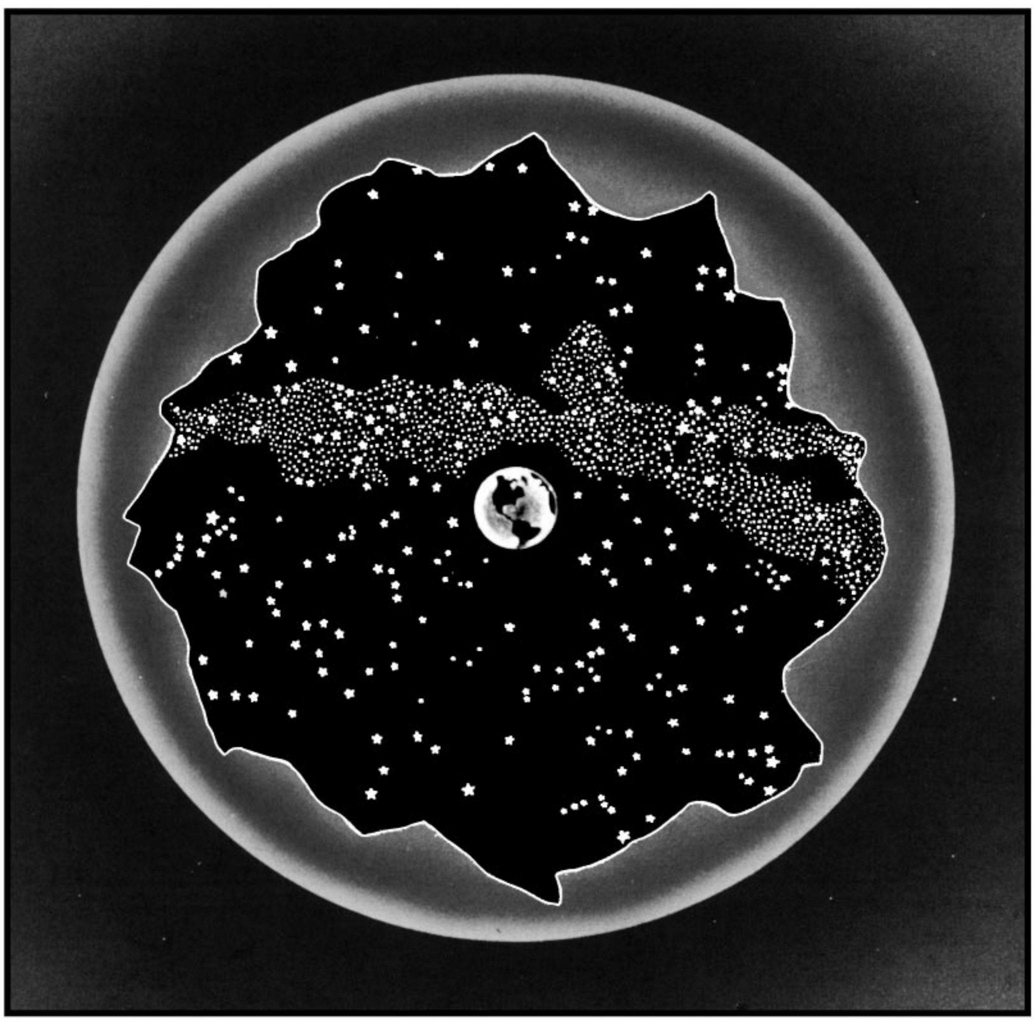

Figure 1501. The celestial sphere.

a distance of nearly a fifth of a mile, and Pluto would be a circle half an inch in diameter at a distance of about seven miles. The nearest star would be one-fifth the actual distance to the moon.

Because of the size of celestial distances, it is inconvenient to measure them in common units such as the mile or kilometer. The mean distance to our nearest neighbor, the moon, is 238,900 miles. For convenience this distance is sometimes expressed in units of the equatorial radius of the earth: 60.27 earth radii.

Distances between the planets are usually expressed in terms of the **astronomical unit (AU)**, the mean distance between the earth and the sun. This is approximately 92,960,000 miles. Thus the mean distance of the earth from the sun is 1 A.U. The mean distance of Pluto, the outermost known planet in our solar system, is 39.5 A.U. Expressed in astronomical units, the mean distance from the earth to the moon is 0.00257 A.U.

Distances to the stars require another leap in units. A commonly-used unit is the **light-year**, the distance light travels in one year. Since the speed of light is about 1.86×10^5 miles per second and there are about 3.16×10^7 seconds per year, the length of one light-year is about 5.88×10^{12} miles. The nearest stars, Alpha Centauri and its neighbor Proxima, are 4.3 light-years away. Relatively few stars are less than 100 light-years away. The nearest galaxies, the Clouds of Magellan, are 150,000 to 200,000 light years away. The most distant galaxies observed by astronomers are several billion light years away.

1504. Magnitude

The relative brightness of celestial bodies is indicated by a scale of stellar **magnitudes**. Initially, astronomers divided the stars into 6 groups according to brightness. The 20 brightest were classified as of the first magnitude, and the dimmest were of the sixth magnitude. In modern times, when it became desirable to define more precisely the limits of magnitude, a first magnitude star was considered 100 times brighter than one of the sixth magnitude. Since the fifth root of 100 is 2.512, this number is considered the **magnitude ratio**. A first magnitude star is 2.512 times as bright as a second magnitude star, which is 2.512 times as bright as a third magnitude star,. A second magnitude is $2.512 \times 2.512 = 6.310$ times as bright as a fourth magnitude star. A first magnitude star is 2.512^{20} times as bright as a star of the 21st magnitude, the dimmest that can be seen through a 200-inch telescope.

Brightness is normally tabulated to the nearest 0.1 magnitude, about the smallest change that can be detected by the unaided eye of a trained observer. All stars of magnitude 1.50 or brighter are popularly called “first magnitude” stars. Those between 1.51 and 2.50 are called “second magnitude” stars, those between 2.51 and 3.50 are called “third magnitude” stars, etc. Sirius, the brightest star, has a magnitude of –1.6. The only other star with a negative magnitude is Canopus, –0.9. At greatest brilliance Venus has a magnitude of about –4.4. Mars, Jupiter, and Saturn are sometimes of negative magnitude. The full moon has a magnitude of about –12.6, but varies somewhat. The magnitude of the sun is about –26.7.

THE UNIVERSE

1505. The Solar System

The **sun**, the most conspicuous celestial object in the sky, is the central body of the solar system. Associated with it are at least nine principal **planets** and thousands of asteroids, comets, and meteors. Some planets like earth have satellites.

1506. Motions Of Bodies Of The Solar System

Astronomers distinguish between two principal motions of celestial bodies. **Rotation** is a spinning motion about an axis within the body, whereas **revolution** is the motion of a body in its orbit around another body. The body around which a celestial object revolves is known as that body’s **primary**. For the satellites, the primary is a planet. For the planets and other bodies of the solar system, the primary is the sun. The entire solar system is held together by the gravitational force of the sun. The whole system revolves around the center of the Milky Way galaxy (section 1515), and the Milky Way is in motion relative to its neighboring galaxies.

The hierarchies of motions in the universe are caused by the force of gravity. As a result of gravity, bodies attract each other in proportion to their masses and to the inverse square of the distances between them. This force causes the planets to go around the sun in nearly circular, elliptical orbits.

In each planet’s orbit, the point nearest the sun is called the **perihelion**. The point farthest from the sun is called the **aphelion**. The line joining perihelion and aphelion is called the **line of apsides**. In the orbit of the moon, the point nearest the earth is called the **perigee**, and that point farthest from the earth is called the **apogee**. Figure 1506 shows the orbit of the earth (with exaggerated eccentricity), and the orbit of the moon around the earth.

1507. The Sun

The sun dominates our solar system. Its mass is nearly a thousand times that of all other bodies of the solar system combined. Its diameter is about 866,000 miles. Since it is a star, it generates its own energy through thermonuclear reactions, thereby providing heat and light for the entire solar system.

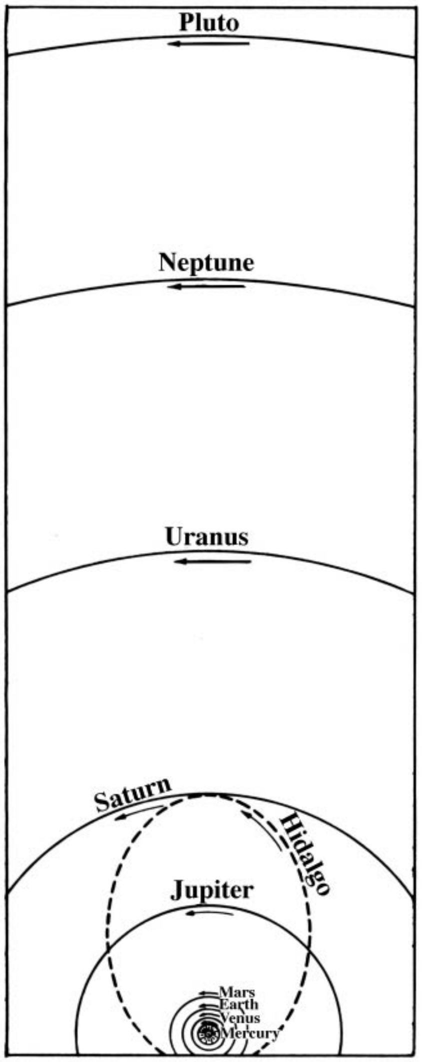

Figure 1505. Relative size of planetary orbits.

The distance from the earth to the sun varies from 91,300,000 at perihelion to 94,500,000 miles at aphelion. When the earth is at perihelion, which always occurs early in January, the sun appears largest, 32.6' in diameter. Six months later at aphelion, the sun's apparent diameter is a minimum of 31.5'.

Observations of the sun's surface (called the **photosphere**) reveal small dark areas called **sunspots**. These are areas of intense magnetic fields in which relatively cool gas (at 7000°F.) appears dark in contrast to the surrounding hotter gas (10,000°F.). Sunspots vary in size from perhaps 50,000 miles in diameter to the smallest spots that can be detected (a few hundred miles in diameter). They generally appear in groups. Large sunspots can be seen without a telescope if the eyes are protected, as by the shade glasses of a sextant.

Surrounding the photosphere is an outer **corona** of very hot but tenuous gas. This can only be seen during an eclipse of the sun, when the moon blocks the light of the photosphere.

The sun is continuously emitting charged particles, which form the **solar wind**. As the solar wind sweeps past the earth, these particles interact with the earth's magnetic field. If the solar wind is particularly strong, the interaction can produce magnetic storms which adversely affect radio signals on the earth. At such times the auroras are particularly brilliant and widespread.

The sun is moving approximately in the direction of Vega at about 12 miles per second, or about two-thirds as fast as the earth moves in its orbit around the sun. This is in addition to the general motion of the sun around the center of our galaxy.

1508. Planets

The principal bodies orbiting the sun are called **planets**. Nine principal planets are known: Mercury, Venus, Earth,

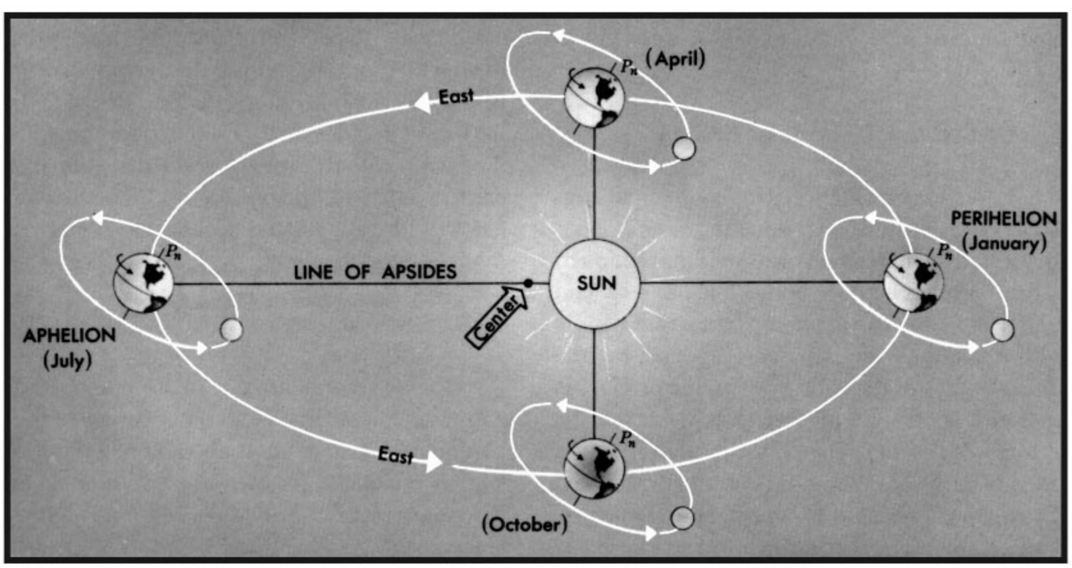

Figure 1506. Orbits of the earth and moon.

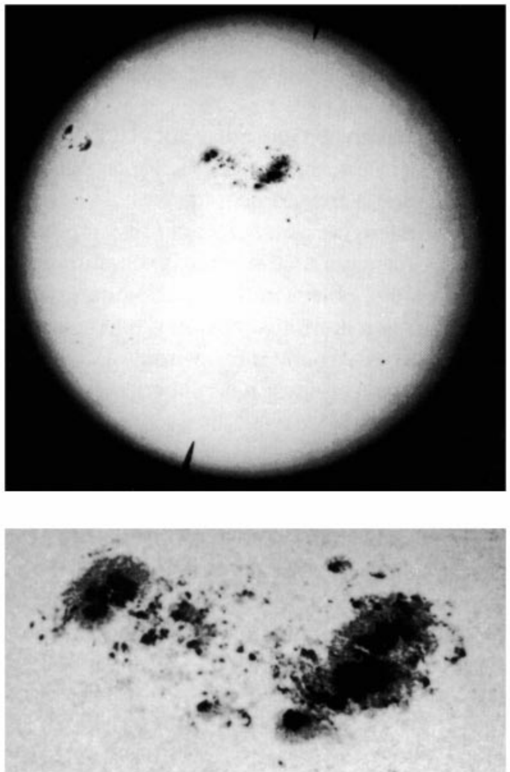

Figure 1507. Whole solar disk and an enlargement of the great spot group of April 7, 1947.
Courtesy of Mt. Wilson and Palomar Observatories.

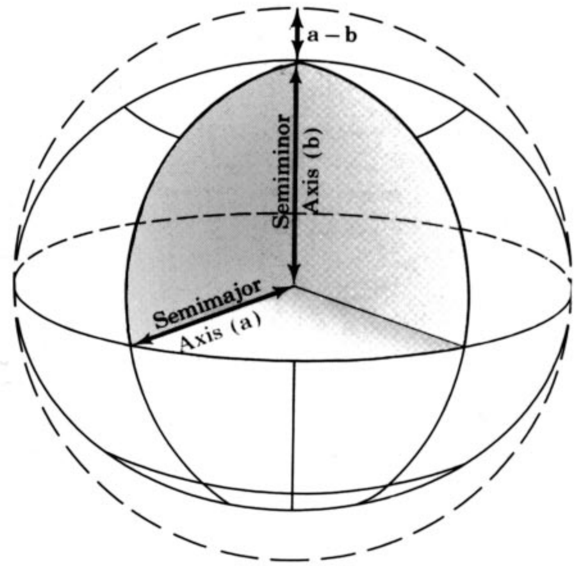

Figure 1509. Oblate spheroid or ellipsoid of revolution.

Figure 1508a

Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto. Of these, only four are commonly used for celestial navigation: Venus, Mars, Jupiter, and Saturn.

Except for Pluto, the orbits of the planets lie in nearly the same plane as the earth's orbit. Therefore, as seen from the earth, the planets are confined to a strip of the celestial sphere called the **ecliptic**.

The two planets with orbits smaller than that of the earth are called **inferior planets**, and those with orbits larger than that of the earth are called **superior planets**. The four planets nearest the sun are sometimes called the inner planets, and the others the outer planets. Jupiter, Saturn, Uranus, and Neptune are so much larger than the others that they are sometimes classed as major planets. Uranus is barely visible to the unaided eye; Neptune and Pluto are not visible without a telescope.

Planets can be identified in the sky because, unlike the stars, they do not twinkle. The stars are so distant that they are virtually point sources of light. Therefore the tiny stream of light from a star is easily scattered by normal motions of air in the atmosphere causing the affect of twinkling. The naked-eye planets, however, are close enough to present perceptible disks. The broader stream of light from a planet is not easily disrupted unless the planet is low on the horizon or the air is especially turbulent.

The orbits of many thousands of tiny minor planets or asteroids lie chiefly between the orbits of Mars and Jupiter. These are all too faint to be seen with the naked eye.

1509. The Earth

In common with other planets, the earth **rotates** on its axis and **revolves** in its orbit around the sun. These motions are the principal source of the daily apparent motions of other celestial bodies. The earth's rotation also causes a deflection of water and air currents to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. Because of the earth's rotation, high tides on the open sea lag behind the meridian transit of the moon.

For most navigational purposes, the earth can be considered a sphere. However, like the other planets, the earth is approximately an **oblate spheroid**, or **ellipsoid of revolution**, flattened at the poles and bulged at the equator. See Figure 1509. Therefore, the polar diameter is less than the equatorial diameter, and the meridians are slightly elliptical, rather than circular. The dimensions of the earth are recomputed from time to time, as additional and more precise measurements become available. Since the earth is not exactly an ellipsoid, results differ slightly when equally precise and extensive measurements are made on different parts of the surface.

1510. Inferior Planets

Since Mercury and Venus are inside the earth's orbit, they always appear in the neighborhood of the sun. Over a period of weeks or months, they appear to oscillate back and forth from one side of the sun to the other. They are seen either in the eastern sky before sunrise or in the western sky after sunset. For brief periods they disappear into the sun's glare. At this time they are between the earth and sun (known as **inferior conjunction**) or on the opposite side of the sun from the earth (**superior conjunction**). On rare occasions at inferior conjunction, the planet will cross the face of the sun as seen from the earth. This is known as a **transit of the sun**.

When Mercury or Venus appears most distant from the sun in the evening sky, it is at greatest eastern elongation. (Although the planet is in the western sky, it is at its easternmost point from the sun.) From night to night the planet will approach the sun until it disappears into the glare of twilight. At this time it is moving between the earth and sun to inferior conjunction. A few days later, the planet will appear in the morning sky at dawn. It will gradually move away from the sun to western elongation, then move back toward the sun. After disappearing in the morning twilight, it will move behind the sun to superior conjunction. After this it will reappear in the evening sky, heading toward eastern elongation.

Mercury is never seen more than about 28° from the sun. For this reason it is not commonly used for navigation. Near greatest elongation it appears near the western horizon after sunset, or the eastern horizon before sunrise. At these times it resembles a first magnitude star and is sometimes reported as a new or strange object in the sky. The interval during which it appears as a morning or evening star can vary from about 30 to 50 days. Around inferior conjunction, Mercury disappears for about 5 days; near superior conjunction, it disappears for about 35 days. Observed with a telescope, Mercury is seen to go through phases similar to those of the moon.

Venus can reach a distance of 47° from the sun, allowing it to dominate the morning or evening sky. At maximum brilliance, about five weeks before and after inferior conjunction, it has a magnitude of about –4.4 and is brighter than any other object in the sky except the sun and moon.

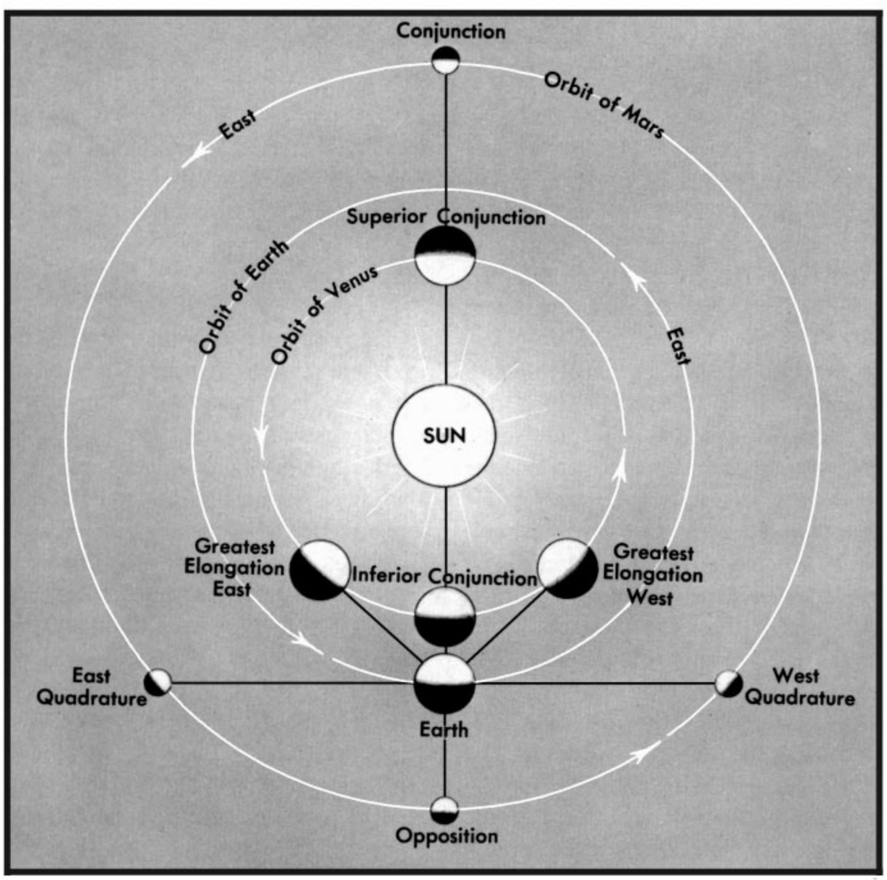

Figure 1510. Planetary configurations.

At these times it can be seen during the day and is sometimes observed for a celestial line of position. It appears as a morning or evening star for approximately 263 days in succession. Near inferior conjunction Venus disappears for 8 days; around superior conjunction it disappears for 50 days. When it transits the sun, Venus can be seen to the naked eye as a small dot about the size of a group of sunspots. Through binoculars, Venus can be seen to go through a full set of phases.

1511. Superior Planets

As planets outside the earth's orbit, the superior planets are not confined to the proximity of the sun as seen from the earth. They can pass behind the sun (conjunction), but they cannot pass between the sun and the earth. Instead we see them move away from the sun until they are opposite the sun in the sky (**opposition**). When a superior planet is near conjunction, it rises and sets approximately with the sun and is thus lost in the sun's glare. Gradually it becomes visible in the early morning sky before sunrise. From day to day, it rises and sets earlier, becoming increasingly visible through the late night hours until dawn. Approaching opposition, the planet will rise in the late evening, until at opposition, it will rise when the sun sets, be visible throughout the night, and set when the sun rises.

Observed against the background stars, the planets normally move eastward in what is called **direct motion**. Approaching opposition, however, a planet will slow down, pause (at a stationary point), and begin moving westward (**retrograde motion**), until it reaches the next stationary point and resumes its direct motion. This is not because the planet is moving strangely in space. This relative, observed motion results because the faster moving earth is catching up with and passing by the slower moving superior planet.

The superior planets are brightest and closest to the earth at opposition. The interval between oppositions is known as the **synodic period**. This period is longest for the closest planet, Mars, and becomes increasingly shorter for the outer planets.

Unlike Mercury and Venus, the superior planets do not go through a full cycle of phases. They are always full or highly gibbous.

Mars can usually be identified by its orange color. It can become as bright as magnitude –2.8 but is more often between –1.0 and –2.0 at opposition. Oppositions occur at intervals of about 780 days. The planet is visible for about 330 days on either side of opposition. Near conjunction it is lost from view for about 120 days. Its two satellites can only be seen in a large telescope.

Jupiter, largest of the known planets, normally outshines Mars, regularly reaching magnitude –2.0 or brighter at opposition. Oppositions occur at intervals of about 400 days, with the planet being visible for about 180 days before and after opposition. The planet disappears for about 32 days at conjunction. Four satellites (of a total 16 currently known) are bright enough to be seen in binoculars. Their motions around Jupiter can be observed over the course of several hours.

Saturn, the outermost of the navigational planets, comes to opposition at intervals of about 380 days. It is visible for about 175 days before and after opposition, and disappears for about 25 days near conjunction. At opposition it becomes as bright as magnitude +0.8 to –0.2. Through good, high powered binoculars, Saturn appears as elongated because of its system of rings. A telescope is needed to examine the rings in any detail. Saturn is now known to have at least 18 satellites, none of which are visible to the unaided eye.

Uranus, **Neptune** and **Pluto** are too faint to be used for navigation; Uranus, at about magnitude 5.5, is faintly visible to the unaided eye.

1512. The Moon

The **moon** is the only satellite of direct navigational interest. It revolves around the earth once in about 27.3 days, as measured with respect to the stars. This is called the **sidereal month**. Because the moon rotates on its axis with the same period with which it revolves around the earth, the same side of the moon is always turned toward the earth. The cycle of phases depends on the moon's revolution with respect to the sun. This synodic month is approximately 29.53 days, but can vary from this average by up to a quarter of a day during any given month.

When the moon is in conjunction with the sun (new moon), it rises and sets with the sun and is lost in the sun's glare. The moon is always moving eastward at about 12.2° per day, so that sometime after conjunction (as little as 16 hours, or as long as two days), the thin lunar crescent can be observed after sunset, low in the west. For the next couple of weeks, the moon will **wax**, becoming more fully illuminated. From day to day, the moon will rise (and set) later, becoming increasingly visible in the evening sky, until (about 7 days after new moon) it reaches first quarter, when the moon rises about noon and sets about midnight. Over the next week the moon will rise later and later in the afternoon until full moon, when it rises about sunset and dominates the sky throughout the night. During the next couple of weeks the moon will **wane**, rising later and later at night. By last quarter (a week after full moon), the moon rises about midnight and sets at noon. As it approaches new moon, the moon becomes an increasingly thin crescent, and is seen only in the early morning sky. Sometime before conjunction (16 hours to 2 days before conjunction) the thin crescent will disappear in the glare of morning twilight.

At full moon, the sun and moon are on opposite sides of the ecliptic. Therefore, in the winter the full moon rises early, crosses the celestial meridian high in the sky, and sets late; as the sun does in the summer. In the summer the full moon rises in the southeastern part of the sky (Northern Hemisphere), remains relatively low in the sky, and sets along the southwestern horizon after a short time above the horizon.

At the time of the autumnal equinox, the part of the ecliptic opposite the sun is most nearly parallel to the horizon. Since the eastward motion of the moon is approximately along the ecliptic, the delay in the time of

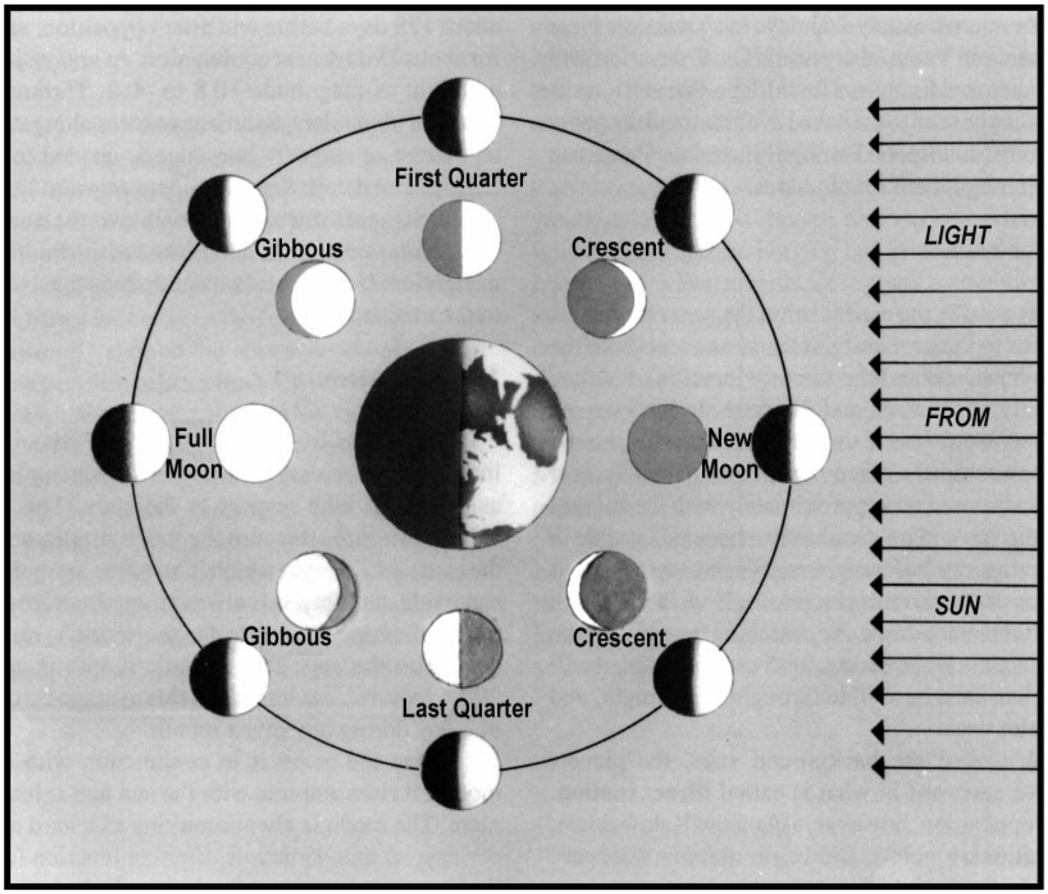

Figure 1512. Phases of the moon. The inner figures of the moon represent its appearance from the earth.

rising of the full moon from night to night is less than at other times of the year. The full moon nearest the autumnal equinox is called the **harvest moon**; the full moon a month later is called the **hunter's moon**. See Figure 1512.

1513. Comets And Meteors

Although **comets** are noted as great spectacles of nature, very few are visible without a telescope. Those that become widely visible do so because they develop long, glowing tails. Comets are swarms of relatively small solid bodies held together by gravity. Around the nucleus, a gaseous head or coma and tail may form as the comet approaches the sun. The tail is directed away from the sun, so that it follows the head while the comet is approaching the sun, and precedes the head while the comet is receding. The total mass of a comet is very small, and the tail is so thin that stars can easily be seen through it. In 1910, the earth passed through the tail of Halley's comet without noticeable effect.

Compared to the well-ordered orbits of the planets, comets are erratic and inconsistent. Some travel east to west and some west to east, in highly eccentric orbits inclined at any angle to the ecliptic. Periods of revolution range from about 3 years to thousands of years. Some comets may speed away from the solar system after gaining velocity as they pass by Jupiter or Saturn.

The short-period comets long ago lost the gasses needed to form a tail. Long period comets, such as Halley's comet, are more likely to develop tails. The visibility of a comet depends very much on how close it approaches the earth. In 1910, Halley's comet spread across the sky. Yet when it returned in 1986, the earth was not well situated to get a good view, and it was barely visible to the unaided eye.

Meteors, popularly called **shooting stars**, are tiny, solid bodies too small to be seen until heated to incandescence by air friction while passing through the earth's atmosphere. A particularly bright meteor is called a **fireball**. One that explodes is called a **bolide**. A meteor that survives its trip through the atmosphere and lands as a solid particle is called a **meteorite**.

Vast numbers of meteors exist. It has been estimated that an average of about 1,000,000 bright enough to be seen enter the earth's atmosphere each hour, and many times this number undoubtedly enter, but are too small to attract attention.

Meteor showers occur at certain times of the year when the earth passes through **meteor swarms**, the scattered remains of comets that have broken up. At these times the

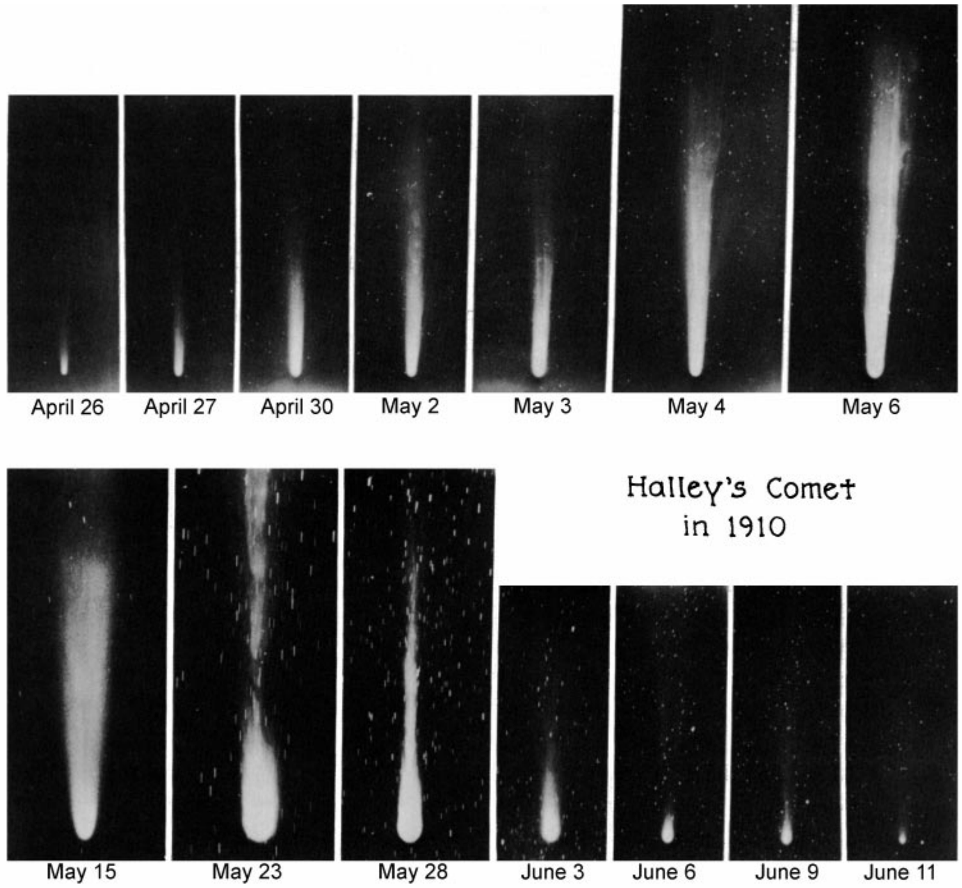

Figure 1513. Halley's Comet; fourteen views, made between April 26 and June 11, 1910.
Courtesy of Mt. Wilson and Palomar Observatories.

number of meteors observed is many times the usual number.

A faint glow sometimes observed extending upward approximately along the ecliptic before sunrise and after sunset has been attributed to the reflection of sunlight from quantities of this material. This glow is called **zodiacal light**. A faint glow at that point of the ecliptic 180° from the sun is called the **gegenschein** or **counterglow**.

1514. Stars

Stars are distant suns, in many ways resembling the body which provides the earth with most of its light and heat. Like the sun, stars are massive balls of gas that create their own energy through thermonuclear reactions.

Although stars differ in size and temperature, these differences are apparent only through analysis by astronomers. Some differences in color are noticeable to the unaided eye. While most stars appear white, some (those of lower temperature) have a reddish hue. In Orion, blue Rigel and red Betelgeuse, located on opposite sides of the belt, constitute a noticeable contrast.

The stars are not distributed uniformly around the sky. Striking configurations, known as **constellations**, were noted by ancient peoples, who supplied them with names and myths. Today astronomers use constellations—88 in all—to identify areas of the sky.

Under ideal viewing conditions, the dimmest star that can be seen with the unaided eye is of the sixth magnitude. In the entire sky there are about 6,000 stars of this magnitude or brighter. Half of these are below the horizon at any time. Because of the greater absorption of light near the horizon, where the path of a ray travels for a greater distance through the atmosphere, not more than perhaps 2,500 stars are visible to the unaided eye at any time. However, the average navigator seldom uses more than perhaps 20 or 30 of the brighter stars.

Stars which exhibit a noticeable change of magnitude are called **variable stars**. A star which suddenly becomes several magnitudes brighter and then gradually fades is called a **nova**. A particularly bright nova is called a **supernova**.

Two stars which appear to be very close together are called a **double star**. If more than two stars are included in the group, it is called a **multiple star**. A group of a few dozen to several hundred stars moving through space together is called an **open cluster**. The Pleiades is an example of an open cluster. There are also spherically symmetric clusters of hundreds of thousands of stars known as **globular clusters**. The globular clusters are all too distant to be seen with the naked eye.

A cloudy patch of matter in the heavens is called a **nebula**. If it is within the galaxy of which the sun is a part, it is called a **galactic nebula**; if outside, it is called an **extragalactic nebula**.

Motion of a star through space can be classified by its vector components. That component in the line of sight is called **radial motion**, while that component across the line of sight, causing a star to change its apparent position relative to the background of more distant stars, is called **proper motion**.

1515. Galaxies

A **galaxy** is a vast collection of clusters of stars and clouds of gas. The earth is located in the Milky Way galaxy, a slowly spinning disk more than 100,000 light years in diameter. All the bright stars in the sky are in the Milky Way. However, the most dense portions of the galaxy are seen as the great, broad band that glows in the summer nighttime sky. When we look toward the constellation Sagittarius, we are looking toward the center of the Milky Way, 30,000 light years away.

Despite their size and luminance, almost all other galaxies are too far away to be seen with the unaided eye. An exception in the northern hemisphere is the Great Galaxy (sometimes called the Great Nebula) in Andromeda, which appears as a faint glow. In the southern hemisphere, the Large and Small Magellanic Clouds (named after Ferdinand Magellan) are the nearest known neighbors of the Milky Way. They are approximately 1,700,000 light years distant. The Magellanic Clouds can be seen as sizable glowing patches in the southern sky.

Figure 1515. Spiral nebula Messier 51, In Canes Venetici. Satellite nebula is NGC 5195.
Courtesy of Mt. Wilson and Palomar Observatories.

APPARENT MOTION

1516. Apparent Motion Due To Rotation Of The Earth

Apparent motion caused by the earth's rotation is much greater than any other observed motion of celestial bodies. It is this motion that causes celestial bodies to appear to rise along the eastern half of the horizon, climb to maximum altitude as they cross the meridian, and set along the western horizon, at about the same point relative to due west as the rising point was to due east. This apparent motion along the daily path, or **diurnal circle**, of the body is approximately parallel to the plane of the equator. It would be exactly so if rotation of the earth were the only motion and the axis of rotation of the earth were stationary in space.

The apparent effect due to rotation of the earth varies with the latitude of the observer. At the equator, where the equatorial plane is vertical (since the axis of rotation of the earth is parallel to the plane of the horizon), bodies appear to rise and set vertically. Every celestial body is above the horizon approximately half the time. The celestial sphere as seen by an observer at the equator is called the right sphere, shown in Figure 1516a.

For an observer at one of the poles, bodies having constant declination neither rise nor set (neglecting precession of the equinoxes and changes in refraction), but circle the sky, always at the same altitude, making one complete trip around the horizon each day. At the North Pole the motion is clockwise, and at the South Pole it is counterclockwise. Approximately half the stars are always above the horizon and the other half never are. The parallel sphere at the poles is illustrated in Figure 1516b.

Between these two extremes, the apparent motion is a combination of the two. On this oblique sphere, illustrated in Figure 1516c, circumpolar celestial bodies remain above the horizon during the entire 24 hours, circling the elevated celestial pole each day. The stars of Ursa Major (the Big Dipper) and Cassiopeia are circumpolar for many observers in the United States. An approximately equal part of the celestial sphere remains below the horizon during the entire day. Crux is not visible to most observers in the United States. Other bodies rise obliquely along the eastern horizon,

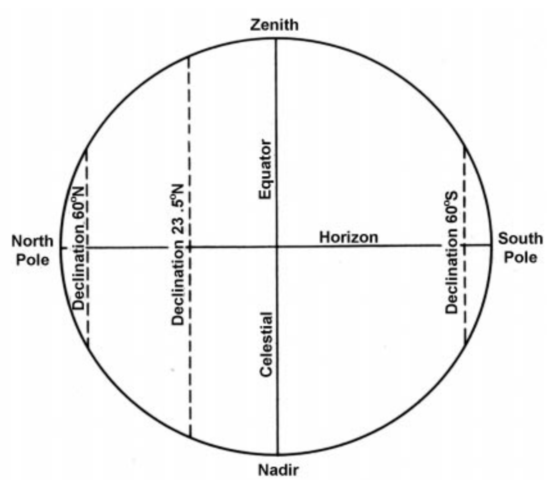

Figure 1516a. The right sphere.

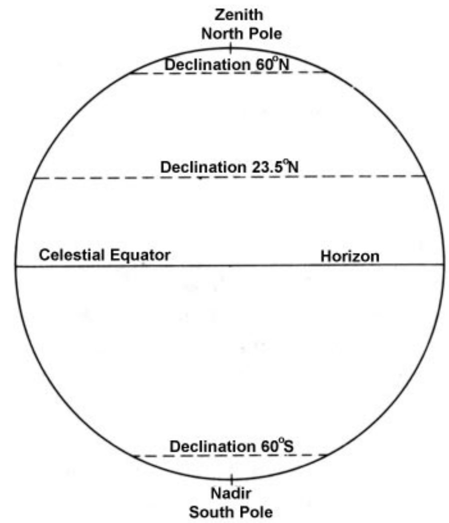

Figure 1516b. The parallel sphere.

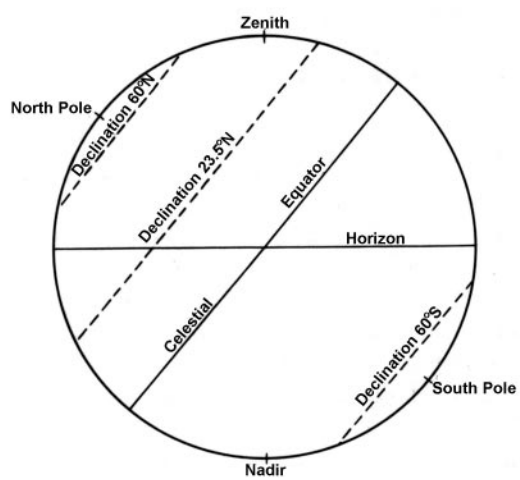

Figure 1516c. The oblique sphere at latitude 40°N.

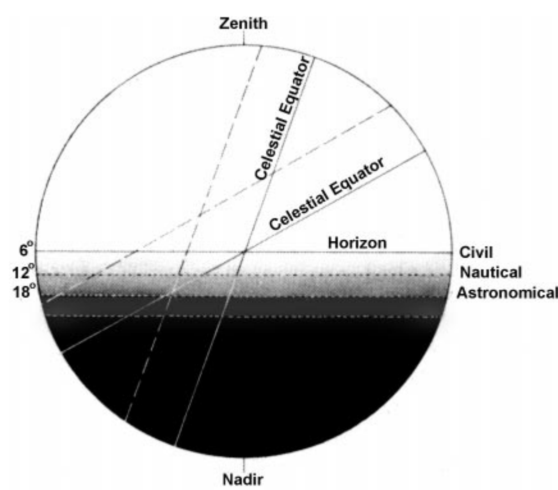

Figure 1516d. The various twilight at latitude 20°N and latitude 60°N.

climb to maximum altitude at the celestial meridian, and set along the western horizon. The length of time above the horizon and the altitude at meridian transit vary with both the latitude of the observer and the declination of the body. At the polar circles of the earth even the sun becomes circumpolar. This is the land of the midnight sun, where the sun does not set during part of the summer and does not rise during part of the winter.

The increased obliquity at higher latitudes explains why days and nights are always about the same length in the tropics, and the change of length of the day becomes greater as the latitude increases. It also explains why twilight lasts longer in higher latitudes. Twilight is the period of incomplete darkness following sunset and preceding sunrise. Evening twilight starts at sunset, and morning twilight ends at sunrise. The darker limit of twilight occurs when the center of the sun is a stated number of degrees below the celestial horizon. Three kinds of twilight are defined: civil, nautical and astronomical.

Twilight	*Lighter limit*	*Darker limit*	*At darker limit*
civil	–0°50'	–6°	Horizon clear; bright stars visible
nautical	–0°50'	–12°	Horizon not visible
astronomical	–0°50'	–18°	Full night

The conditions at the darker limit are relative and vary considerably under different atmospheric conditions

In Figure 1516d, the twilight band is shown, with the darker limits of the various kinds indicated. The nearly vertical celestial equator line is for an observer at latitude 20°N. The nearly horizontal celestial equator line is for an observer at latitude 60°N. The broken line in each case is the diurnal circle of the sun when its declination is 15°N. The relative duration of any kind of twilight at the two latitudes is indicated by the portion of the diurnal circle between the horizon and the darker limit, although it is not directly proportional to the relative length of line shown since the projection is orthographic. The duration of twilight at the higher latitude is longer, proportionally, than shown. Note that complete darkness does not occur at latitude 60°N when the declination of the sun is 15°N.

1517. Apparent Motion Due To Revolution Of The Earth

If it were possible to stop the rotation of the earth so that the celestial sphere would appear stationary, the effects of the revolution of the earth would become more noticeable. In one year the sun would appear to make one complete trip around the earth, from west to east. Hence, it would seem to move eastward a little less than 1° per day. This motion can be observed by watching the changing position of the sun among the stars. But since both sun and stars generally are not visible at the same time, a better way is to observe the constellations at the same time each night. On any night a star rises nearly four minutes earlier than on the previous night. Thus, the celestial sphere appears to shift westward nearly 1° each night, so that different constellations are associated with different seasons of the year.

Apparent motions of planets and the moon are due to a combination of their motions and those of the earth. If the rotation of the earth were stopped, the combined apparent motion due to the revolutions of the earth and other bodies would be similar to that occurring if both rotation and revolution of the earth were stopped. Stars would appear nearly stationary in the sky but would undergo a small annual cycle of change due to aberration. The motion of the earth in its orbit is sufficiently fast to cause the light from stars to appear to shift slightly in the direction of the earth's motion. This is similar to the effect one experiences when walking in vertically-falling rain that appears to come from ahead due to the observer's own forward motion. The apparent direction of the light ray from the star is the vector difference of the motion of light and the motion of the earth, similar to that of apparent wind on a moving vessel. This effect is most apparent for a body perpendicular to the line of travel of the earth in its orbit, for which it reaches a maximum value of 20.5". The effect of aberration can be noted by comparing the coordinates (declination and sidereal hour angle) of various stars throughout the year. A change is observed in some bodies as the year progresses, but at the end of the year the values have returned almost to what they were at the beginning. The reason they do not return exactly is due to proper motion and precession of the equinoxes. It is also due to nutation, an irregularity in the motion of the earth due to the disturbing effect of other celestial bodies, principally the moon. Polar motion is a slight wobbling of the earth about its axis of rotation and sometimes wandering of the poles. This motion, which does not exceed 40 feet from the mean position, produces slight variation of latitude and longitude of places on the earth.

1518. Apparent Motion Due To Movement Of Other Celestial Bodies

Even if it were possible to stop both the rotation and revolution of the earth, celestial bodies would not appear stationary on the celestial sphere. The moon would make one revolution about the earth each sidereal month, rising in the west and setting in the east. The inferior planets would appear to move eastward and westward relative to the sun, staying within the zodiac. Superior planets would appear to make one revolution around the earth, from west to east, each sidereal period.

Since the sun (and the earth with it) and all other stars are in motion relative to each other, slow apparent motions would result in slight changes in the positions of the stars relative to each other. This space motion is, in fact, observed by telescope. The component of such motion across the line of sight, called proper motion, produces a change in the apparent position of the star. The maximum which has been observed is that of Barnard's Star, which is moving at the rate of 10.3 seconds per year. This is a tenth-magnitude star, not visible to the unaided eye. Of the 57 stars listed on the daily pages of the almanacs, Rigil Kentaurus has the greatest proper motion, about 3.7 seconds per year. Arcturus, with 2.3 seconds per year, has the greatest proper motion of the navigational stars in the Northern Hemisphere. In a few thousand years proper motion will be sufficient to materially alter some familiar configurations of stars, notably Ursa Major.

1519. The Ecliptic

The **ecliptic** is the path the sun appears to take among the stars due to the annual revolution of the earth in its orbit. It is considered a great circle of the celestial sphere, inclined at an angle of about 23°26' to the celestial equator, but undergoing a continuous slight change. This angle is called the **obliquity of the ecliptic**. This inclination is due to the fact that the axis of rotation of the earth is not perpendicular to its orbit. It is this inclination which causes the sun to appear to move north and south during the year, giving the earth its seasons and changing lengths of periods of daylight.

Refer to Figure 1519a. The earth is at perihelion early in January and at aphelion 6 months later. On or about June 21, about 10 or 11 days before reaching aphelion, the northern part of the earth's axis is tilted toward the sun. The north polar regions are having continuous sunlight; the Northern Hemisphere is having its summer with long, warm days and short nights; the Southern Hemisphere is having winter with short days and long, cold nights; and the south polar region is in continuous darkness. This is the **summer solstice**. Three months later, about September 23, the earth has moved a quarter of the way around the sun, but its axis of rotation still points in about the same direction in space. The sun shines equally on both hemispheres, and days and nights are the same length over the entire world. The sun is setting at the North Pole and rising at the South Pole. The Northern Hemisphere is having its autumn, and the Southern Hemisphere its spring. This is the **autumnal equinox**. In another three months, on or about December 22, the Southern Hemisphere is tilted toward the sun and conditions are the reverse of those six months earlier; the Northern Hemisphere is having its winter, and the Southern Hemisphere its summer. This is the **winter solstice**. Three months later, when both hemispheres again receive equal amounts of sunshine, the Northern Hemisphere is having spring and the Southern Hemisphere autumn, the reverse of conditions six months before. This is the **vernal equinox**.

The word "equinox," meaning "equal nights," is applied because it occurs at the time when days and nights are of approximately equal length all over the earth. The word "solstice," meaning "sun stands still," is applied because the sun stops its apparent northward or southward motion and momentarily "stands still" before it starts in the opposite direction. This action, somewhat analogous to the "stand" of the tide, refers to the motion in a north-south direction only, and not to the daily apparent revolution around the earth. Note that it does not occur when the earth is at perihelion or aphelion. Refer to Figure 1519a. At the time of the vernal equinox, the sun is directly over the equator, crossing from the Southern Hemisphere to the Northern Hemisphere. It rises due east and sets due west, remaining above the horizon for approximately 12 hours. It is not exactly 12 hours because of refraction, semidiameter, and the height of the eye of the observer. These cause it to be above the horizon a little longer than below the horizon. Following the vernal equi-

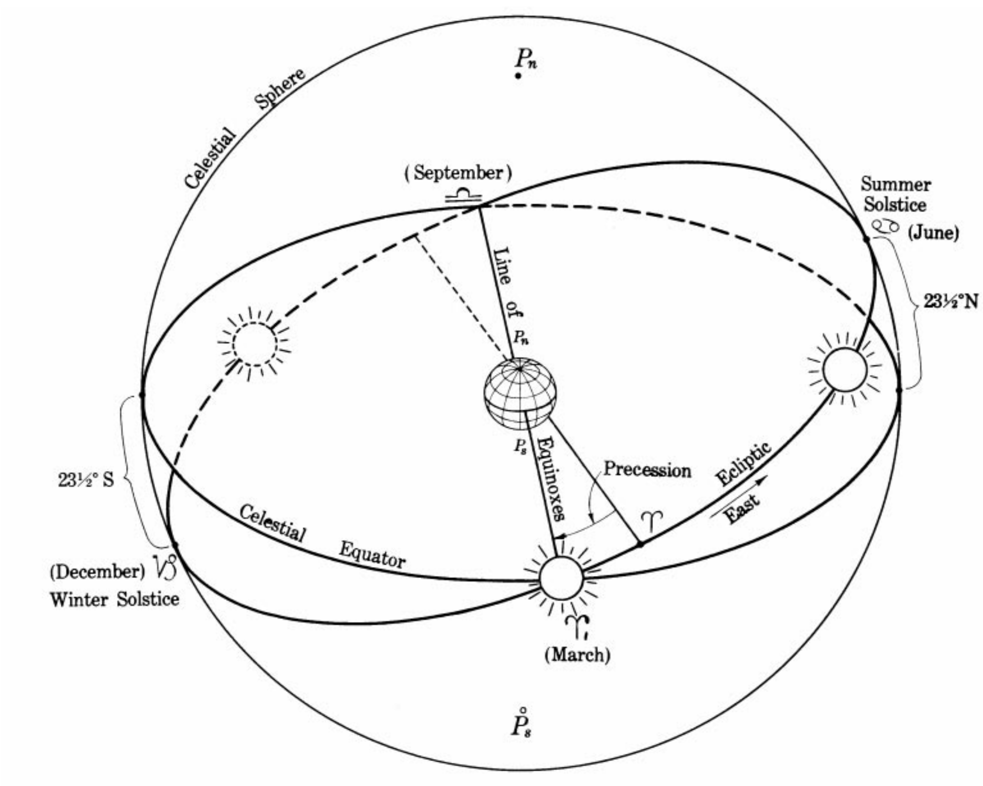

Figure 1519a. Apparent motion of the sun in the ecliptic.

nox, the northerly declination increases, and the sun climbs higher in the sky each day (at the latitudes of the United States), until the summer solstice, when a declination of about 23°26' north of the celestial equator is reached. The sun then gradually retreats southward until it is again over the equator at the autumnal equinox, at about 23°26' south of the celestial equator at the winter solstice, and back over the celestial equator again at the next vernal equinox.

The sun is nearest the earth during the northern hemisphere winter; it is not the distance between the earth and sun that is responsible for the difference in temperature during the different seasons. The reason is to be found in the altitude of the sun in the sky and the length of time it remains above the horizon. During the summer the rays are more nearly vertical, and hence more concentrated, as shown in Figure 1519b. Since the sun is above the horizon more than half the time, heat is being added by absorption during a longer period than it is being lost by radiation. This explains the lag of the seasons. Following the longest day, the earth continues to receive more heat than it dissipates, but at a decreasing proportion. Gradually the proportion decreases until a balance is reached, after which the earth cools, losing more heat than it gains. This is analogous to the day, when the highest temperatures normally occur several hours after the sun reaches maximum altitude at meridian transit. A similar lag occurs at other seasons of the year. Astronomically, the seasons begin at the equinoxes and solstices. Meteorologically, they differ from place to place.

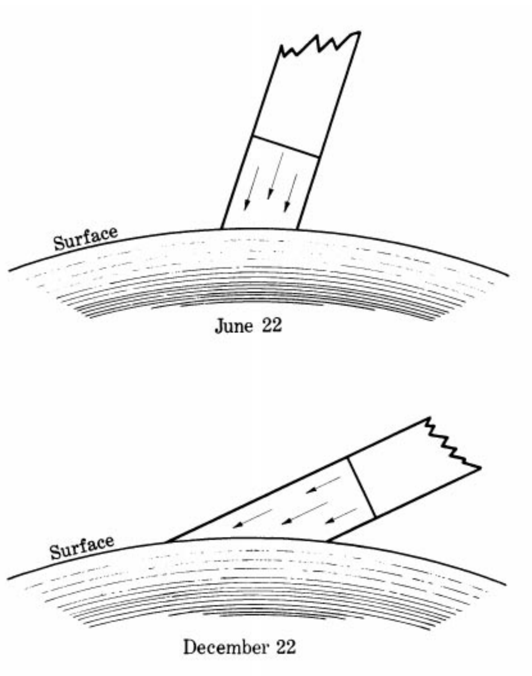

Figure 1519b. Sunlight in summer and winter. Compare the surface covered by the same amount of sunlight on the two dates.

Since the earth travels faster when nearest the sun, the northern hemisphere (astronomical) winter is shorter than its summer by about seven days.

Everywhere between the parallels of about 23°26'N and about 23°26'S the sun is directly overhead at some time during the year. Except at the extremes, this occurs twice: once as the sun appears to move northward, and the second time as it moves southward. This is the **torrid zone**. The northern limit is the **Tropic of Cancer**, and the southern limit's the **Tropic of Capricorn**. These names come from the constellations which the sun entered at the solstices when the names were first applied more than 2,000 years ago. Today, the sun is in the next constellation toward the west because of precession of the equinoxes. The parallels about 23°26' from the poles, marking the approximate limits of the circumpolar sun, are called **polar circles**, the one in the Northern Hemisphere being the **Arctic Circle** and the one in the Southern Hemisphere the **Antarctic Circle**. The areas inside the polar circles are the north and south **frigid zones**. The regions between the frigid zones and the torrid zones are the north and south **temperate zones**.

The expression "vernal equinox" and associated expressions are applied both to the *times* and *points of occurrence* of the various phenomena. Navigationally, the vernal equinox is sometimes called the **first point of Aries** (symbol ♈) because, when the name was given, the sun entered the constellation Aries, the ram, at this time. This point is of interest to navigators because it is the origin for measuring **sidereal hour angle**. The expressions March equinox, June solstice, September equinox, and December solstice are occasionally applied as appropriate, because the more common names are associated with the seasons in the Northern Hemisphere and are six months out of step for the Southern Hemisphere.

The axis of the earth is undergoing a precessional motion similar to that of a top spinning with its axis tilted. In about 25,800 years the axis completes a cycle and returns to the position from which it started. Since the celestial equator is 90° from the celestial poles, it too is moving. The result is a slow westward movement of the equinoxes and solstices, which has already carried them about 30°, or one constellation, along the ecliptic from the positions they occupied when named more than 2,000 years ago. Since sidereal hour angle is measured from the vernal equinox, and declination from the celestial equator, the coordinates of celestial bodies would be changing even if the bodies themselves were stationary. This westward motion of the equinoxes along the ecliptic is called **precession of the equinoxes**. The total amount, called **general precession**, is about 50.27 seconds per year (in 1975). It may be considered divided into two components: precession in right ascension (about 46.10 seconds per year) measured along the celestial equator, and precession in declination (about 20.04" per year) measured perpendicular to the celestial equator. The annual change in the coordinates of any given star, due to precession alone, depends upon its position on the celestial sphere, since these coordinates are measured relative to the polar axis while the precessional motion is relative to the ecliptic axis.

Due to precession of the equinoxes, the celestial poles are slowly describing circles in the sky. The north celestial pole is moving closer to Polaris, which it will pass at a distance of approximately 28 minutes about the year 2102. Following this, the polar distance will increase, and eventually other stars, in their turn, will become the Pole Star.

The precession of the earth's axis is the result of gravitational forces exerted principally by the sun and moon on the earth's equatorial bulge. The spinning earth responds to these forces in the manner of a gyroscope. Regression of the nodes introduces certain irregularities known as nutation in the precessional motion.

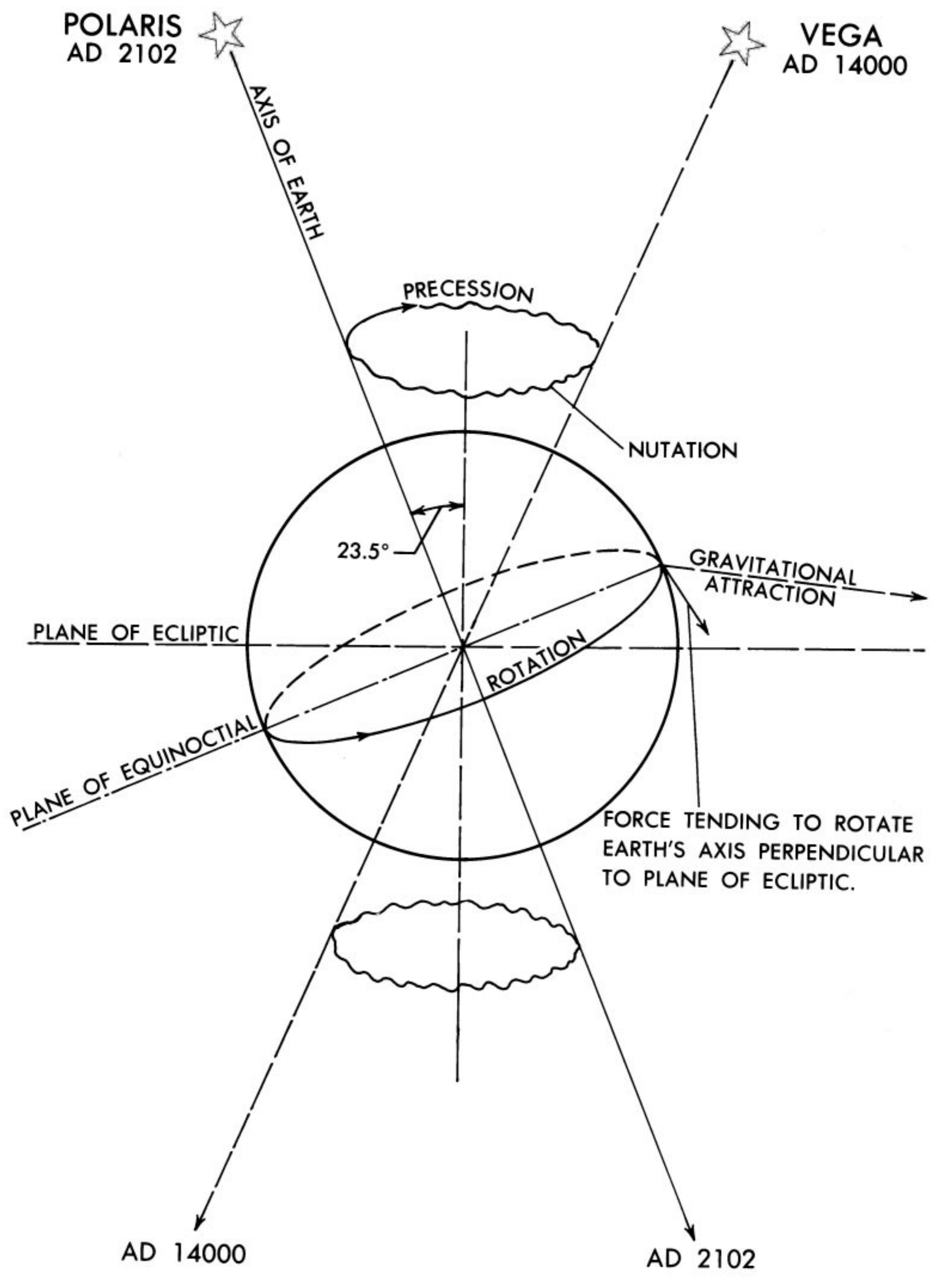

Figure 1519c. Precession and nutation.

1520. The Zodiac

The **zodiac** is a circular band of the sky extending 8° on each side of the ecliptic. The navigational planets and the moon are within these limits. The zodiac is divided into 12 sections of 30° each, each section being given the name and symbol ("sign") of a constellation. These are shown in Figure 1520. The names were assigned more than 2,000 years ago, when the sun entered Aries at the vernal equinox, Cancer at the summer solstice, Libra at the autumnal equinox, and Capricornus at the winter solstice. Because of precession, the zodiacal signs have shifted with respect to the constellations. Thus at the time of the vernal equinox, the sun is said to be at the "first point of Aries," though it is in the constellation Pisces. The complete list of signs and names is given below.

1521. Time And The Calendar

Traditionally, astronomy has furnished the basis for measurement of time, a subject of primary importance to the navigator. The **year** is associated with the revolution of the earth in its orbit. The **day** is one rotation of the earth about its axis.

The duration of one rotation of the earth depends upon the external reference point used. One rotation relative to the sun is called a **solar day**. However, rotation relative to the apparent sun (the actual sun that appears in the sky) does not provide time of uniform rate because of variations in the rate of revolution and rotation of the earth. The error due to lack of uniform rate of revolution is removed by using a fictitious **mean sun**. Thus, mean solar time is nearly equal to the average apparent solar time. Because the accumulated difference between these times, called the **equation of time**, is continually changing, the period of daylight is shifting slightly, in addition to its increase or decrease in length due to changing declination. Apparent and mean suns seldom cross the celestial meridian at the same time. The earliest sunset (in latitudes of the United States) occurs about two weeks before the winter solstice, and the latest sunrise occurs about two weeks after winter solstice. A similar but smaller apparent discrepancy occurs at the summer solstice.

Universal Time is a particular case of the measure known in general as mean solar time. Universal Time is the mean solar time on the Greenwich meridian, reckoned in days of 24 mean solar hours beginning with 0 hours at midnight. Universal Time and sidereal time are rigorously related by a formula so that if one is known the other can be found. Universal Time is the standard in the application of astronomy to navigation.

If the vernal equinox is used as the reference, a **sidereal day** is obtained, and from it, **sidereal time**. This indicates the approximate positions of the stars, and for this reason it is the basis of star charts and star finders. Because of the revolution of the earth around the sun, a sidereal day is about 3 minutes 56 seconds shorter than a solar day, and there is one more sidereal than solar days in a year. One

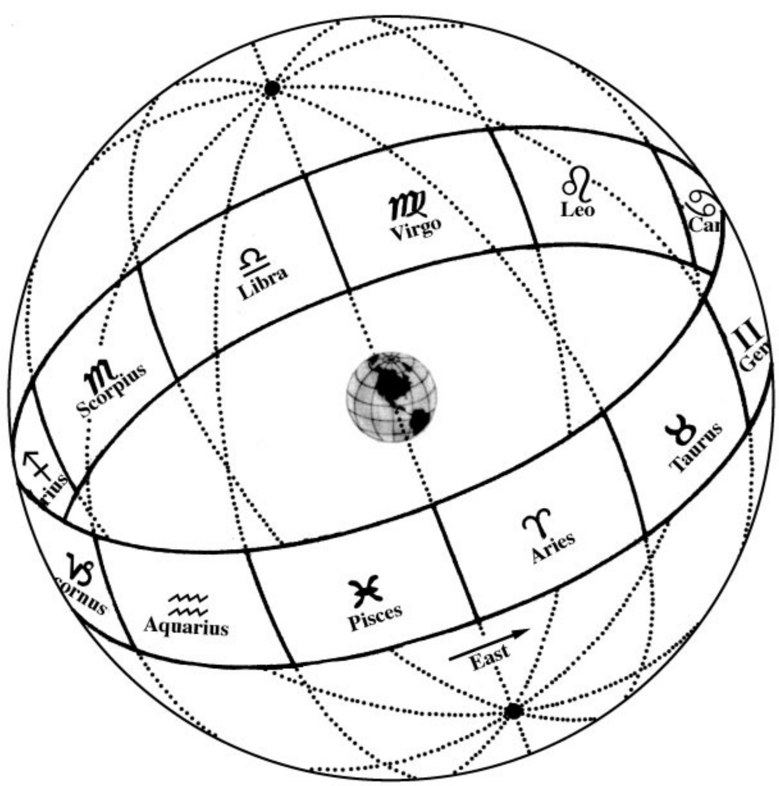

Figure 1520. The zodiac.

mean solar day equals 1.00273791 mean sidereal days. Because of precession of the equinoxes, one rotation of the earth with respect to the stars is not quite the same as one rotation with respect to the vernal equinox. One mean solar day averages 1.0027378118868 rotations of the earth with respect to the stars.

In tide analysis, the moon is sometimes used as the reference, producing a **lunar day** averaging 24 hours 50 minutes (mean solar units) in length, and lunar time.

Since each kind of day is divided arbitrarily into 24 hours, each hour having 60 minutes of 60 seconds, the length of each of these units differs somewhat in the various kinds of time.

Time is also classified according to the terrestrial meridian used as a reference. **Local time** results if one's own meridian is used, **zone time** if a nearby reference meridian is used over a spread of longitudes, and **Greenwich** or **Universal Time** if the Greenwich meridian is used.

The period from one vernal equinox to the next (the cycle of the seasons) is known as the **tropical year**. It is approximately 365 days, 5 hours, 48 minutes, 45 seconds, though the length has been slowly changing for many centuries. Our calendar, the Gregorian calendar, approximates the tropical year with a combination of common years of 365 days and leap years of 366 days. A leap year is any year divisible by four, unless it is a century year, which must be divisible by 400 to be a leap year. Thus, 1700, 1800, and 1900 were not leap years, but 2000 will be. A critical mistake was made by John Hamilton Moore in calling 1800 a leap year, causing an error in the tables in his book, *The Practical Navigator*. This error caused the loss of at least one ship and was later discovered by Nathaniel Bowditch while writing the first edition of *The New American Practical Navigator*.

See Chapter 18 for an in-depth discussion of time.

1522. Eclipses

If the orbit of the moon coincided with the plane of the ecliptic, the moon would pass in front of the sun at every new moon, causing a solar eclipse. At full moon, the moon would pass through the earth's shadow, causing a lunar eclipse. Because of the moon's orbit is inclined 5° with respect to the ecliptic, the moon usually passes above or below the sun at new moon and above or below the earth's shadow at full moon. However, there are two points at which the plane of the moon's orbit intersects the ecliptic. These are the **nodes** of the moon's orbit. If the moon passes one of these points at the same time as the sun, a **solar eclipse** takes place. This is shown in Figure 1522.

The sun and moon are of nearly the same apparent size to an observer on the earth. If the moon is at perigee, the moon's apparent diameter is larger than that of the sun, and its shadow reaches the earth as a nearly round dot only a few miles in diameter. The dot moves rapidly across the earth, from west to east, as the moon continues in its orbit. Within the dot, the sun is completely hidden from view, and a total eclipse of the sun occurs. For a considerable distance around the shadow, part of the surface of the sun is obscured, and a **partial eclipse** occurs. In the line of travel of the shadow a partial eclipse occurs as the round disk of the moon appears to move slowly across the surface of the sun, hiding an ever-increasing part of it, until the total eclipse occurs. Because of the uneven edge of the mountainous moon, the light is not cut off evenly. But several last illuminated portions appear through the valleys or passes between the mountain peaks. These are called **Baily's Beads**. A total eclipse is a spectacular phenomenon. As the last light from the sun is cut off, the solar **corona**, or envelope of thin, illuminated gas around the sun becomes visible. Wisps of more dense gas may appear as **solar prominences**. The only light reaching the observer is that diffused by the atmosphere surrounding the shadow. As the moon appears to continue on across the face of the sun, the sun finally emerges from the other side, first as Baily's Beads, and then as an ever widening crescent until no part of its surface is obscured by the moon.

The duration of a total eclipse depends upon how nearly the moon crosses the center of the sun, the location of the shadow on the earth, the relative orbital speeds of the moon and earth, and (principally) the relative apparent diameters of the sun and moon. The maximum length that can occur is a little more than seven minutes.

If the moon is near apogee, its apparent diameter is less than that of the sun, and its shadow does not quite reach the earth. Over a small area of the earth directly in line with the moon and sun, the moon appears as a black disk almost covering the surface of the sun, but with a thin ring of the sun around its edge. This **annular eclipse** occurs a little more often than a total eclipse.

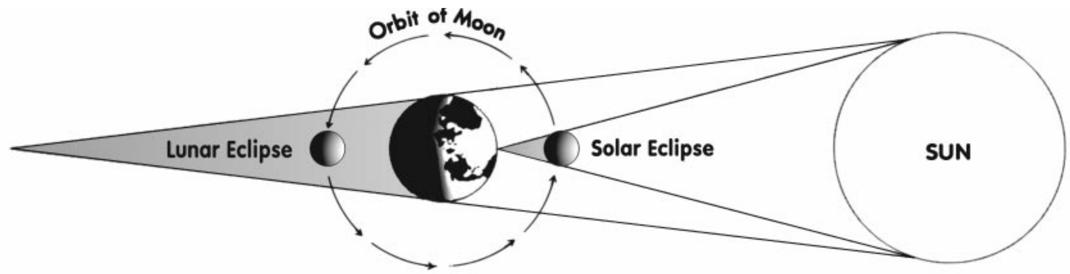

Figure 1522. Eclipses of the sun and moon.

If the shadow of the moon passes close to the earth, but not directly in line with it, a partial eclipse may occur without a total or annular eclipse.

An eclipse of the moon (or **lunar eclipse**) occurs when the moon passes through the shadow of the earth, as shown in Figure 1522. Since the diameter of the earth is about 3 $^1/_2$ times that of the moon, the earth's shadow at the distance of the moon is much larger than that of the moon. A total eclipse of the moon can last nearly 1 $^3/_4$ hours, and some part of the moon may be in the earth's shadow for almost 4 hours.

During a total solar eclipse no part of the sun is visible because the moon is in the line of sight. But during a lunar eclipse some light does reach the moon, diffracted by the atmosphere of the earth, and hence the eclipsed full moon is visible as a faint reddish disk. A lunar eclipse is visible over the entire hemisphere of the earth facing the moon. Anyone who can see the moon can see the eclipse.

During any one year there may be as many as five eclipses of the sun, and always there are at least two. There may be as many as three eclipses of the moon, or none. The total number of eclipses during a single year does not exceed seven, and can be as few as two. There are more solar than lunar eclipses, but the latter can be seen more often because of the restricted areas over which solar eclipses are visible.

The sun, earth, and moon are nearly aligned on the line of nodes twice each eclipse year of 346.6 days. This is less than a calendar year because of **regression of the nodes**. In a little more than 18 years the line of nodes returns to approximately the same position with respect to the sun, earth, and moon. During an almost equal period, called the **saros**, a cycle of eclipses occurs. During the following saros the cycle is repeated with only minor differences.

COORDINATES

1523. Latitude And Longitude

Latitude and **longitude** are coordinates used to locate positions on the earth. This section discusses three different definitions of these coordinates.

Astronomic latitude is the angle (ABQ, Figure 1523) between a line in the direction of gravity (AB) at a station and the plane of the equator (QQ'). **Astronomic longitude** is the angle between the plane of the celestial meridian at a station and the plane of the celestial meridian at Greenwich. These coordinates are customarily found by means of celestial observations. If the earth were perfectly homogeneous and round, these positions would be consistent and satisfactory. However, because of deflection of the vertical due to uneven distribution of the mass of the earth, lines of equal astronomic latitude and longitude are not circles, although the irregularities are small. In the United States the prime vertical component (affecting longitude) may be a little more than 18", and the meridional component (affecting latitude) as much as 25".

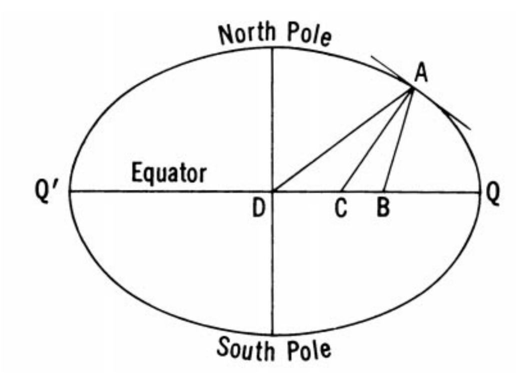

Figure 1523. Three kinds of latitude at point A.

Geodetic latitude is the angle (ACQ, Figure 1523) between a normal to the spheroid (AC) at a station and the plane of the geodetic equator (QQ'). **Geodetic longitude** is the angle between the plane defined by the normal to the spheroid and the axis of the earth and the plane of the geodetic meridian at Greenwich. These values are obtained when astronomical latitude and longitude are corrected for deflection of the vertical. These coordinates are used for charting and are frequently referred to as **geographic latitude** and **geographic longitude**, although these expressions are sometimes used to refer to astronomical latitude.

Geocentric latitude is the angle (ADQ, Figure 1523) at the center of the ellipsoid between the plane of its equator (QQ') and a straight line (AD) to a point on the surface of the earth. This differs from geodetic latitude because the earth is a spheroid rather than a sphere, and the meridians are ellipses. Since the parallels of latitude are considered to be circles, geodetic longitude is geocentric, and a separate expression is not used. The difference between geocentric and geodetic latitudes is a maximum of about 11.6' at latitude 45°.

Because of the oblate shape of the ellipsoid, the length of a degree of geodetic latitude is not everywhere the same, increasing from about 59.7 nautical miles at the equator to about 60.3 nautical miles at the poles. The value of 60 nautical miles customarily used by the navigator is correct at about latitude 45°.

MEASUREMENTS ON THE CELESTIAL SPHERE

1524. Elements Of The Celestial Sphere

The **celestial sphere** (section 1501) is an imaginary sphere of infinite radius with the earth at its center (Figure 1524a). The north and south celestial poles of this sphere are located by extension of the earth's axis. The **celestial equator** (sometimes called **equinoctial**) is formed by projecting the plane of the earth's equator to the celestial sphere. A **celestial meridian** is formed by the intersection of the plane of a terrestrial meridian and the celestial sphere. It is the arc of a great circle through the poles of the celestial sphere.

The point on the celestial sphere vertically overhead of an observer is the **zenith**, and the point on the opposite side of the sphere vertically below him is the **nadir**. The zenith and nadir are the extremities of a diameter of the celestial sphere through the observer and the common center of the earth and the celestial sphere. The arc of a celestial meridian between the poles is called the **upper branch** if it contains the zenith and the **lower branch** if it contains the nadir. The upper branch is frequently used in navigation, and references to a celestial meridian are understood to mean only its upper branch unless otherwise stated. Celestial meridians take the names of their terrestrial counterparts, such as 65° west.

An **hour circle** is a great circle through the celestial poles and a point or body on the celestial sphere. It is similar to a celestial meridian, but moves with the celestial sphere as it rotates about the earth, while a celestial meridian remains fixed with respect to the earth.

The location of a body on its hour circle is defined by the body's angular distance from the celestial equator. This distance, called **declination**, is measured north or south of the celestial equator in degrees, from 0° through 90°, similar to latitude on the earth.

A circle parallel to the celestial equator is called a **parallel of declination**, since it connects all points of equal declination. It is similar to a parallel of latitude on the earth. The path of a celestial body during its daily apparent revolution around the earth is called its **diurnal circle**. It is not

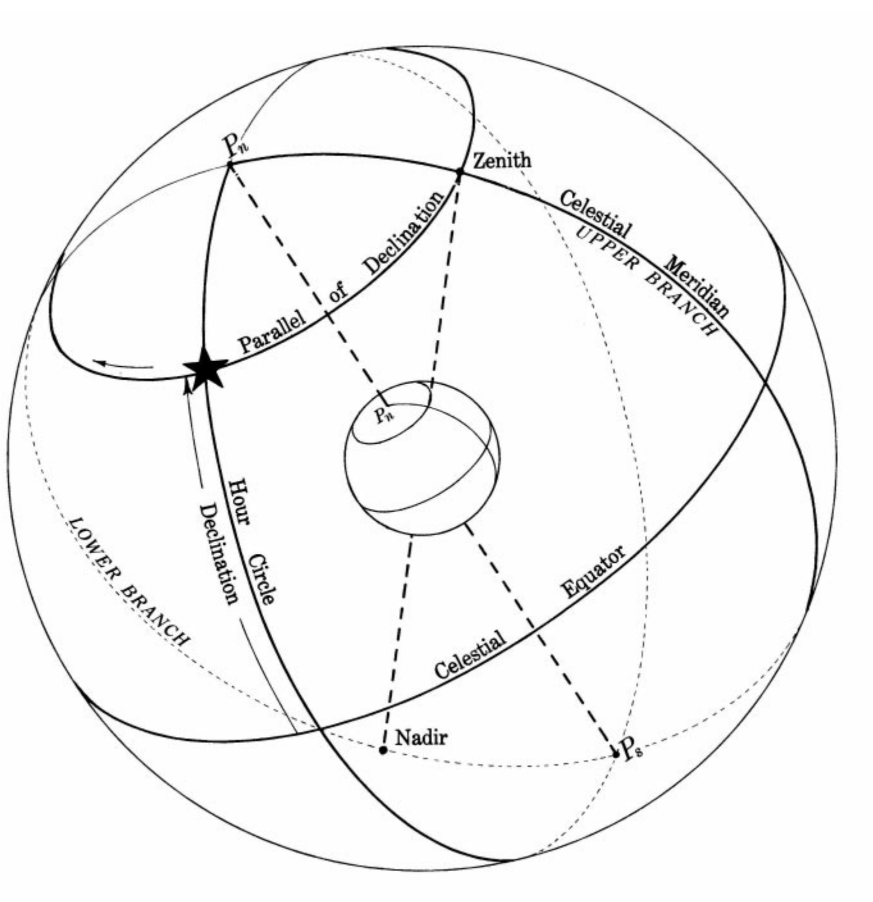

Figure 1524a. Elements of the celestial sphere. The celestial equator is the primary great circle.

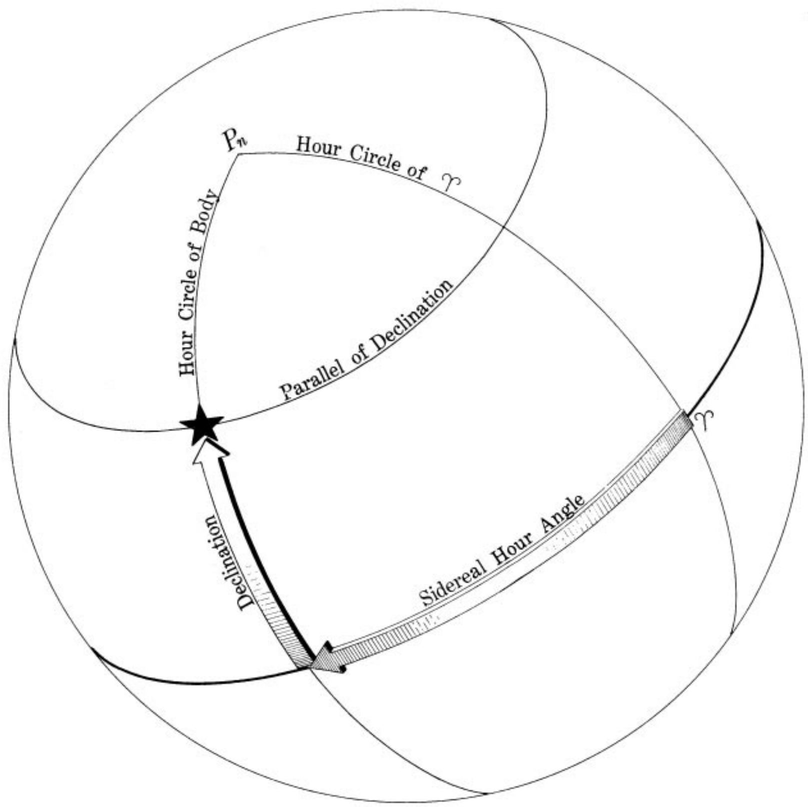

Figure 1524b. A point on the celestial sphere can be located by its declination and sidereal hour angle.

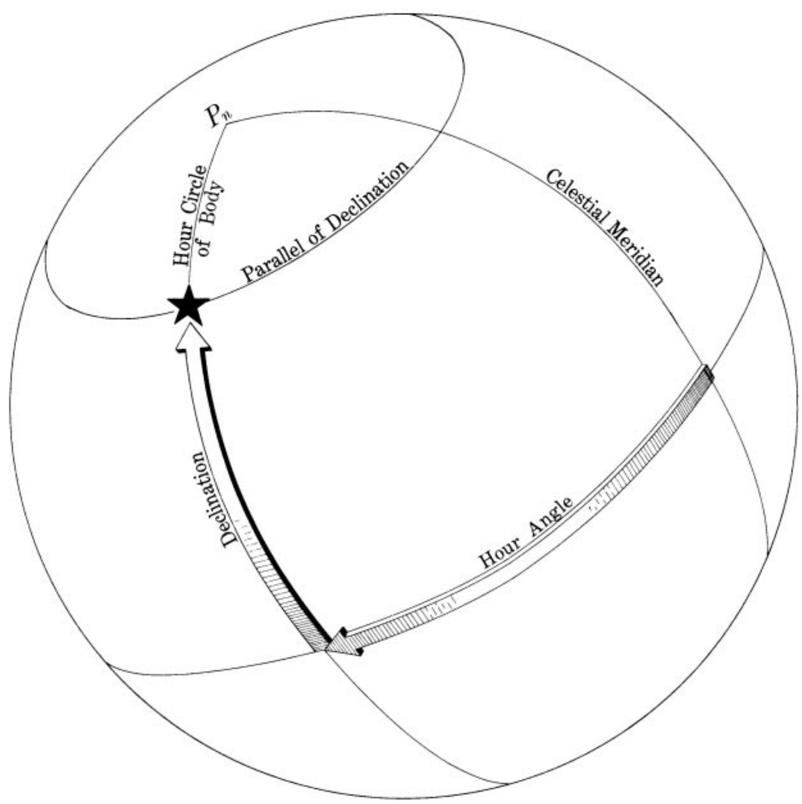

Figure 1524c. A point on the celestial sphere can be located by its declination and hour angle.

actually a circle if a body changes its declination. Since the declination of all navigational bodies is continually changing, the bodies are describing flat, spherical spirals as they circle the earth. However, since the change is relatively slow, a diurnal circle and a parallel of declination are usually considered identical.

A point on the celestial sphere may be identified at the intersection of its parallel of declination and its hour circle. The parallel of declination is identified by the declination.

Two basic methods of locating the hour circle are in use. First, the angular distance west of a reference hour circle through a point on the celestial sphere, called the vernal equinox or first point of Aries, is called **sidereal hour angle (SHA)** (Figure 1524b). This angle, measured eastward from the vernal equinox, is called **right ascension** and is usually expressed in time units.

The second method of locating the hour circle is to indicate its angular distance west of a celestial meridian (Figure 1524c). If the Greenwich celestial meridian is used as the reference, the angular distance is called **Greenwich hour angle (GHA)**, and if the meridian of the observer, it is called **local hour angle (LHA)**. It is sometimes more convenient to measure hour angle either eastward or westward, as longitude is measured on the earth, in which case it is called **meridian angle** (designated "t").

A point on the celestial sphere may also be located using altitude and azimuth coordinates based upon the horizon as the primary great circle instead of the celestial equator.

COORDINATE SYSTEMS

1525. The Celestial Equator System Of Coordinates

If the familiar graticule of latitude and longitude lines is expanded until it reaches the celestial sphere of infinite radius, it forms the basis of the celestial equator system of coordinates. On the celestial sphere latitude becomes declination, while longitude becomes sidereal hour angle, measured from the vernal equinox.

Declination is angular distance north or south of the celestial equator (d in Figure 1525a). It is measured along an hour circle, from 0° at the celestial equator through 90° at the celestial poles. It is labeled N or S to indicate the direction of measurement. All points having the same declination lie along a parallel of declination.

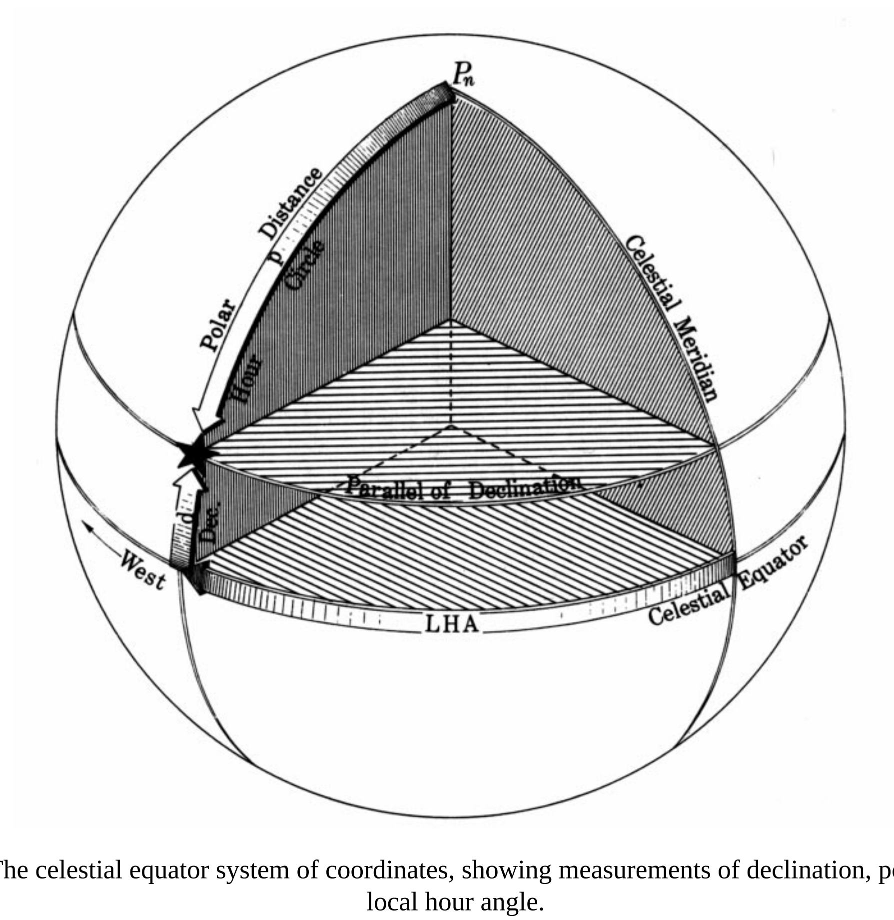

Figure 1525a. The celestial equator system of coordinates, showing measurements of declination, polar distance, and local hour angle.

Polar distance (p) is angular distance from a celestial pole, or the arc of an hour circle between the celestial pole and a point on the celestial sphere. It is measured along an hour circle and may vary from 0° to 180°, since either pole may be used as the origin of measurement. It is usually considered the complement of declination, though it may be either 90° – d or 90° + d, depending upon the pole used.

Local hour angle (LHA) is angular distance west of the local celestial meridian, or the arc of the celestial equator between the upper branch of the local celestial meridian and the hour circle through a point on the celestial sphere, measured westward from the local celestial meridian, through 360°. It is also the similar arc of the parallel of declination and the angle at the celestial pole, similarly measured. If the Greenwich (0°) meridian is used as the reference, instead of the local meridian, the expression **Greenwich hour angle (GHA)** is applied. It is sometimes convenient to measure the arc or angle in either an easterly or westerly direction from the local meridian, through 180°, when it is called **meridian angle (t)** and labeled E or W to indicate the direction of measurement. All bodies or other points having the same hour angle lie along the same hour circle.

Because of the apparent daily rotation of the celestial sphere, hour angle continually increases, but meridian angle increases from 0° at the celestial meridian to 180°W, which is also 180°E, and then decreases to 0° again. The rate of change for the mean sun is 15° per hour. The rate of all other bodies except the moon is within 3' of this value.

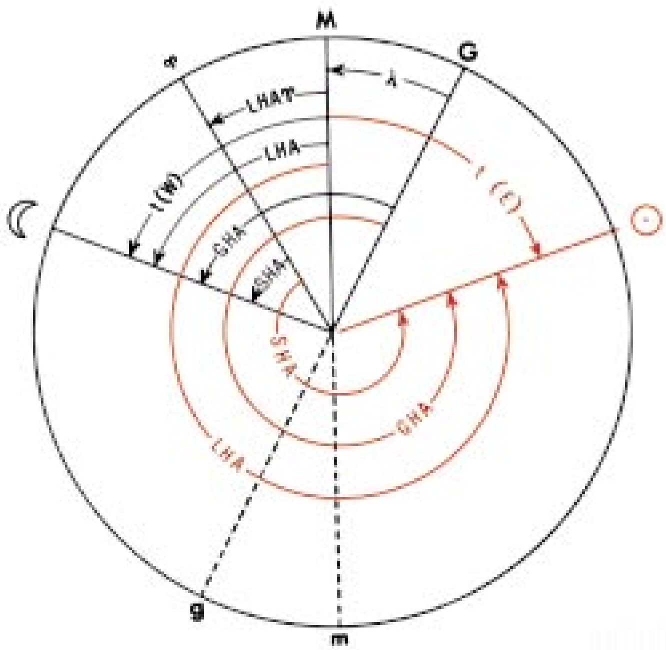

Figure 1525b. Time diagram. Local hour angle, Greenwich hour angle, and sidereal hour angle are measured westward through 360°. Meridian angle is measured eastward or westward through 180° and labeled E or W to indicate the direction of measurement.

The average rate of the moon is about 15.5°.

As the celestial sphere rotates, each body crosses each branch of the celestial meridian approximately once a day. This crossing is called **meridian transit** (sometimes called culmination). It may be called **upper transit** to indicate crossing of the upper branch of the celestial meridian, and **lower transit** to indicate crossing of the lower branch.

The **time diagram** shown in Figure 1525b illustrates the relationship between the various hour angles and meridian angle. The circle is the celestial equator as seen from above the South Pole, with the upper branch of the observer's meridian (P_sM) at the top. The radius P_sG is the Greenwich meridian; P_s ♈ is the hour circle of the vernal equinox. The sun's hour circle is to the east of the observer's meridian; the moon's hour circle is to the west of the observer's meridian Note that when LHA is less than 180°, t is numerically the same and is labeled W, but that when LHA is greater than 180°, t = 360° – LHA and is labeled E. In Figure 1525b arc GM is the longitude, which in this case is west. The relationships shown apply equally to other arrangements of radii, except for relative magnitudes of the quantities involved.

1526. The Horizons

The second set of celestial coordinates with which the navigator is directly concerned is based upon the horizon as the primary great circle. However, since several different horizons are defined, these should be thoroughly understood before proceeding with a consideration of the horizon system of coordinates.

The line where earth and sky appear to meet is called the **visible** or **apparent horizon**. On land this is usually an irregular line unless the terrain is level. At sea the visible horizon appears very regular and often very sharp. However, its position relative to the celestial sphere depends primarily upon (1) the refractive index of the air and (2) the height of the observer's eye above the surface.

Figure 1526 shows a cross section of the earth and celestial sphere through the position of an observer at A above the surface of the earth. A straight line through A and the center of the earth O is the vertical of the observer and contains his zenith (Z) and nadir (Na). A plane perpendicular to the true vertical is a horizontal plane, and its intersection with the celestial sphere is a horizon. It is the **celestial horizon** if the plane passes through the center of the earth, the **geoidal horizon** if it is tangent to the earth, and the **sensible horizon** if it passes through the eye of the observer at A. Since the radius of the earth is considered negligible with respect to that of the celestial sphere, these horizons become superimposed, and most measurements are referred only to the celestial horizon. This is sometimes called the **rational horizon**.

If the eye of the observer is at the surface of the earth, his visible horizon coincides with the plane of the geoidal horizon; but when elevated above the surface, as at A, his eye becomes the vertex of a cone which is tangent to the earth atthe small circle BB, and which intersects the celestial

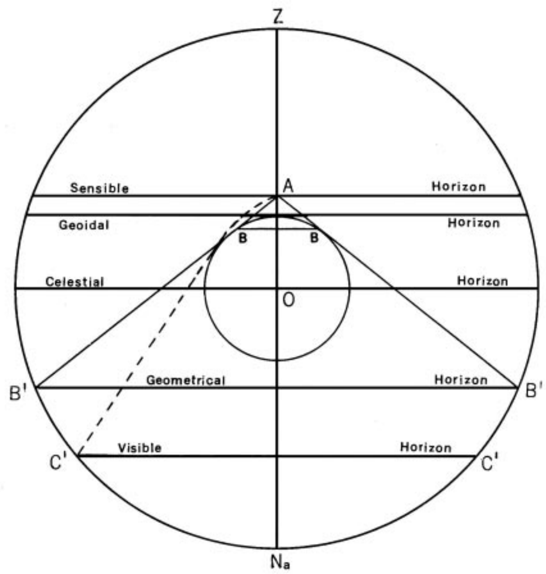

Figure 1526. The horizons used in navigation.

sphere in B'B', the **geometrical horizon**. This expression is sometimes applied to the celestial horizon.

Because of refraction, the visible horizon C'C' appears above but is actually slightly below the geometrical horizon as shown in Figure 1526.

For any elevation above the surface, the celestial horizon is usually above the geometrical and visible horizons, the difference increasing as elevation increases. It is thus possible to observe a body which is above the visible horizon but below the celestial horizon. That is, the body's altitude is negative and its zenith distance is greater than 90°.

1527. The Horizon System Of Coordinates

This system is based upon the celestial horizon as the primary great circle and a series of secondary vertical circles which are great circles through the zenith and nadir of the observer and hence perpendicular to his horizon (Figure 1527a). Thus, the celestial horizon is similar to the equator, and the vertical circles are similar to meridians, but with one important difference. The celestial horizon and vertical circles are dependent upon the position of the observer and hence move with him as he changes position, while the primary and secondary great circles of both the geographical and celestial equator systems are independent of the observer. The horizon and celestial equator systems coincide for an observer at the geographical pole of the earth and are mutually perpendicular for an observer on the equator. At all other places the two are oblique.

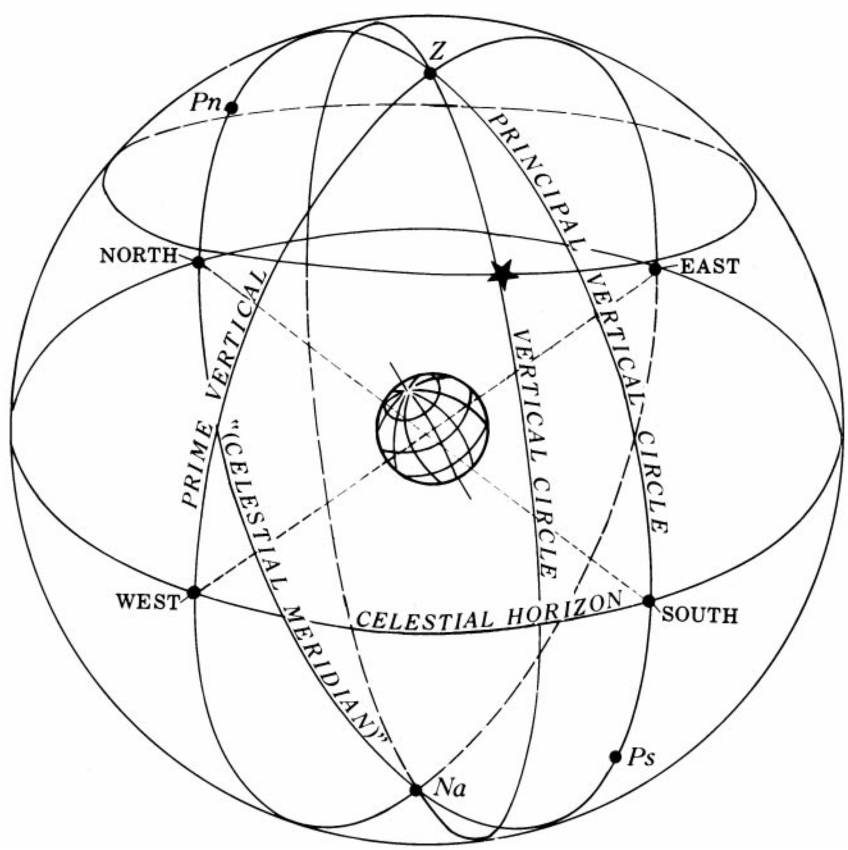

Figure 1527a. Elements of the celestial sphere. The celestial horizon is the primary great circle.

The vertical circle through the north and south points of the horizon passes through the poles of the celestial equator system of coordinates. One of these poles (having the same name as the latitude) is above the horizon and is called the **elevated pole**. The other, called the **depressed pole**, is below the horizon. Since this vertical circle is a great circle through the celestial poles, and includes the zenith of the observer, it is also a celestial meridian. In the horizon system it is called the **principal vertical circle**. The vertical circle through the east and west points of the horizon, and hence perpendicular to the principal vertical circle, is called the **prime vertical circle**, or simply the **prime vertical**.

As shown in Figure 1527b, altitude is angular distance above the horizon. It is measured along a vertical circle, from 0° at the horizon through 90° at the zenith. Altitude measured from the visible horizon may exceed 90° because of the dip of the horizon, as shown in Figure 1526. Angular distance below the horizon, called negative altitude, is provided for by including certain negative altitudes in some tables for use in celestial navigation. All points having the same altitude lie along a parallel of altitude.

Zenith distance (z) is angular distance from the zenith, or the arc of a vertical circle between the zenith and a point on the celestial sphere. It is measured along a vertical circle from 0° through 180°. It is usually considered the complement of altitude. For a body above the celestial horizon it is equal to 90° – h and for a body below the celestial horizon it is equal to 90° – (– h) or 90° + h.

The horizontal direction of a point on the celestial sphere, or the bearing of the geographical position, is called **azimuth** or **azimuth angle** depending upon the method of measurement. In both methods it is an arc of the horizon (or parallel of altitude), or an angle at the zenith. It is **azimuth** (Zn) if measured clockwise through 360°, starting at the north point on the horizon, and **azimuth angle** (Z) if measured either clockwise or counterclockwise through 180°, starting at the north point of the horizon in north latitude and the south point of the horizon in south latitude.

The ecliptic system is based upon the ecliptic as the primary great circle, analogous to the equator. The points 90° from the ecliptic are the north and south ecliptic poles. The series of great circles through these poles, analogous to meridians, are circles of latitude. The circles parallel to the plane of the ecliptic, analogous to parallels on the earth, are parallels of latitude or circles of longitude. Angular distance north or south of the ecliptic, analogous to latitude, is celestial latitude. Celestial longitude is measured eastward along the ecliptic through 360°, starting at the vernal equinox. This system of coordinates is of interest chiefly to astronomers.

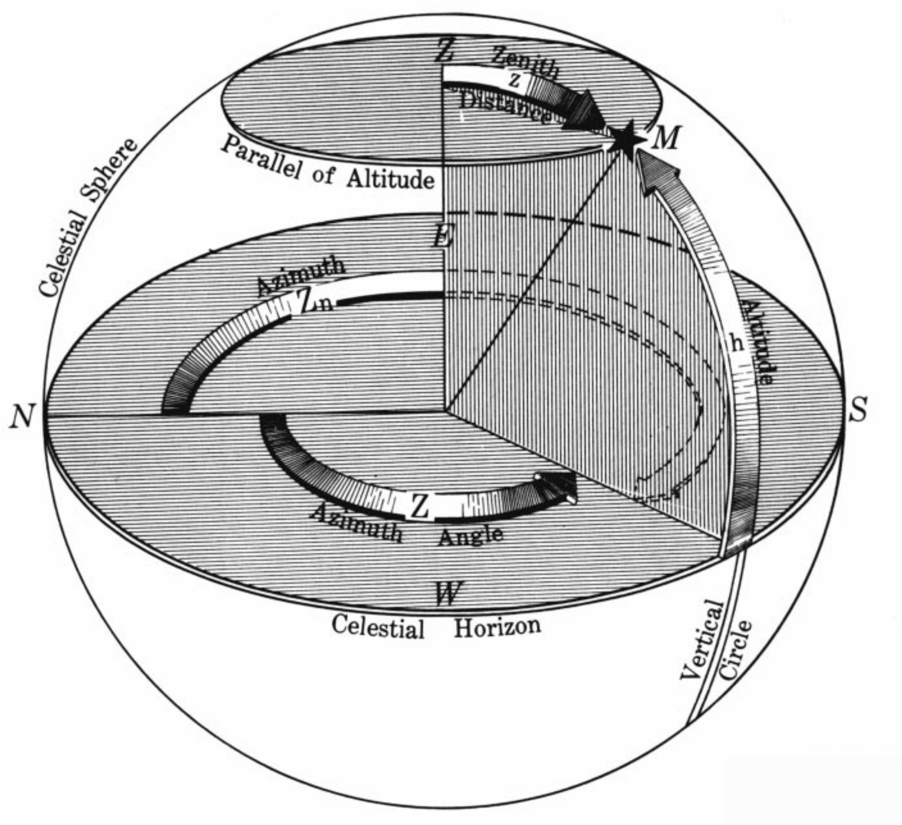

Figure 1527b. The horizon system of coordinates, showing measurement of altitude, zenith distance, azimuth, and azimuth angle.

Earth	*Celestial Equator*	*Horizon*	*Ecliptic*
equator	celestial equator	horizon	ecliptic
poles	celestial poles	zenith; nadir	ecliptic poles
meridians	hours circle; celestial meridians	vertical circles	circles of latitude
prime meridian	hour circle of Aries	principal or prime vertical circle	circle of latitude through Aries
parallels	parallels of declination	parallels of altitude	parallels of latitude
latitude	declination	altitude	celestial altitude
colatitude	polar distance	zenith distance	celestial colatitude
longitude	SHA; RA; GHA; LHA; t	azimuth; azimuth angle; amplitude	celestial longitude

Figure 1528. The four systems of celestial coordinates and their analogous terms.

1528. Summary Of Coordinate Systems

The four systems of celestial coordinates are analogous to each other and to the terrestrial system, although each has distinctions such as differences in directions, units, and limits of measurement. Figure 1528 indicates the analogous term or terms under each system.

1529. Diagram On The Plane Of The Celestial Meridian

From an imaginary point outside the celestial sphere and over the celestial equator, at such a distance that the view would be orthographic, the great circle appearing as the outer limit would be a celestial meridian. Other celestial meridians would appear as ellipses. The celestial equator

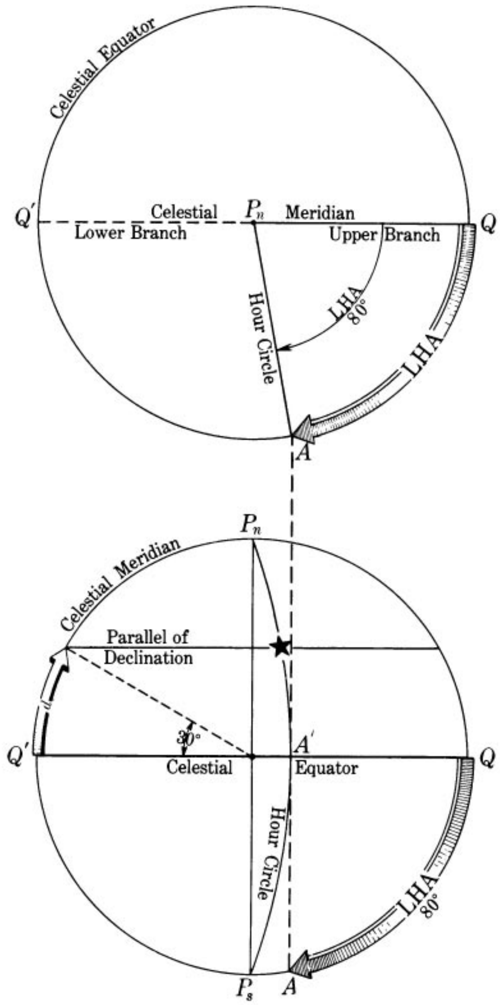

Figure 1529a. Measurement of celestial equator system of coordinates.

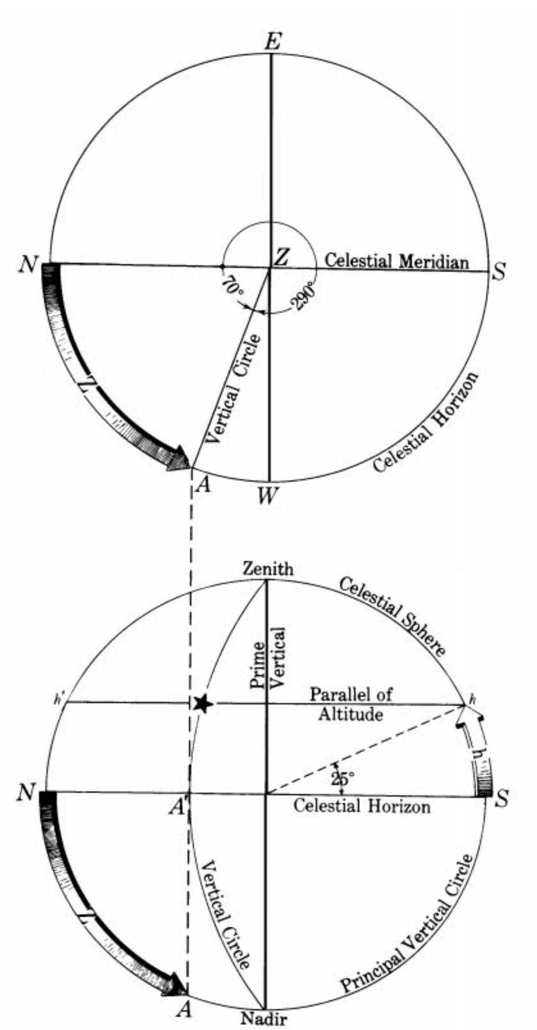

Figure 1529b. Measurement of horizon system of coordinates.

would appear as a diameter 90° from the poles, and parallels of declination as straight lines parallel to the equator. The view would be similar to an orthographic map of the earth.

A number of useful relationships can be demonstrated by drawing a diagram on the plane of the celestial meridian showing this orthographic view. Arcs of circles can be substituted for the ellipses without destroying the basic relationships. Refer to Figure 1529a. In the lower diagram the circle represents the celestial meridian, QQ' the celestial equator, Pn and Ps the north and south celestial poles, respectively. If a star has a declination of 30° N, an angle of 30° can be measured from the celestial equator, as shown. It could be measured either to the right or left, and would have been toward the south pole if the declination had been south. The parallel of declination is a line through this point and parallel to the celestial equator. The star is somewhere on this line (actually a circle viewed on edge).

To locate the hour circle, draw the upper diagram so that Pn is directly above Pn of the lower figure (in line with the polar axis Pn-Ps), and the circle is of the same diameter as that of the lower figure. This is the plan view, looking down on the celestial sphere from the top. The circle is the celestial equator. Since the view is from above the north celestial pole, west is clockwise. The diameter QQ' is the celestial meridian shown as a circle in the lower diagram. If the right half is considered the upper branch, local hour angle is measured clockwise from this line to the hour circle, as shown. In this case the LHA is 80°. The intersection of the hour circle and celestial equator, point A, can be projected down to the lower diagram (point A') by a straight line parallel to the polar axis. The elliptical hour circle can be represented approximately by an arc of a circle through A', Pn, Ps. The center of this circle is somewhere along the celestial equator line QQ', extended if necessary. It is usually found by trial and error. The intersection of the hour circle and parallel of declination locates the star.

Since the upper diagram serves only to locate point A' in the lower diagram, the two can be combined. That is, the LHA arc can be drawn in the lower diagram, as shown, and point A projected upward to A'. In practice, the upper diagram is not drawn, being shown here for illustrative purposes.

In this example the star is on that half of the sphere toward the observer, or the western part. If LHA had been greater than 180°, the body would have been on the eastern or “back” side.

From the east or west point over the celestial horizon, the orthographic view of the horizon system of coordinates would be similar to that of the celestial equator system from a point over the celestial equator, since the celestial meridian is also the principal vertical circle. The horizon would appear as a diameter, parallels of altitude as straight lines parallel to the horizon, the zenith and nadir as poles 90° from the horizon, and vertical circles as ellipses through the zenith and nadir, except for the principal vertical circle, which would appear as a circle, and the prime vertical, which would appear as a diameter perpendicular to the horizon.

A celestial body can be located by altitude and azimuth in a manner similar to that used with the celestial equator system. If the altitude is 25°, this angle is measured from the horizon toward the zenith and the parallel of altitude is drawn as a straight line parallel to the horizon, as shown at hh' in the lower diagram of Figure 1529b. The plan view from above the zenith is shown in the upper diagram. If north is taken at the left, as shown, azimuths are measured clockwise from this point. In the figure the azimuth is 290° and the azimuth angle is N70°W. The vertical circle is located by measuring either arc. Point A thus located can be projected vertically downward to A' on the horizon of the lower diagram, and the vertical circle represented approximately by the arc of a circle through A' and the zenith and nadir. The center of this circle is on NS, extended if necessary. The body is at the intersection of the parallel of altitude and the vertical circle. Since the upper diagram serves only to locate A' on the lower diagram, the two can be combined, point A located on the lower diagram and projected upward to A', as shown. Since the body of the example has an azimuth greater than 180°, it is on the western or “front” side of the diagram.

Since the celestial meridian appears the same in both the celestial equator and horizon systems, the two diagrams can be combined and, if properly oriented, a body can be located by one set of coordinates, and the coordinates of the other system can be determined by measurement.

Refer to Figure 1529c, in which the black lines represent the celestial equator system, and the red lines the horizon system. By convention, the zenith is shown at the top and the north point of the horizon at the left. The west point on the horizon is at the center, and the east point directly behind it. In the figure the latitude is 37°N. Therefore, the zenith is 37° north of the celestial equator. Since the zenith is established at the top of the diagram, the equator can be found by measuring an arc of 37° toward the south, along the celestial meridian. If the declination is 30°N and the LHA is 80°, the body can be located as shown by the black lines, and described above.

The altitude and azimuth can be determined by the reverse process to that described above. Draw a line hh' through the body and parallel to the horizon, NS. The altitude, 25°, is found by measurement, as shown. Draw the arc of a circle through the body and the zenith and nadir. From A', the intersection of this arc with the horizon, draw a vertical line intersecting the circle at A. The azimuth, N70°W, is found by measurement, as shown. The prefix N is applied to agree with the latitude. The body is left (north) of ZNa, the prime vertical circle. The suffix W applies because the LHA, 80°, shows that the body is west of the meridian.

If altitude and azimuth are given, the body is located by means of the red lines. The parallel of declination is then drawn parallel to QQ', the celestial equator, and the declination determined by measurement. Point L' is located by drawing the arc of a circle through Pn, the star, and Ps. From L' a line is drawn perpendicular to QQ', locating L. The meridian angle is then found by measurement. The dec-

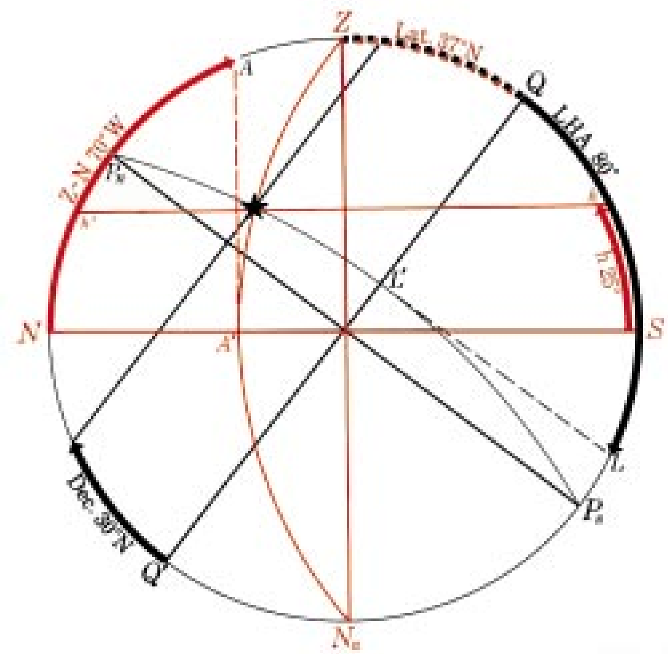

Figure 1529c. Diagram on the plane of the celestial meridian.

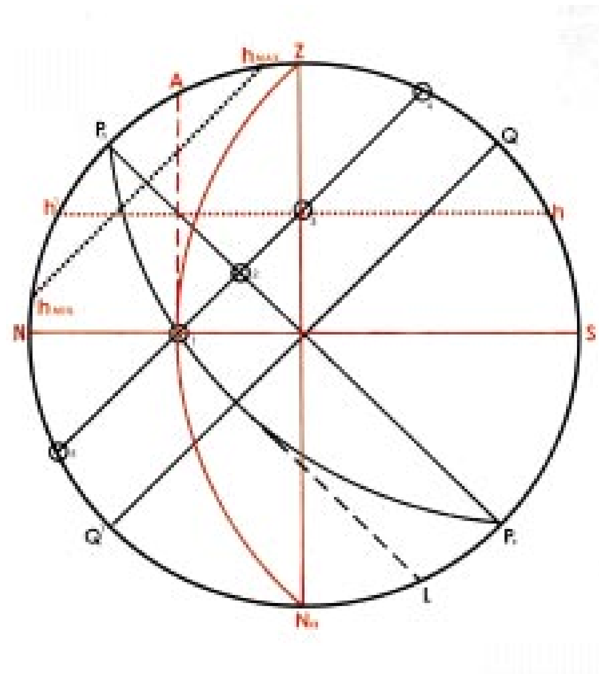

Figure 1529d. A diagram on the plane of the celestial meridian for lat. 45°N.

lination is known to be north because the body is between the celestial equator and the north celestial pole. The meridian angle is west, to agree with the azimuth, and hence LHA is numerically the same.

Since QQ'and PnPs are perpendicular, and ZNa and NS are also perpendicular, arc NPn is equal to arc ZQ. That is, the altitude of the elevated pole is equal to the declination of the zenith, which is equal to the latitude. This relationship is the basis of the method of determining latitude by an observation of Polaris.

The diagram on the plane of the celestial meridian is useful in approximating a number of relationships. Consider Figure 1529d. The latitude of the observer (NPn or ZQ) is 45°N. The declination of the sun (Q4) is 20°N. Neglecting the change in declination for one day, note the following: At sunrise, position 1, the sun is on the horizon (NS), at the "back" of the diagram. Its altitude, h, is 0°. Its azimuth angle, Z, is the arc NA, N63°E. This is prefixed N to agree with the latitude and suffixed E to agree with the meridian angle of the sun at sunrise. Hence, Zn = 063°. The amplitude, A, is the arc ZA, E27°N. The meridian angle, t, is the arc QL, 110°E. The suffix E is applied because the sun is east of the meridian at rising. The LHA is 360° – 110° = 250°.

As the sun moves upward along its parallel of declination, its altitude increases. It reaches position 2 at about 0600, when t = 90°E. At position 3 it is on the prime vertical, ZNa. Its azimuth angle, Z, is N90°E, and Zn = 090°. The altitude is Nh' or Sh, 27°.

Moving on up its parallel of declination, it arrives at position 4 on the celestial meridian about noon-when t and LHA are both 0°, by definition. On the celestial meridian a body's azimuth is 000° or 180°. In this case it is 180° because the body is south of the zenith. The maximum altitude occurs at meridian transit. In this case the arc S4 represents the maximum altitude, 65°. The zenith distance, z, is the arc Z4, 25°. A body is not in the zenith at meridian transit unless its declination's magnitude and name are the same as the latitude.

Continuing on, the sun moves downward along the "front" or western side of the diagram. At position 3 it is again on the prime vertical. The altitude is the same as when previously on the prime vertical, and the azimuth angle is numerically the same, but now measured toward the west. The azimuth is 270°. The sun reaches position 2 six hours after meridian transit and sets at position 1. At this point, the azimuth angle is numerically the same as at sunrise, but westerly, and Zn = 360° – 63° = 297°. The amplitude is W27°N.

After sunset the sun continues on downward, along its parallel of declination, until it reaches position 5, on the lower branch of the celestial meridian, about midnight. Its negative altitude, arc N5, is now greatest, 25°, and its azimuth is 000°. At this point it starts back up along the "back" of the diagram, arriving at position 1 at the next sunrise, to start another cycle.

Half the cycle is from the crossing of the 90° hour circle (the PnPs line, position 2) to the upper branch of the celestial meridian (position 4) and back to the PnPs line (position 2). When the declination and latitude have the same name (both north or both south), more than half the parallel of declination (position 1 to 4 to 1) is above the horizon, and the body is above the horizon more than half the time, crossing the 90° hour circle above the horizon. It rises and sets on the same side of the prime vertical as the elevated pole. If the declination is of the same name but numerically smaller than the latitude, the body crosses the prime vertical above the horizon. If the declination and latitude have the same name and are numerically equal, the body is in the zenith at upper transit. If the declination is of the same name but numerically greater than the latitude, the body crosses the upper branch of the celestial meridian between the zenith and elevated pole and does not cross the prime vertical. If the declination is of the same name as the latitude and complementary to it (d + L = 90°), the body is on the horizon at lower transit and does not set. If the declination is of the same name as the latitude and numerically greater than the colatitude, the body is above the horizon during its entire daily cycle and has maximum and minimum altitudes. This is shown by the black dotted line in Figure 1529d.

If the declination is 0° at any latitude, the body is above the horizon half the time, following the celestial equator QQ', and rises and sets on the prime vertical. If the declination is of contrary name (one north and the other south), the body is above the horizon less than half the time and crosses the 90° hour circle below the horizon. It rises and sets on the opposite side of the prime vertical from the elevated pole. If the declination is of contrary name and numerically smaller than the latitude, the body crosses the prime vertical below the horizon. This is the situation with the sun in winter follows when days are short. If the declination is of contrary name and numerically equal to the latitude, the body is in the nadir at lower transit. If the declination is of contrary name and complementary to the latitude, the body is on the horizon at upper transit. If the declination is of contrary name and numerically greater than the colatitude, the body does not rise.

All of these relationships, and those that follow, can be derived by means of a diagram on the plane of the celestial meridian. They are modified slightly by atmospheric refraction, height of eye, semidiameter, parallax, changes in declination, and apparent speed of the body along its diurnal circle.

It is customary to keep the same orientation in south latitude, as shown in Figure 1529e. In this illustration the latitude is 45°S, and the declination of the body is 15°N. Since Ps is the elevated pole, it is shown above the southern horizon, with both SPs and ZQ equal to the latitude, 45°. The body rises at position 1, on the opposite side of the prime vertical from the elevated pole. It moves upward along its parallel of declination to position 2, on the upper branch of the celestial meridian, bearing north; and then it moves downward along the “front” of the diagram to position 1, where it sets. It remains above the horizon for less than half the time because declination and latitude are of contrary name. The azimuth at rising is arc NA, the amplitude ZA, and the azimuth angle SA. The altitude circle at meridian transit is shown at hh'.

A diagram on the plane of the celestial meridian can be used to demonstrate the effect of a change in latitude. As the latitude increases, the celestial equator becomes more nearly parallel to the horizon. The colatitude becomes smaller,

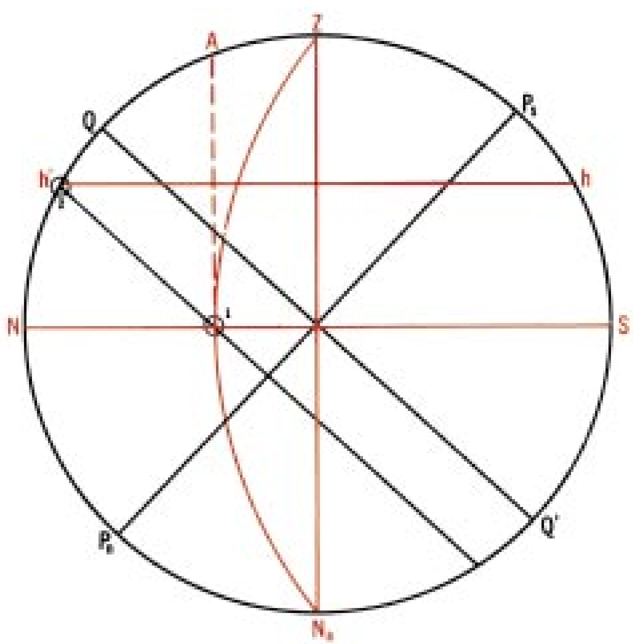

Figure 1529e. A diagram on the plane of the celestial meridian for lat. 45°S.

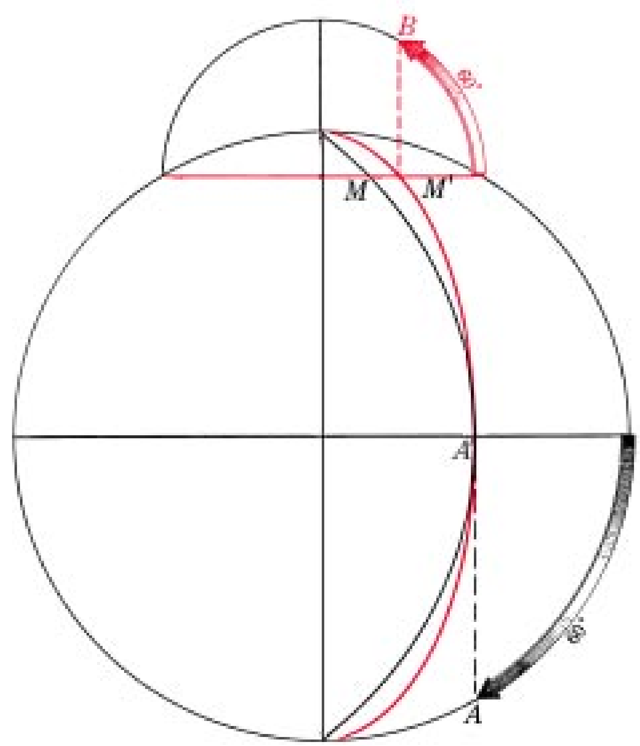

Figure 1529f. Locating a point on an ellipse of a diagram on the plane of the celestial meridian.

NAVIGATIONAL COORDINATES

Coordinate	Symbol	Measured from	Measured along	Direc-tion	Measured to	Units	Prec i-sion	Maximum value	Labels
latitude	L, lat.	equator	meridian	N, S	parallel	°, ′	0′.1	90°	N, S
colatitude	colat.	poles	meridian	S, N	parallel	°, ′	0′.1	90°	—
longitude	λ, long.	prime meridian	parallel	E, W	local meridian	°, ′	0′.1	180°	E, W
declination	d, dec.	celestial equator	hour circle	N, S	parallel of declination	°, ′	0′.1	90°	N, S
polar distance	p	elevated pole	hour circle	S, N	parallel of declination	°, ′	0′.1	180°	—
altitude	h	horizon	vertical circle	up	parallel of altitude	°, ′	0′.1	90°*	—
zenith distance	z	zenith	vertical circle	down	parallel of altitude	°, ′	0′.1	180°	—
azimuth	Zn	north	horizon	E	vertical circle	°	0°.1	360°	—
azimuth angle	Z	north, south	horizon	E, W	vertical circle	°	0°.1	180° or 90°	N, S...E, W
amplitude	A	east, west	horizon	N, S	body	°	0°.1	90°	E, W...N, S
Greenwich hour angle	GHA	Greenwich celestial meridian	parallel of declination	W	hour circle	°, ′	0′.1	360°	—
local hour angle	LHA	local celestial meridian	parallel of declination	W	hour circle	°, ′	0′.1	360°	—
meridian angle	t	local celestial meridian	parallel of declination	E, W	hour circle	°, ′	0′.1	180°	E, W
sidereal hour angle	SHA	hour circle of vernal equinox	parallel of declination	W	hour circle	°, ′	0′.1	360°	—
right ascension	RA	hour circle of vernal equinox	parallel of declination	E	hour circle	h, m, s	1^s	24^h	—
Greenwich mean time	GMT	lower branch Greenwich celestial meridian	parallel of declination	W	hour circle mean sun	h, m, s	1^s	24^h	—
local mean time	LMT	lower branch local celestial meridian	parallel of declination	W	hour circle mean sun	h, m, s	1^s	24^h	—
zone time	ZT	lower branch zone celestial meridian	parallel of declination	W	hour circle mean sun	h, m, s	1^s	24^h	—
Greenwich apparent time	GAT	lower branch Greenwich celestial meridian	parallel of declination	W	hour circle apparent sun	h, m, s	1^s	24^h	—
local apparent time	LAT	lower branch local celestial meridian	parallel of declination	W	hour circle apparent sun	h, m, s	1^s	24^h	—
Greenwich sidereal time	GST	Greenwich celestial meridian	parallel of declination	W	hour circle vernal equinox	h, m, s	1^s	24^h	—
local sidereal time	LST	local celestial meridian	parallel of declination	W	hour circle vernal equinox	h, m, s	1^s	24^h	—

*When measured from celestial horizon.

Figure 1529g. Navigational Coordinates.

increasing the number of circumpolar bodies and those which neither rise nor set. It also increases the difference in the length of the days between summer and winter. At the poles celestial bodies circle the sky, parallel to the horizon. At the equator the 90° hour circle coincides with the horizon. Bodies rise and set vertically; and are above the horizon half the time. At rising and setting the amplitude is equal to the declination. At meridian transit the altitude is equal to the codeclination. As the latitude changes name, the same-contrary name relationship with declination reverses. This accounts for the fact that one hemisphere has winter while the other is having summer.

The error arising from showing the hour circles and vertical circles as arcs of circles instead of ellipses increases with increased declination or altitude. More accurate results can be obtained by measurement of azimuth on the parallel of altitude instead of the horizon, and of hour angle on the parallel of declination instead of the celestial equator. Refer to Figure 1529f. The vertical circle shown is for a body having an azimuth angle of S60°W. The arc of a circle is shown in black, and the ellipse in red. The black arc is obtained by measurement around the horizon, locating A' by means of A, as previously described. The intersection of this arc with the altitude circle at 60° places the body at M. If a semicircle is drawn with the altitude circle as a diameter, and the azimuth angle measured around this, to B, a perpendicular to the hour circle locates the body at M', on the ellipse. By this method the altitude circle, rather than the horizon, is, in effect, rotated through 90° for the measurement. This refinement is seldom used because actual values are usually found mathematically, the diagram on the plane of the meridian being used primarily to indicate relationships.

With experience, one can visualize the diagram on the plane of the celestial meridian without making an actual drawing. Devices with two sets of spherical coordinates, on either the orthographic or stereographic projection, pivoted at the center, have been produced commercially to provide a mechanical diagram on the plane of the celestial meridian. However, since the diagram's principal use is to illustrate certain relationships, such a device is not a necessary part of the navigator's equipment.

Figure 1529g summarizes navigation coordinate systems.

1530. The Navigational Triangle

A triangle formed by arcs of great circles of a sphere is called a **spherical triangle**. A spherical triangle on the celestial sphere is called a **celestial triangle**. The spherical triangle of particular significance to navigators is called the **navigational triangle**, formed by arcs of a *celestial meridian*, an *hour circle*, and a *vertical circle*. Its vertices are the *elevated pole*, the *zenith*, and a *point on the celestial sphere* (usually a celestial body). The terrestrial counterpart is also called a navigational triangle, being formed by arcs of two meridians and the great circle connecting two places on the earth, one on each meridian. The vertices are the two places and a pole. In great-circle sailing these places are the point of departure and the destination. In celestial navigation they are the assumed position (AP) of the observer and the geographical position (GP) of the body (the place having the body in its zenith). The GP of the sun is sometimes called the **subsolar point**, that of the moon the **sublunar point**, that of a satellite (either natural or artificial) the **subsatellite point**, and that of a star its **substellar** or **subastral point**. When used to solve a celestial observation, either the celestial or terrestrial triangle may be called the **astronomical triangle**.

The navigational triangle is shown in Figure 1530a on a diagram on the plane of the celestial meridian. The earth is at the center, O. The star is at M, dd' is its parallel of declination, and hh' is its altitude circle.

In the figure, arc QZ of the celestial meridian is the latitude of the observer, and PnZ, one side of the triangle, is the colatitude. Arc AM of the vertical circle is the altitude of the body, and side ZM of the triangle is the zenith distance, or coaltitude. Arc LM of the hour circle is the declination of the body, and side PnM of the triangle is the polar distance, or codeclination.

The angle at the elevated pole, ZPnM, having the hour circle and the celestial meridian as sides, is the meridian angle, t. The angle at the zenith, PnZM, having the vertical circle and that arc of the celestial meridian, which includes the elevated pole, as sides, is the azimuth angle. The angle at the celestial body, ZMPn, having the hour circle and the vertical circle as sides, is the parallactic angle (X) (sometimes called the position angle), which is not generally used

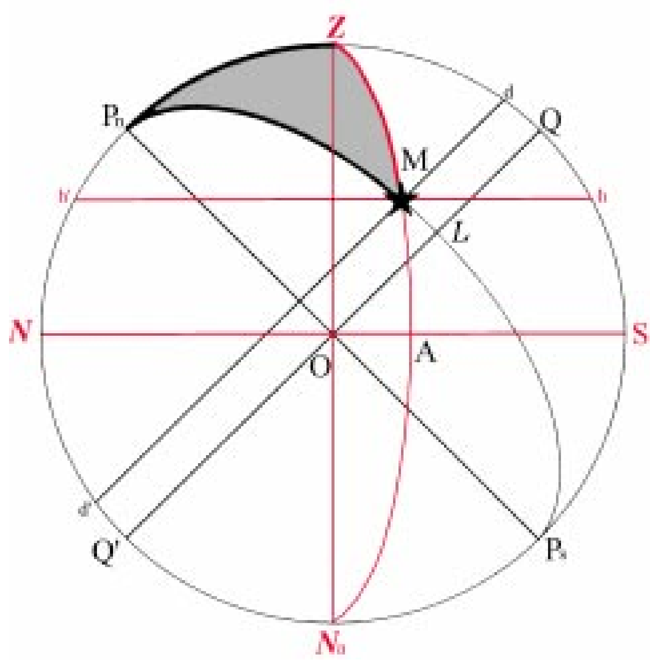

Figure 1530a. The navigational triangle.

by the navigator.

A number of problems involving the navigational triangle are encountered by the navigator, either directly or indirectly. Of these, the most common are:

1. Given latitude, declination, and meridian angle, to find altitude and azimuth angle. This is used in the reduction of a celestial observation to establish a line of position.
2. Given latitude, altitude, and azimuth angle, to find declination and meridian angle. This is used to identify an unknown celestial body.
3. Given meridian angle, declination, and altitude, to find azimuth angle. This may be used to find azimuth when the altitude is known.
4. Given the latitude of two places on the earth and the difference of longitude between them, to find the initial great-circle course and the great-circle distance. This involves the same parts of the triangle as in 1, above, but in the terrestrial triangle, and hence is defined differently.

Both celestial and terrestrial navigational triangles are shown in perspective in Figure 1530b.

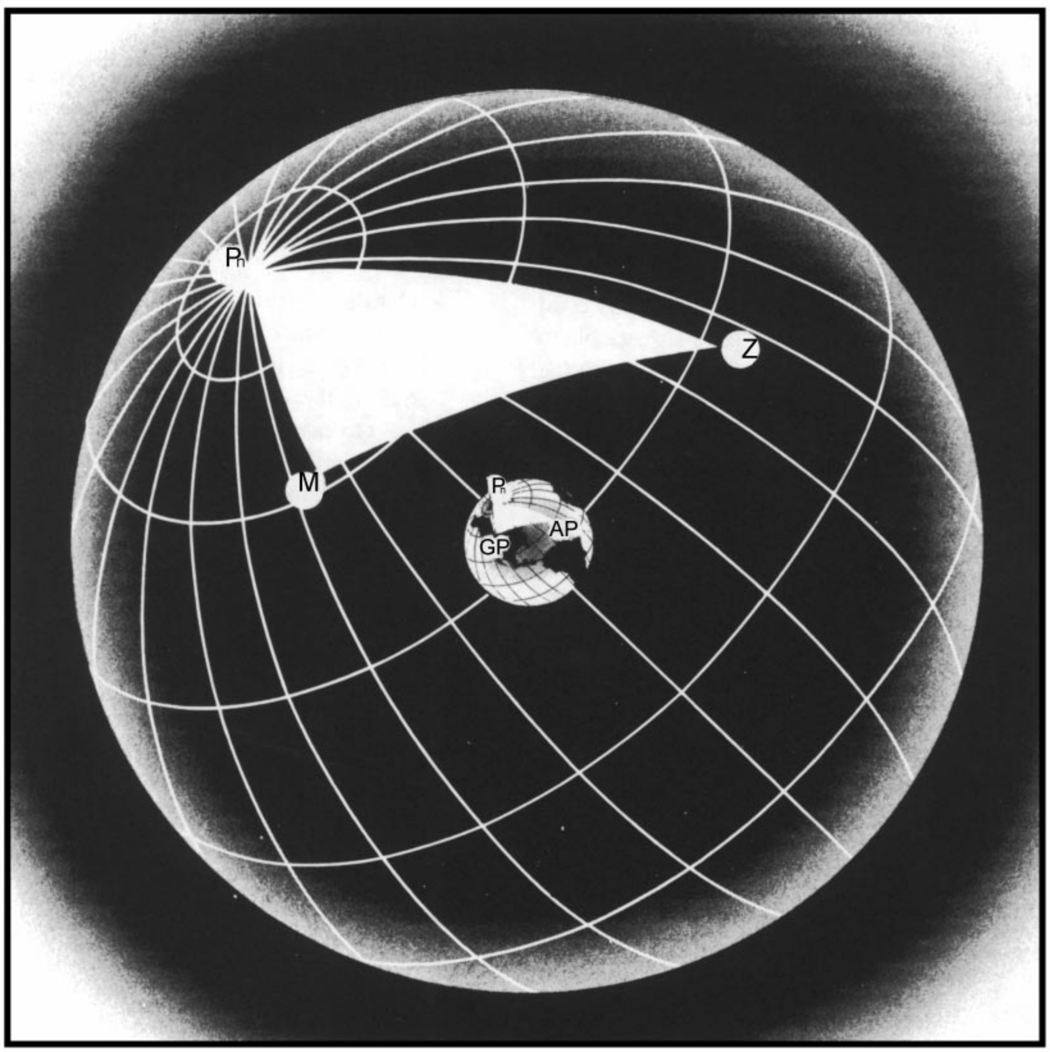

Figure 1530b. The navigational triangle in perspective.

IDENTIFICATION OF STARS AND PLANETS

1531. Introduction

A basic requirement of celestial navigation is the ability to identify the bodies observed. This is not difficult because relatively few stars and planets are commonly used for navigation, and various aids are available to assist in their identification. Some navigators may have access to a computer which can identify the celestial body observed given inputs of DR position and observed altitude. No problem is encountered in the identification of the sun and moon. However, the planets can be mistaken for stars. A person working continually with the night sky recognizes a planet by its changing position among the relatively fixed stars. The planets are identified by noting their positions relative to each other, the sun, the moon, and the stars. They remain within the narrow limits of the zodiac, but are in almost constant motion relative to the stars. The magnitude and color may be helpful. The information needed is found in the Nautical Almanac. The "Planet Notes" near the front of that volume are particularly useful.

Sometimes the light from a planet seems steadier than that from a star. This is because fluctuation of the unsteady atmosphere causes scintillation or twinkling of a star, which has no measurable diameter with even the most powerful telescopes. The navigational planets are less susceptible to the twinkling because of the broader apparent area giving light.

Planets can also be identified by planet diagram, star finder, sky diagram, or by computation.

1532. Stars

The Nautical Almanac lists full navigational information on 19 first magnitude stars and 38 second magnitude stars, plus Polaris. Abbreviated information is listed for 115 more. Additional stars are listed in The Astronomical Almanac and in various star catalogs. About 6,000 stars of the sixth magnitude or brighter (on the entire celestial sphere) are visible to the unaided eye on a clear, dark night.

Stars are designated by one or more of the following naming systems:

- **Common Name:** Most names of stars, as now used, were given by the ancient Arabs and some by the Greeks or Romans. One of the stars of the Nautical Almanac, Nunki, was named by the Babylonians. Only a relatively few stars have names. Several of the stars on the daily pages of the almanacs had no name prior to 1953.

- **Bayer's Name:** Most bright stars, including those with names, have been given a designation consisting of a Greek letter followed by the possessive form of the name of the constellation, such as α Cygni (Deneb, the brightest star in the constellation Cygnus, the swan). Roman letters are used when there are not enough Greek letters. Usually, the letters are assigned in order of brightness within the constellation; however, this is not always the case. For example, the letter designations of the stars in Ursa Major or the Big Dipper are assigned in order from the outer rim of the bowl to the end of the handle. This system of star designation was suggested by John Bayer of Augsburg, Germany, in 1603. All of the 173 stars included in the list near the back of the Nautical Almanac are listed by Bayer's name, and, when applicable, their common name.

- **Flamsteed's Number:** This system assigns numbers to stars in each constellation, from west to east in the order in which they cross the celestial meridian. An example is 95 Leonis, the 95th star in the constellation Leo. This system was suggested by John Flamsteed (1646-1719).

- **Catalog Number:** Stars are sometimes designated by the name of a star catalog and the number of the star as given in the catalog, such as A. G. Washington 632. In these catalogs, stars are listed in order from west to east, without regard to constellation, starting with the hour circle of the vernal equinox. This system is used primarily for fainter stars having no other designation. Navigators seldom have occasion to use this system.

1533. Star Charts

It is useful to be able to identify stars by relative position. A **star chart** (Figure 1533) is helpful in locating these relationships and others which may be useful. This method is limited to periods of relatively clear, dark skies with little or no overcast. Stars can also be identified by the Air Almanac **sky diagrams**, a **star finder**, *Pub. No. 249*, or by computation by hand or calculator.

Star charts are based upon the celestial equator system of coordinates, using declination and sidereal hour angle (or right ascension). The zenith of the observer is at the intersection of the parallel of declination equal to his latitude, and the hour circle coinciding with his celestial meridian. This hour circle has an SHA equal to 360° – LHA ♈ (or RA = LHA ♈). The horizon is everywhere 90° from the zenith. A **star globe** is similar to a terrestrial sphere, but with stars (and often constellations) shown instead of geographical positions. The Nautical Almanac includes instructions for using this

NAVIGATIONAL STARS AND THE PLANETS

Name	Pronunciation	Bayer name	Origin of name	Meaning of name	Distance*
Acamar	ā'kȧ·mär	θ Eridani	Arabic	another form of Achernar	120
Achernar	ā'kēr·när	α Eridani	Arabic	end of the river (Eridanus)	72
Acrux	ā'krŭks	α Crucis	Modern	coined from Bayer name	220
Adhara	ȧ·dā'rȧ	ε Canis Majoris	Arabic	the virgin(s)	350
Aldebaran	ăl dĕb'ȧ·răn	α Tauri	Arabic	follower (of the Pleiades)	64
Alioth	ăl'ĭ·ôth	ε Ursa Majoris	Arabic	another form of Capella	49
Alkaid	ăl·kād'	η Ursa Majoris	Arabic	leader of the daughters of the bier	190
Al Na'ir	ăl·nār'	α Gruis	Arabic	bright one (of the fish's tail)	90
Alnilam	ăl'nĭ·lăm	ε Orionis	Arabic	string of pearls	410
Alphard	ăl'färd	α Hydrae	Arabic	solitary star of the serpent	200
Alphecca	ăl·fĕk'ȧ	α Corona Borealis	Arabic	feeble one (in the crown)	76
Alpheratz	ăl·fē'răts	α Andromeda	Arabic	the horse's navel	120
Altair	ăl·tār'	α Aquilae	Arabic	flying eagle or vulture	16
Ankaa	än'kä	α Phoenicis	Arabic	coined name	93
Antares	ăn·tā'rēz	α Scorpii	Greek	rival of Mars (in color)	250
Arcturus	ärk·tū'rŭs	α Bootis	Greek	the bear's guard	37
Atria	ăt'rĭ·ȧ	α Trianguli Australis	Modern	coined from Bayer name	130
Avior	ā'vĭ·ôr	ε Carinae	Modern	coined name	350
Bellatrix	bĕ·lā'trĭks.	γ Orionis	Latin	female warrior	250
Betelgeuse	bĕt'ĕl·jūz	α Orionis	Arabic	the arm pit (of Orion)	300
Canopus	kȧ·nō'pŭs	α Carinae	Greek	city of ancient Egypt	230
Capella	kȧ·pĕl'ȧ	α Aurigae	Latin	little she-goat	46
Deneb	dĕn'ĕb	α Cygni	Arabic	tail of the hen	600
Denebola	dĕ·nĕb'ō·lȧ	β Leonis	Arabic	tail of the lion	42
Diphda	dĭf'dȧ	β Ceti	Arabic	the second frog (Fomalhaut was once the first)	57
Dubhe	dŭb'ē	α Ursa Majoris	Arabic	the bear's back	100
Elnath	ĕl'năth	β Tauri	Arabic	one butting with horns	130
Eltanin	ĕl·tā'nĭn	γ Draconis	Arabic	head of the dragon	150
Enif	ĕn'ĭf	ε Pegasi	Arabic	nose of the horse	250
Fomalhaut	fō'măl·ôt	α Piscis Austrini	Arabic	mouth of the southern fish	23
Gacrux	gā'krŭks	γ Crucis	Modern	coined from Bayer name	72
Gienah	jē'nȧ	γ Corvi	Arabic	right wing of the raven	136
Hadar	hā'där	β Centauri	Modern	leg of the centaur	200
Hamal	hăm'ȧl	α Arietis	Arabic	full-grown lamb	76
Kaus Australis	kôs ôs·trā'lĭs	ε Sagittarii	Ar., L.	southern part of the bow	163
Kochab	kō'kăb	β Ursa Minoris	Arabic	shortened form of "north star" (named when it was that, c. 1500 BC–AD 300)	100
Markab	mär'kăb	α Pegasi	Arabic	saddle (of Pegasus)	100
Menkar	mĕn'kär	α Ceti	Arabic	nose (of the whale)	1,100
Menkent	mĕn'kĕnt	θ Centauri	Modern	shoulder of the centaur	55
Miaplacidus	mī'ȧ·plăs'ĭ·dŭs	β Carinae	Ar., L.	quiet or still waters	86
Mirfak	mĭr'făk	α Persei	Arabic	elbow of the Pleiades	130
Nunki	nŭn'kē	σ Sagittarii	Bab.	constellation of the holy city (Eridu)	150
Peacock	pē'kŏk	α Pavonis	Modern	coined from English name of constellation	250
Polaris	pō·lā'rĭs	α Ursa Minoris	Latin	the pole (star)	450
Pollux	pŏl'ŭks	β Geminorum	Latin	Zeus' other twin son (Castor, α Geminorum, is first twin)	33
Procyon	prō'sĭ·ŏn	α Canis Minoris	Greek	before the dog (rising before the dog star, Sirius)	11
Rasalhague	răs'ăl·hā'gwē	α Ophiuchi	Arabic	head of the serpent charmer	67
Regulus	rĕg'ū·lŭs	α Leonis	Latin	the prince	67
Rigel	rī'jĕl	β Orionis	Arabic	foot (left foot of Orion)	500
Rigil Kentaurus	rī'jĭl kĕn·tô'rŭs	α Centauri	Arabic	foot of the centaur	4.3
Sabik	sā'bĭk	η Ophiuchi	Arabic	second winner or conqueror	69
Schedar	shĕd'ȧr	α Cassiopeiae	Arabic	the breast (of Cassiopeia)	360
Shaula	shô'lȧ	λ Scorpii	Arabic	cocked-up part of the scorpion's tail	200
Sirius	sĭr'ĭ·ŭs	α Canis Majoris	Greek	the scorching one (popularly, the dog star)	8.6
Spica	spī'kȧ	α Virginis	Latin	the ear of corn	155
Suhail	sōō·hāl'	λ Velorum	Arabic	shortened form of Al Suhail, one Arabic name for Canopus	200
Vega	vē'gȧ	α Lyrae	Arabic	the falling eagle or vulture	27
Zubenelgenubi	zōō·bĕn'ĕl·jē·nū'bē	α Librae	Arabic	southern claw (of the scorpion)	66

PLANETS

Name	Pronunciation	Origin of name	Meaning of name
Mercury	mûr'kū·rĭ	Latin	god of commerce and gain
Venus	vē'nŭs	Latin	goddess of love
Earth	ûrth	Mid. Eng.	—
Mars	märz	Latin	god of war
Jupiter	jōō'pĭ·tēr	Latin	god of the heavens, identified with the Greek Zeus, chief of the Olympian gods
Saturn	săt'ērn	Latin	god of seed-sowing
Uranus	ū'rȧ·nŭs	Greek	the personification of heaven
Neptune	nĕp'tūn	Latin	god of the sea
Pluto	plōō'tō	Greek	god of the lower world (Hades)

Guide to pronunciations:
fāte, ădd, finȧl, låst, ȧbound, ärm; bē, ĕnd, camĕl, readēr; īce, bĭt, anĭmal; ōver, pōetic, hŏt, lôrd, mōōn; tūbe, ūnite, tŭb, circŭs, ûrn

*Distances in light-years. One light-year equals approximately 63,300 AU, or 5,880,000,000,000 miles. Authorities differ on distances of the stars; the values given are representative.

Figure 1531a. Navigational stars and the planets.

CONSTELLATIONS

Name	Pronunciation	Genitive	Pronunciation	Meaning	Navigational stars or approximate position
Hydra*	hī′drȧ	Hydrae	hī′drē	water monster	Alphard
Hydrus	hī′drŭs	Hydri	hī′drī	water snake	d 70°S, SHA 320°
Indus	ĭn′dŭs	Indi	ĭn′dī	Indian	d 60°S, SHA 35°
Lacerta	lȧ·sûr′tȧ	Lacertae	lȧ·sŭr′tē	lizard	d 45°N, SHA 25°
Leo (♌)*	lē′ō	Leonis	lē̇·ō′nĭs	lion	Denebola, Regulus
Leo Minor	lē′ō mī′nēr	Leonis Minoris	lē̇·ō′nĭs mĭ·nō′rĭs	smaller lion	d 35°N, SHA 205°
Lepus*	lē′pŭs	Leporis	lĕp′ŏ·rĭs	hare	d 20°S, SHA 275°
Libra (♎)*	lī′brȧ	Librae	lī′brē	balance [scales]†	Zubenelgenubi
Lupus*	lū′pŭs	Lupi	lū′pī	wolf	d 45°S, SHA 130°
Lynx	lĭngks	Lyncis	lĭn′sĭs	lynx	d 50°N, SHA 240°
Lyra*	lī′rȧ	Lyrae	lī′rē	lyre	Vega
Mensa	mĕn′sȧ	Mensae	mĕn′sē	table (mountain)††	d 75°S, SHA 275°
Microscopium	mī′krȱ·skō′pĭ·ŭm	Microscopii	mī′krȱ·skō′pĭ·ī	microscope	d 35°S, SHA 45°
Monoceros	mȱ·nŏs′ēr·ŏs	Monocerotis	mȱ·nŏs′ēr·ō′tĭs	unicorn	d 0°, SHA 255°
Musca	mŭs′kȧ	Muscae	mŭs′sē	fly	d 70°S, SHA 175°
Norma	nôr′mȧ	Normae	nôr′mē	square (and rule)††	d 50°S, SHA 120°
Octans	ŏk′tănz	Octantis	ŏk·tăn′tĭs	octant	d 85°S, SHA 40°
Ophiuchus*	ŏf′ĭ·ū′kŭs	Ophiuchi	ŏf′ĭ·ū′kī	serpent holder	Rasalhague, Sabik
Orion*	ȱ·rī′ŏn	Orionis	ō′rĭ·ō′nĭs	Orion [the hunter]†	Alnilam, Bellatrix, Betelgeuse, Rigel
Pavo	pā′vō	Pavonis	pǡ·vō′nĭs	peacock	Peacock
Pegasus*	pĕg′ȧ·sŭs	Pegasi	pĕg′ȧ·sī	Pegasus [winged horse]†	Enif, Markab
Perseus*	pûr′sūs	Persei	pûr′sē̇·ī	Perseus [mythological character]†	Mirfak
Phoenix	fē′nĭks	Phoenicis	fē̇·nī′sĭs	phoenix [the immortal bird]†	Ankaa
Pictor	pĭk′tēr	Pictoris	pĭk·tō′rĭs	painter (easel of)††	d 55°S, SHA 275°
Pisces (♓)*	pĭs′ēz	Piscium	pĭsh′ĭ·ŭm	fishes	d 15°N, SHA 355°
Piscis Austrinus*	pĭs′ĭs ôs·trī′nŭs	Piscis Austrini	pĭs′ĭs ôs·trī′nī	southern fish	Fomalhaut
Puppis**	pŭp′ĭs	Puppis	pŭp′ĭs	stern [of ship]†	d 30°S, SHA 245°
Pyxis**	pĭk′sĭs	Pyxidis	pĭk′sĭ·dĭs	mariner's compass	d 25°S, SHA 230°
Reticulum	rē̇·tĭk′ū̇·lŭm	Reticuli	rē̇·tĭk′ū̇·lī	net	d 60°S, SHA 300°
Sagitta*	sȧ·jĭt′ȧ	Sagittae	sȧ·jĭt′ē	arrow	d 20°N, SHA 65°
Sagittarius (♐)*	săj′ĭ·tā′rĭ·ŭs	Sagittarii	săj′ĭ·tā′rĭ·ī	archer	Kaus Australis, Nunki
Scorpius (♏)*	skôr′pĭ·ŭs	Scorpii	skôr′pĭ·ī	scorpion	Antares, Shaula
Sculptor	skŭlp′tēr	Sculptoris	skŭlp·tō′rĭs	sculptor (workshop of)††	d 30°S, SHA 355°
Scutum	skū′tŭm	Scuti	skū′tī	shield	d 10°S, SHA 80°
Serpens*	sûr′pĕnz	Serpentis	sēr·pĕn′tĭs	serpent	d 10°N, SHA 125°
Sextans	sĕks′tănz	Sextantis	sĕks·tăn′tĭs	sextant	d 0°, SHA 205°
Taurus (♉)*	tô′rŭs	Tauri	tô′rī	bull	Aldebaran, Elnath
Telescopium	tĕl′ē̇·skō′pĭ·ŭm	Telescopii	tĕl′ē̇·skō′pĭ·ī	telescope	d 50°S, SHA 75°
Triangulum*	trī·ăng′gū̇·lŭm	Trianguli	trī·ăng′gū̇·lī	triangle	d 30°N, SHA 330°
Triangulum Australe	trī·ăng′gū̇·lŭm ôs·trā′lē	Trianguli Australis	trī·ăng′gū̇·lī ôs·trā′lĭs	southern triangle	Atria
Tucana	tū̇·kā′nȧ	Tucanae	tū̇·kā′nē	toucan [a bird]†	d 65°S, SHA 5°
Ursa Major*	ŭr′sȧ mā′jēr	Ursae Majoris	ûr′sē mā·jō′rĭs	larger bear	Alioth, Alkaid, Dubhe
Ursa Minor*	ûr′sȧ mī′nēr	Ursae Minoris	ûr′sē mĭ·nō′rĭs	smaller bear	Kochab, Polaris
Vela**	vē′lȧ	Velorum	vē̇·lō′rŭm	sails	Suhail
Virgo (♍)*	vûr′gō	Virginis	vûr′jĭ·nĭs	virgin	Spica
Volans	vō′lănz	Volantis	vȱ·lăn′tĭs	flying (fish)††	d 70°S, SHA 240°
Vulpecula	vŭl·pĕk′ū̇·lȧ	Vulpeculae	vŭl·pĕk′ū̇·lē	little fox	d 25°N, SHA 60°

Zodiacal constellations are given in bold type, with their symbols.
*One of the original constellations of Ptolemy.
**Part of the single constellation Argo Navis of Ptolemy.
†Parts within brackets are amplifications of the meanings of constellation names.
††Parts within parentheses are the meanings of words deleted from former, more complete constellation names.

Guide to pronunciations:

fāte, cȧre, hăt, finȧl, ȧbound, sofȧ, ärm; bē, crē̇ate, ĕnd, readēr; īce, bĭt; ōver, pȱetic, hŏt, cŏnnect, lôrd, mōōn; tūbe, ū̇nite, tŭb, circŭs, ûrn.

Figure 1531b. Constellations.

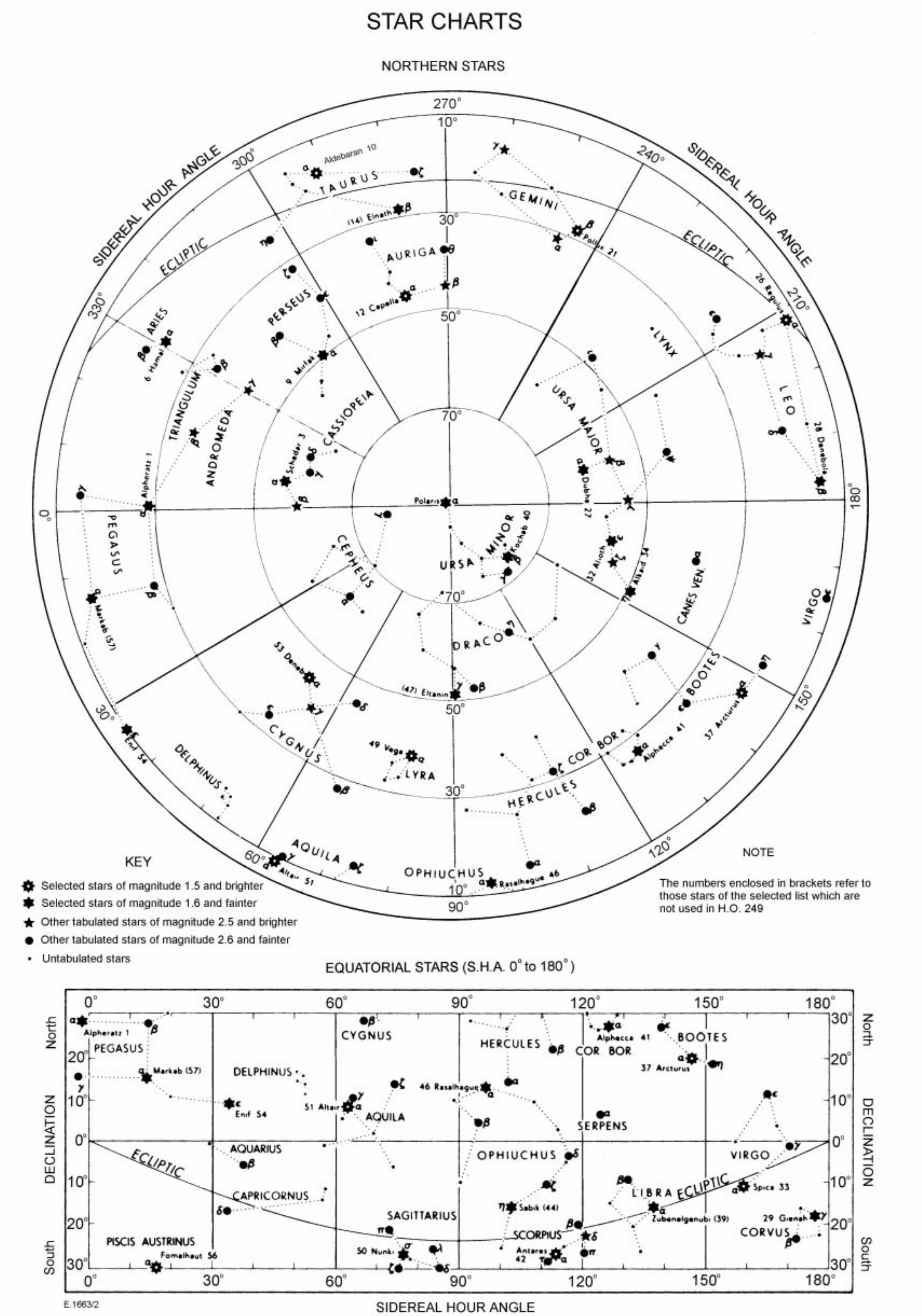

Figure 1533. Star chart.

device. On a star globe the celestial sphere is shown as it would appear to an observer outside the sphere. Constellations appear reversed. Star charts may show a similar view, but more often they are based upon the view from inside the sphere, as seen from the earth. On these charts, north is at the top, as with maps, but east is to the left and west to the right. The directions seem correct when the chart is held overhead, with the top toward the north, so the relationship is similar to the sky.

The Nautical Almanac has four star charts. The two principal ones are on the polar azimuthal equidistant projection, one centered on each celestial pole. Each chart extends from its pole to declination 10° (same name as pole). Below each polar chart is an auxiliary chart on the Mercator projection, from 30°N to 30°S. On any of these charts, the zenith can be located as indicated, to determine which stars are overhead. The horizon is 90° from the zenith. The charts can also be used to determine the location of a star relative to surrounding stars.

The Air Almanac contains a folded chart on the rectangular projection. This projection is suitable for indicating the coordinates of the stars, but excessive distortion occurs in regions of high declination. The celestial poles are represented by the top and bottom horizontal lines the same length as the celestial equator. To locate the horizon on this chart, first locate the zenith as indicated above, and then locate the four cardinal points. The north and south points are 90° from the zenith, along the celestial meridian. The distance to the elevated pole (having the same name as the latitude) is equal to the colatitude of the observer. The remainder of the 90° (the latitude) is measured from the same pole, along the lower branch of the celestial meridian, 180° from the upper branch containing the zenith. The east and west points are on the celestial equator at the hour circle 90° east and west (or 90° and 270° in the same direction) from the celestial meridian. The horizon is a sine curve through the four cardinal points. Directions on this projection are distorted.

The star charts shown in Figure 1534 through Figure 1537, on the transverse Mercator projection, are designed to assist in learning Polaris and the stars listed on the daily pages of the Nautical Almanac. Each chart extends about 20° beyond each celestial pole, and about 60° (four hours) each side of the central hour circle (at the celestial equator). Therefore, they do not coincide exactly with that half of the celestial sphere above the horizon at any one time or place. The zenith, and hence the horizon, varies with the position of the observer on the earth. It also varies with the rotation of the earth (apparent rotation of the celestial sphere). The charts show all stars of fifth magnitude and brighter as they appear in the sky, but with some distortion toward the right and left edges.

The overprinted lines add certain information of use in locating the stars. Only Polaris and the 57 stars listed on the daily pages of the Nautical Almanac are named on the charts. The almanac star charts can be used to locate the additional stars given near the back of the Nautical Almanac and the Air Almanac. Dashed lines connect stars of some of the more prominent constellations. Solid lines indicate the celestial equator and useful relationships among stars in different constellations. The celestial poles are marked by crosses, and labeled. By means of the celestial equator and the poles, one can locate his zenith approximately along the mid hour circle, when this coincides with his celestial meridian, as shown in the table below. At any time earlier than those shown in the table the zenith is to the right of center, and at a later time it is to the left, approximately one-quarter of the distance from the center to the outer edge (at the celestial equator) for each hour that the time differs from that shown. The stars in the vicinity of the North Pole can be seen in proper perspective by inverting the chart, so that the zenith of an observer in the Northern Hemisphere is up from the pole.

1534. Stars In The Vicinity Of Pegasus

In autumn the evening sky has few first magnitude stars. Most are near the southern horizon of an observer in the latitudes of the United States. A relatively large number of second and third magnitude stars seem conspicuous, perhaps because of the small number of brighter stars. High in the southern sky three third magnitude stars and one second magnitude star form a square with sides nearly 15° of arc in length. This is Pegasus, the winged horse.

	Fig. 1534	Fig.1535	Fig. 1536	Fig. 1537
Local sidereal time	0000	0600	1200	1800
LMT 1800	Dec. 21	Mar. 22	June 22	Sept. 21
LMT 2000	Nov. 21	Feb. 20	May 22	Aug. 21
LMT 2200	Oct. 21	Jan. 20	Apr. 22	July 22
LMT 0000	Sept. 22	Dec. 22	Mar. 23	June 22
LMT 0200	Aug. 22	Nov. 22	Feb. 21	May 23
LMT 0400	July 23	Oct. 22	Jan 21	Apr. 22
LMT 0600	June 22	Sept. 21	Dec. 22	Mar. 23

Table 1533. Locating the zenith on the star diagrams.

Only Markab at the southwestern corner and Alpheratz

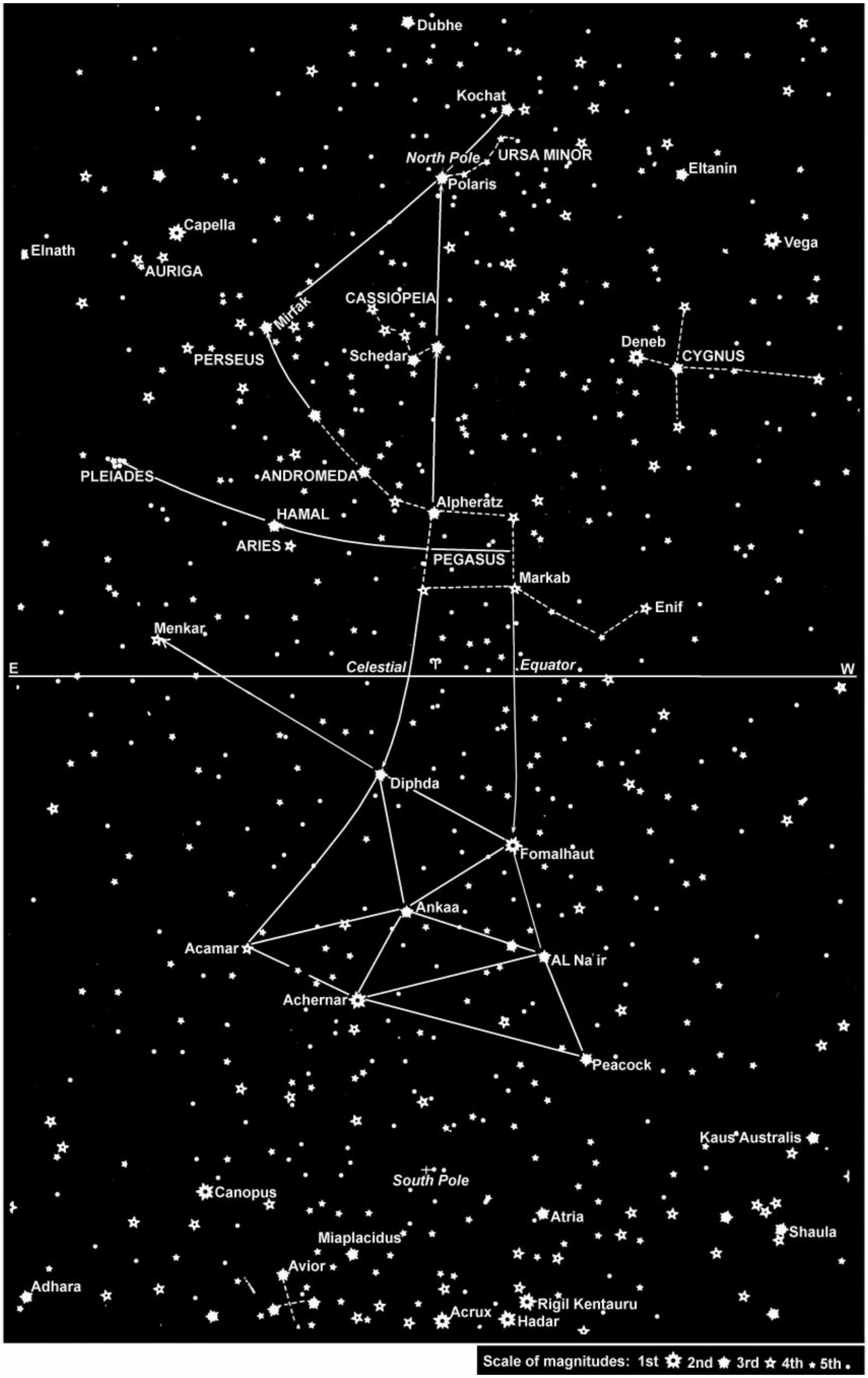

Figure 1534. Stars in the vicinity of Pegasus.

at the northeastern corner are listed on the daily pages of the Nautical Almanac. Alpheratz is part of the constellation Andromeda, the princess, extending in an arc toward the northeast and terminating at Mirfak in Perseus, legendary rescuer of Andromeda.

A line extending northward through the eastern side of the square of Pegasus passes through the leading (western) star of M-shaped (or W-shaped) Cassiopeia, the legendary mother of the princess Andromeda. The only star of this constellation listed on the daily pages of the Nautical Almanac is Schedar, the second star from the leading one as the configuration circles the pole in a counterclockwise direction. If the line through the eastern side of the square of Pegasus is continued on toward the north, it leads to second magnitude Polaris, the North Star (less than 1° from the north celestial pole) and brightest star of Ursa Minor, the Little Dipper. Kochab, a second magnitude star at the other end of Ursa Minor, is also listed in the almanacs. At this season Ursa Major is low in the northern sky, below the celestial pole. A line extending from Kochab through Polaris leads to Mirfak, assisting in its identification when Pegasus and Andromeda are near or below the horizon.

Deneb, in Cygnus, the swan, and Vega are bright, first magnitude stars in the northwestern sky.

The line through the eastern side of the square of Pegasus approximates the hour circle of the vernal equinox, shown at Aries on the celestial equator to the south. The sun is at Aries on or about March 21, when it crosses the celestial equator from south to north. If the line through the eastern side of Pegasus is extended southward and curved slightly toward the east, it leads to second magnitude Diphda. A longer and straighter line southward through the western side of Pegasus leads to first magnitude Fomalhaut. A line extending northeasterly from Fomalhaut through Diphda leads to Menkar, a third magnitude star, but the brightest in its vicinity. Ankaa, Diphda, and Fomalhaut form an isosceles triangle, with the apex at Diphda. Ankaa is near or below the southern horizon of observers in latitudes of the United States. Four stars farther south than Ankaa may be visible when on the celestial meridian, just above the horizon of observers in latitudes of the extreme southern part of the United States. These are Acamar, Achernar, Al Na'ir, and Peacock. These stars, with each other and with Ankaa, Fomalhaut, and Diphda, form a series of triangles as shown in Figure 1534. Almanac stars near the bottom of Figure 1534 are discussed in succeeding articles.

Two other almanac stars can be located by their positions relative to Pegasus. These are Hamal in the constellation Aries, the ram, east of Pegasus, and Enif, west of the southern part of the square, identified in Figure 1534. The line leading to Hamal, if continued, leads to the Pleiades (the Seven Sisters), not used by navigators for celestial observations, but a prominent figure in the sky, heralding the approach of the many conspicuous stars of the winter evening sky.

1535. Stars In The Vicinity Of Orion

As Pegasus leaves the meridian and moves into the western sky, Orion, the hunter, rises in the east. With the possible exception of Ursa Major, no other configuration of stars in the entire sky is as well known as Orion and its immediate surroundings. In no other region are there so many first magnitude stars.

The belt of Orion, nearly on the celestial equator, is visible in virtually any latitude, rising and setting almost on the prime vertical, and dividing its time equally above and below the horizon. Of the three second magnitude stars forming the belt, only Alnilam, the middle one, is listed on the daily pages of the Nautical Almanac.

Four conspicuous stars form a box around the belt. Rigel, a hot, blue star, is to the south. Betelgeuse, a cool, red star lies to the north. Bellatrix, bright for a second magnitude star but overshadowed by its first magnitude neighbors, is a few degrees west of Betelgeuse. Neither the second magnitude star forming the southeastern corner of the box, nor any star of the dagger, is listed on the daily pages of the Nautical Almanac.

A line extending eastward from the belt of Orion, and curving toward the south, leads to Sirius, the brightest star in the entire heavens, having a magnitude of –1.6. Only Mars and Jupiter at or near their greatest brilliance, the sun, moon, and Venus are brighter than Sirius. Sirius is part of the constellation Canis Major, the large hunting dog of Orion. Starting at Sirius a curved line extends northward through first magnitude Procyon, in Canis Minor, the small hunting dog; first magnitude Pollux and second magnitude Castor (not listed on the daily pages of the Nautical Almanac), the twins of Gemini; brilliant Capella in Auriga, the charioteer; and back down to first magnitude Aldebaran, the follower, which trails the Pleiades, the seven sisters. Aldebaran, brightest star in the head of Taurus, the bull, may also be found by a curved line extending northwestward from the belt of Orion. The V-shaped figure forming the outline of the head and horns of Taurus points toward third magnitude Menkar. At the summer solstice the sun is between Pollux and Aldebaran.

If the curved line from Orion's belt southeastward to Sirius is continued, it leads to a conspicuous, small, nearly equilateral triangle of three bright second magnitude stars of nearly equal brilliancy. This is part of Canis Major. Only Adhara, the westernmost of the three stars, is listed on the daily pages of the Nautical Almanac. Continuing on with somewhat less curvature, the line leads to Canopus, second brightest star in the heavens and one of the two stars having a negative magnitude (–0.9). With Suhail and Miaplacidus, Canopus forms a large, equilateral triangle which partly encloses the group of stars often mistaken for Crux. The brightest star within this triangle is Avior, near its center. Canopus is also at one apex of a triangle formed with Adhara to the north and Suhail to the east, another triangle with Acamar to the west and Achernar to the southwest, and an-

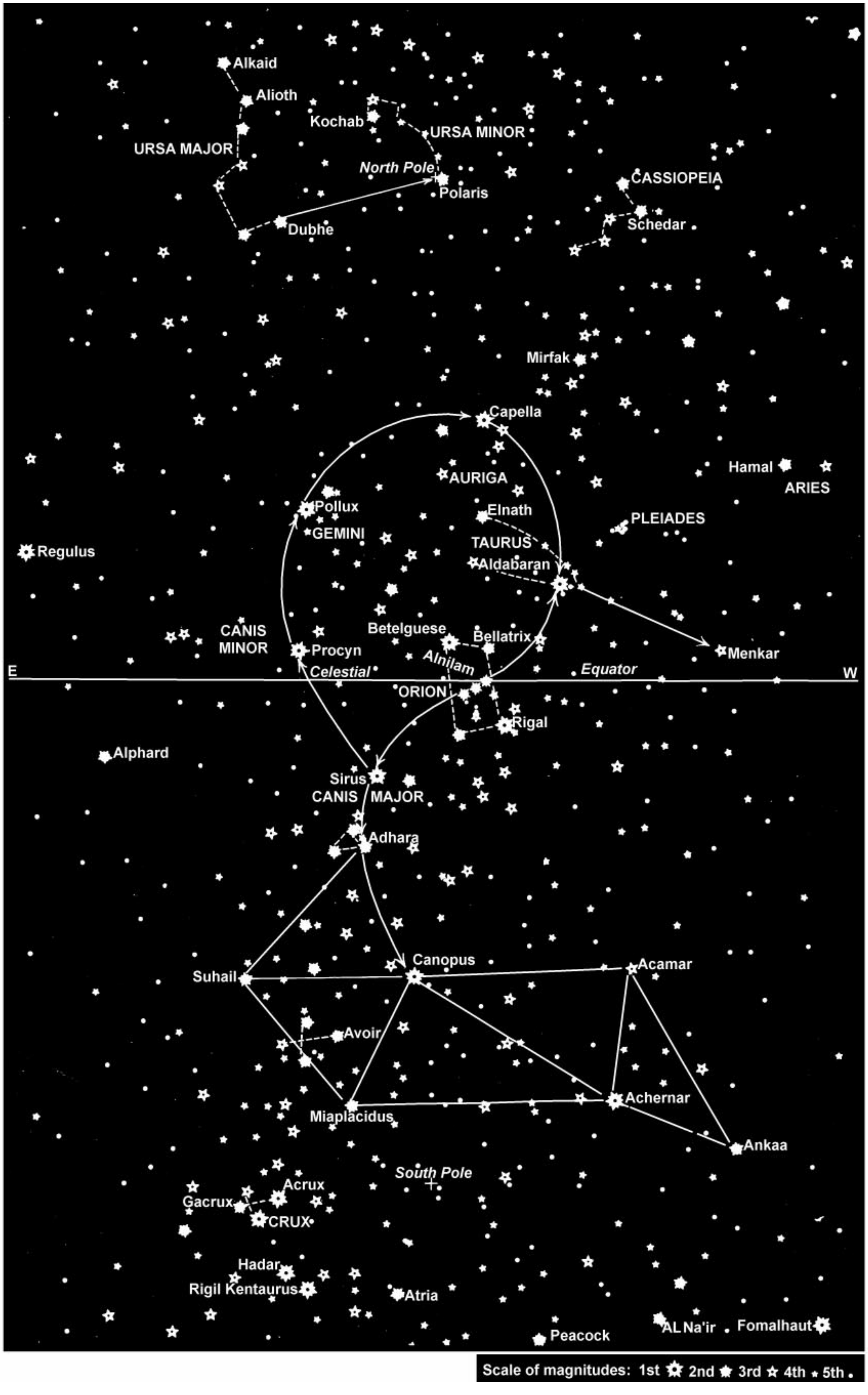

Figure 1535. Stars in the vicinity of Orion.

other with Achernar and Miaplacidus. Acamar, Achernar, and Ankaa form still another triangle toward the west. Because of chart distortion, these triangles do not appear in the sky in exactly the relationship shown on the star chart. Other daily-page almanac stars near the bottom of Figure 1535 are discussed in succeeding articles.

In the winter evening sky, Ursa Major is east of Polaris, Ursa Minor is nearly below it, and Cassiopeia is west of it. Mirfak is northwest of Capella, nearly midway between it and Cassiopeia. Hamal is in the western sky. Regulus and Alphard are low in the eastern sky, heralding the approach of the configurations associated with the evening skies of spring.

1536. Stars In The Vicinity Of Ursa Major

As if to enhance the splendor of the sky in the vicinity of Orion, the region toward the east, like that toward the west, has few bright stars, except in the vicinity of the south celestial pole. However, as Orion sets in the west, leaving Capella and Pollux in the northwestern sky, a number of good navigational stars move into favorable positions for observation.

Ursa Major, the great bear, appears prominently above the north celestial pole, directly opposite Cassiopeia, which appears as a "W" just above the northern horizon of most observers in latitudes of the United States. Of the seven stars forming Ursa Major, only Dubhe, Alioth, and Alkaid are listed on the daily pages of the Nautical Almanac.

The two second magnitude stars forming the outer part of the bowl of Ursa Major are often called the pointers because a line extending northward (down in spring evenings) through them points to Polaris. Ursa Minor, the Little Bear, contains Polaris at one end and Kochab at the other. Relative to its bowl, the handle of Ursa Minor curves in the opposite direction to that of Ursa Major.

A line extending southward through the pointers, and curving somewhat toward the west, leads to first magnitude Regulus, brightest star in Leo, the lion. The head, shoulders, and front legs of this constellation form a sickle, with Regulus at the end of the handle. Toward the east is second magnitude Denebola, the tail of the lion. On toward the southwest from Regulus is second magnitude Alphard, brightest star in Hydra, the sea serpent. A dark sky and considerable imagination are needed to trace the long, winding body of this figure.

A curved line extending the arc of the handle of Ursa Major leads to first magnitude Arcturus. With Alkaid and Alphecca, brightest star in Corona Borealis, the Northern Crown, Arcturus forms a large, inconspicuous triangle. If the arc through Arcturus is continued, it leads next to first magnitude Spica and then to Corvus, the crow. The brightest star in this constellation is Gienah, but three others are nearly as bright. At autumnal equinox, the sun is on the celestial equator, about midway between Regulus and Spica.

A long, slightly curved line from Regulus, east-southeasterly through Spica, leads to Zubenelgenubi at the southwestern corner of an inconspicuous box-like figure called Libra, the scales.

Returning to Corvus, a line from Gienah, extending diagonally across the figure and then curving somewhat toward the east, leads to Menkent, just beyond Hydra.

Far to the south, below the horizon of most northern hemisphere observers, a group of bright stars is a prominent feature of the spring sky of the Southern Hemisphere. This is Crux, the Southern Cross. Crux is about 40° south of Corvus. The "false cross" to the west is often mistaken for Crux. Acrux at the southern end of Crux and Gacrux at the northern end are listed on the daily pages of the Nautical Almanac.

The triangles formed by Suhail, Miaplacidus, and Canopus, and by Suhail, Adhara, and Canopus, are west of Crux. Suhail is in line with the horizontal arm of Crux. A line from Canopus, through Miaplacidus, curved slightly toward the north, leads to Acrux. A line through the east-west arm of Crux, eastward and then curving toward the south, leads first to Hadar and then to Rigil Kentaurus, both very bright stars. Continuing on, the curved line leads to small Triangulum Australe, the Southern Triangle, the easternmost star of which is Atria.

1537. Stars In The Vicinity Of Cygnus

As the celestial sphere continues in its apparent westward rotation, the stars familiar to a spring evening observer sink low in the western sky. By midsummer, Ursa Major has moved to a position to the left of the north celestial pole, and the line from the pointers to Polaris is nearly horizontal. Ursa Minor, is standing on its handle, with Kochab above and to the left of the celestial pole. Cassiopeia is at the right of Polaris, opposite the handle of Ursa Major.

The only first magnitude star in the western sky is Arcturus, which forms a large, inconspicuous triangle with Alkaid, the end of the handle of Ursa Major, and Alphecca, the brightest star in Corona Borealis, the Northern Crown.

The eastern sky is dominated by three very bright stars. The westernmost of these is Vega, the brightest star north of the celestial equator, and third brightest star in the heavens, with a magnitude of 0.1. With a declination of a little less than 39°N, Vega passes through the zenith along a path across the central part of the United States, from Washington in the east to San Francisco on the Pacific coast. Vega forms a large but conspicuous triangle with its two bright neighbors, Deneb to the northeast and Altair to the southeast. The angle at Vega is nearly a right angle. Deneb is at the end of the tail of Cygnus, the swan. This configuration is sometimes called the Northern Cross, with Deneb at the head. To modern youth it more nearly resembles a dive bomber, while it is still well toward the east, with Deneb at the nose of the fuselage. Altair has two fainter stars close by, on opposite sides. The line formed by Altair and its two fainter companions, if extended in a northwesterly direction, passes through Vega, and on to second magnitude Eltanin. The angular distance from Vega to Eltanin is about half that from Altair to Vega. Vega and Altair,

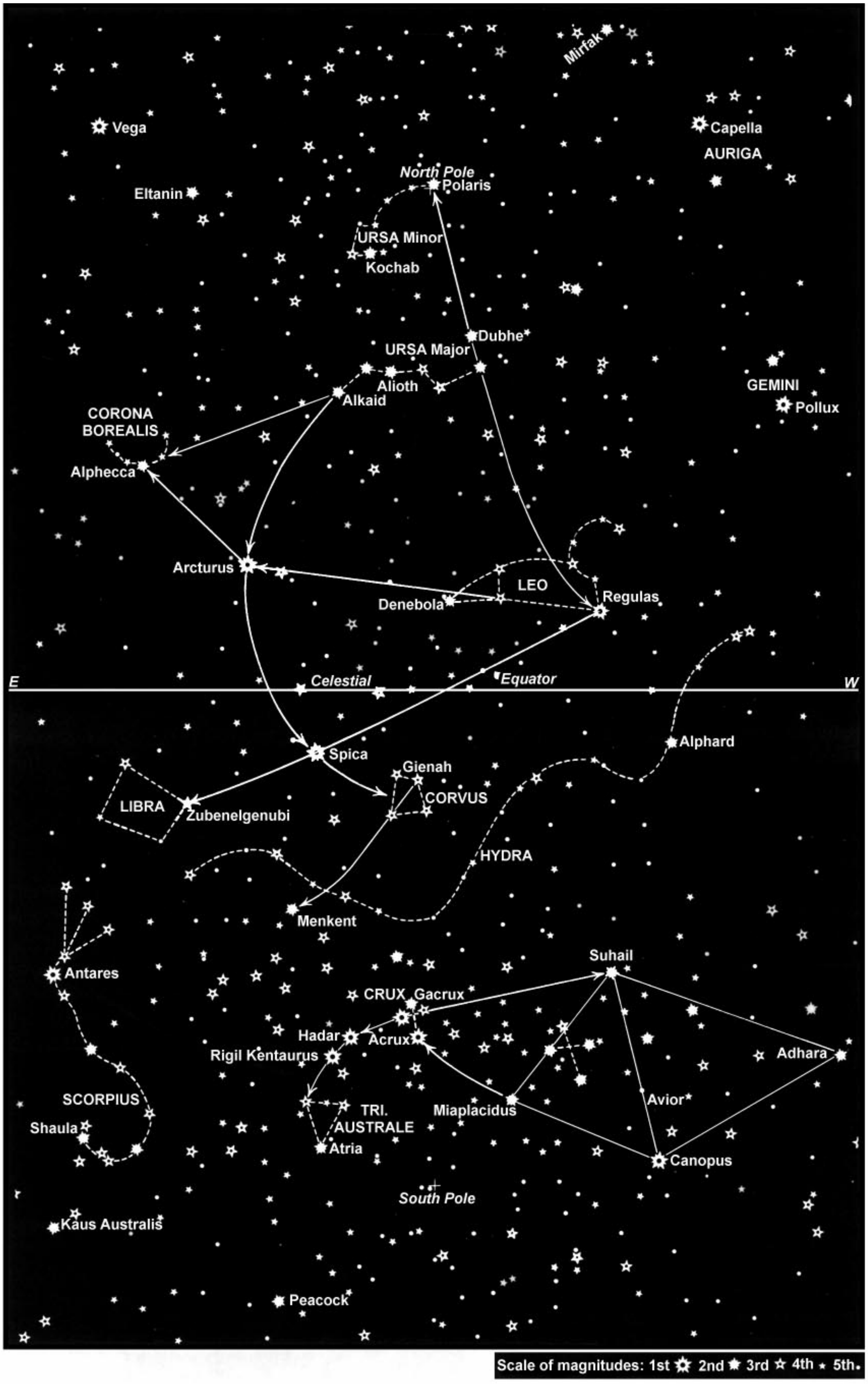

Figure 1536. Stars in the vicinity of Ursa Major.

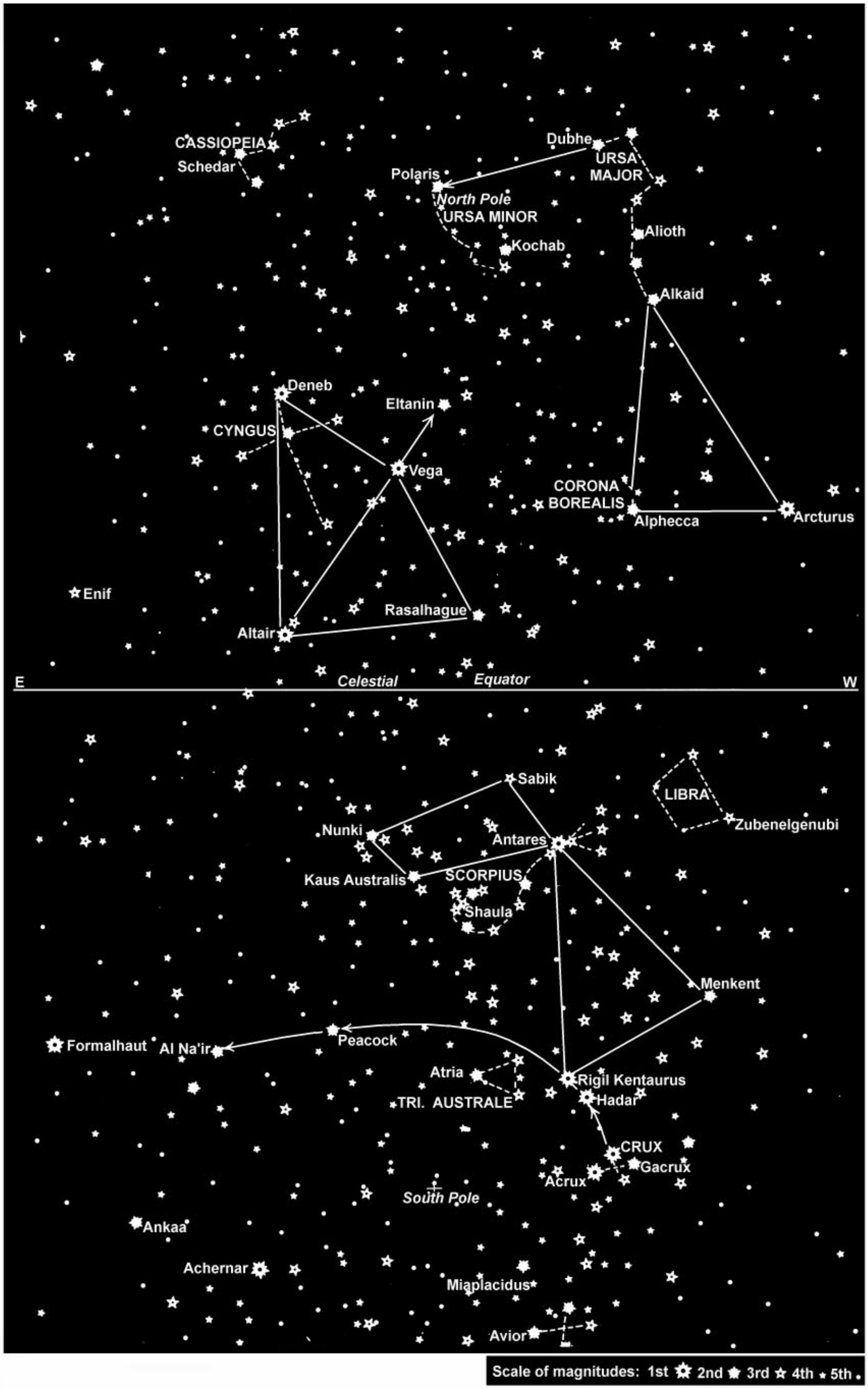

Figure 1537. Stars in the vicinity of Cygnus.

with second magnitude Rasalhague to the west, form a large equilateral triangle. This is less conspicuous than the Vega-Deneb-Altair triangle because the brilliance of Rasalhague is much less than that of the three first magnitude stars, and the triangle is overshadowed by the brighter one.

Far to the south of Rasalhague, and a little toward the west, is a striking configuration called Scorpius, the scorpion. The brightest star, forming the head, is red Antares. At the tail is Shaula.

Antares is at the southwestern corner of an approximate parallelogram formed by Antares, Sabik, Nunki, and Kaus Australis. With the exception of Antares, these stars are only slightly brighter than a number of others nearby, and so this parallelogram is not a striking figure. At winter solstice the sun is a short distance northwest of Nunki.

Northwest of Scorpius is the box-like Libra, the scales, of which Zubenelgenubi marks the southwest corner.

With Menkent and Rigil Kentaurus to the southwest, Antares forms a large but unimpressive triangle. For most observers in the latitudes of the United States, Antares is low in the southern sky, and the other two stars of the triangle are below the horizon. To an observer in the Southern Hemisphere Crux is to the right of the south celestial pole, which is not marked by a conspicuous star. A long, curved line, starting with the now-vertical arm of Crux and extending northward and then eastward, passes successively through Hadar, Rigil Kentaurus, Peacock, and Al Na'ir.

Fomalhaut is low in the southeastern sky of the southern hemisphere observer, and Enif is low in the eastern sky at nearly any latitude. With the appearance of these stars it is not long before Pegasus will appear over the eastern horizon during the evening, and as the winged horse climbs evening by evening to a position higher in the sky, a new annual cycle approaches.

1538. Planet Diagram

The planet diagram in the Nautical Almanac shows, in graphical form for any date during the year, the LMT of meridian passage of the sun, for the five planets Mercury, Venus, Mars, Jupiter, and Saturn, and of each 30° of SHA. The diagram provides a general picture of the availability of planets and stars for observation, and thus shows:

1. Whether a planet or star is too close to the sun for observation.
2. Whether a planet is a morning or evening star.
3. Some indication of the planet's position during twilight.
4. The proximity of other planets.
5. Whether a planet is visible from evening to morning twilight.

A band 45^m wide is shaded on each side of the curve marking the LMT of meridian passage of the sun. Any planet and most stars lying within the shaded area are too close to the sun for observation.

When the meridian passage occurs at midnight, the body is in opposition to the sun and is visible all night; planets may be observable in both morning and evening twilights. As the time of meridian passage decreases, the body ceases to be observable in the morning, but its altitude above the eastern horizon during evening twilight gradually increases; this continues until the body is on the meridian at twilight. From then onwards the body is observable above the western horizon and its altitude at evening twilight gradually decreases; eventually the body comes too close to the sun for observation. When the body again becomes visible, it is seen as a morning star low in the east. Its altitude at twilight increases until meridian passage occurs at the time of morning twilight. Then, as the time of meridian passage decreases to 0^h, the body is observable in the west in the morning twilight with a gradually decreasing altitude, until it once again reaches opposition.

Only about one-half the region of the sky along the ecliptic, as shown on the diagram, is above the horizon at one time. At sunrise (LMT about 6^h) the sun and, hence, the region near the middle of the diagram, are rising in the east; the region at the bottom of the diagram is setting in the west. The region half way between is on the meridian. At sunset (LMT about 18^h) the sun is setting in the west; the region at the top of the diagram is rising in the east. Marking the planet diagram of the Nautical Almanac so that east is at the top of the diagram and west is at the bottom can be useful to interpretation.

If the curve for a planet intersects the vertical line connecting the date graduations below the shaded area, the planet is a morning star; if the intersection is above the shaded area, the planet is an evening star.

A similar planet location diagram in the Air Almanac represents the region of the sky along the ecliptic within which the sun, moon, and planets always move; it shows, for each date, the sun in the center and the relative positions of the moon, the five planets Mercury, Venus, Mars, Jupiter, Saturn and the four first magnitude stars Aldebaran, Antares, Spica, and Regulus, and also the position on the ecliptic which is north of Sirius (i.e. Sirius is 40° south of this point). The first point of Aries is also shown for reference. The magnitudes of the planets are given at suitable intervals along the curves. The moon symbol shows the correct phase. A straight line joining the date on the left-hand side with the same date of the right-hand side represents a complete circle around the sky, the two ends of the line representing the point 180° from the sun; the intersections with the curves show the spacing of the bodies along the ecliptic on the date. The time scale indicates roughly the local mean time at which an object will be on the observer's meridian.

At any time only about half the region on the diagram is above the horizon. At sunrise the sun (and hence the region near the middle of the diagram), is rising in the east and the region at the end marked "West" is setting in the west; the region half-way between these extremes is on the meridian, as will be indicated by the local time (about 6^h). At the time of sunset (local time about 18^h) the sun is setting in the west, and the region at the end marked "East" is rising in the east.

The diagram should be used in conjunction with the Sky Diagrams.

1539. Star Finders

Various devices have been devised to help an observer find individual stars. The most widely used is the **Star Finder and Identifier**, formerly published by the U.S. Navy Hydrographic Office, and now published commercially. The current model, No. 2102D, as well as the previous 2102C model, patented by E. B. Collins, employs the same basic principle as that used in the Rude Star Finder patented by Captain G. T. Rude, USC&GS, and later sold to the Hydrographic Office. Successive models reflect various modifications to meet changing conditions and requirements.

The star base of No. 2102D consists of a thin, white, opaque, plastic disk about 8 $^1/_2$ inches in diameter, with a small peg in the center. On one side the north celestial pole is shown at the center, and on the opposite side the south celestial pole is at the center. All of the stars listed on the daily pages of the Nautical Almanac are shown on a polar azimuthal equidistant projection extending to the opposite pole. The south pole side is shown in Figure 1539a. Many copies of an older edition, No. 2102C, showing the stars listed in the almanacs prior to 1953, and having other minor differences, are still in use. These are not rendered obsolete by the newer edition, but should be corrected by means of the current almanac. The rim of each side is graduated to half a degree of LHA ♈ (or 360° – SHA).

Ten transparent templates of the same diameter as the star base are provided. There is one template for each 10° of latitude, labeled 5°, 15°, 25°, etc., plus a 10th (printed in red) showing meridian angle and declination. The older edition (No. 2102C) did not have the red meridian angle-declination template. Each template can be used on either

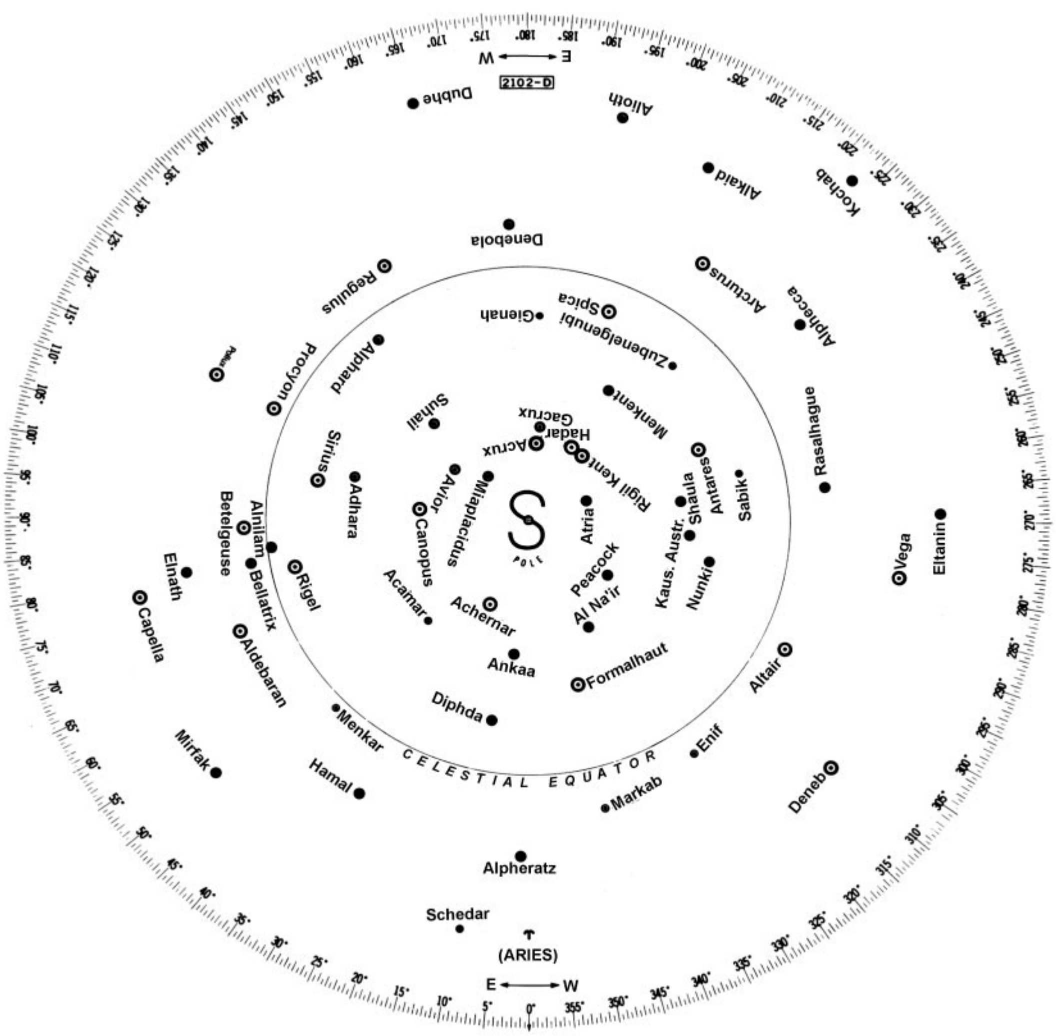

Figure 1539a. The south pole side of the star base of No. 2102D.

side of the star base, being centered by placing a small center hole in the template over the center peg of the star base. Each latitude template has a family of altitude curves at 5° intervals from the horizon (from altitude 10° on the older No. 2102C) to 80°. A second family of curves, also at 5° intervals, indicates azimuth. The north-south azimuth line is the celestial meridian. The star base, templates, and a set of instructions are kept in a circular leatherette container.

Since the sun, moon, and planets continually change apparent position relative to the "fixed" stars, they are not shown on the star base. However, their positions at any time, as well as the positions of additional stars, can be plotted. To do this, determine 360° – SHA of the body. For the stars and planets, SHA is listed in the Nautical Almanac. For the sun and moon, 360° – SHA is found by subtracting GHA of the body from GHA ♈ at the same time. Locate 360° – SHA on the scale around the rim of the star base. A straight line from this point to the center represents the hour circle of the body. From the celestial equator, shown as a circle midway between the center and the outer edge, measure the declination (from the almanac) of the body toward the center if the pole and declination have the same name (both N or both S), and away from the center if they are of contrary name. Use the scale along the north-south azimuth line of any template as a declination scale. The meridian angle-declination template (the latitude 5° template of No. 2102C) has an open slot with declination graduations along one side, to assist in plotting positions, as shown in Figure 1539b. In the illustration, the celestial body being located has a 360° – SHA of 285°, and a declination of 14.5°S. It is not practical to attempt to plot to greater precision than the nearest 0.1°. Positions of Venus, Mars, Jupiter, and Saturn, on June 1, 1975, are shown plotted on the star base in Figure 1539c. It is sometimes desirable to plot positions of the sun and moon to assist in planning. Plotted positions of stars need not be changed. Plotted positions of bodies of the solar system should be replotted from time to time, the more rap-

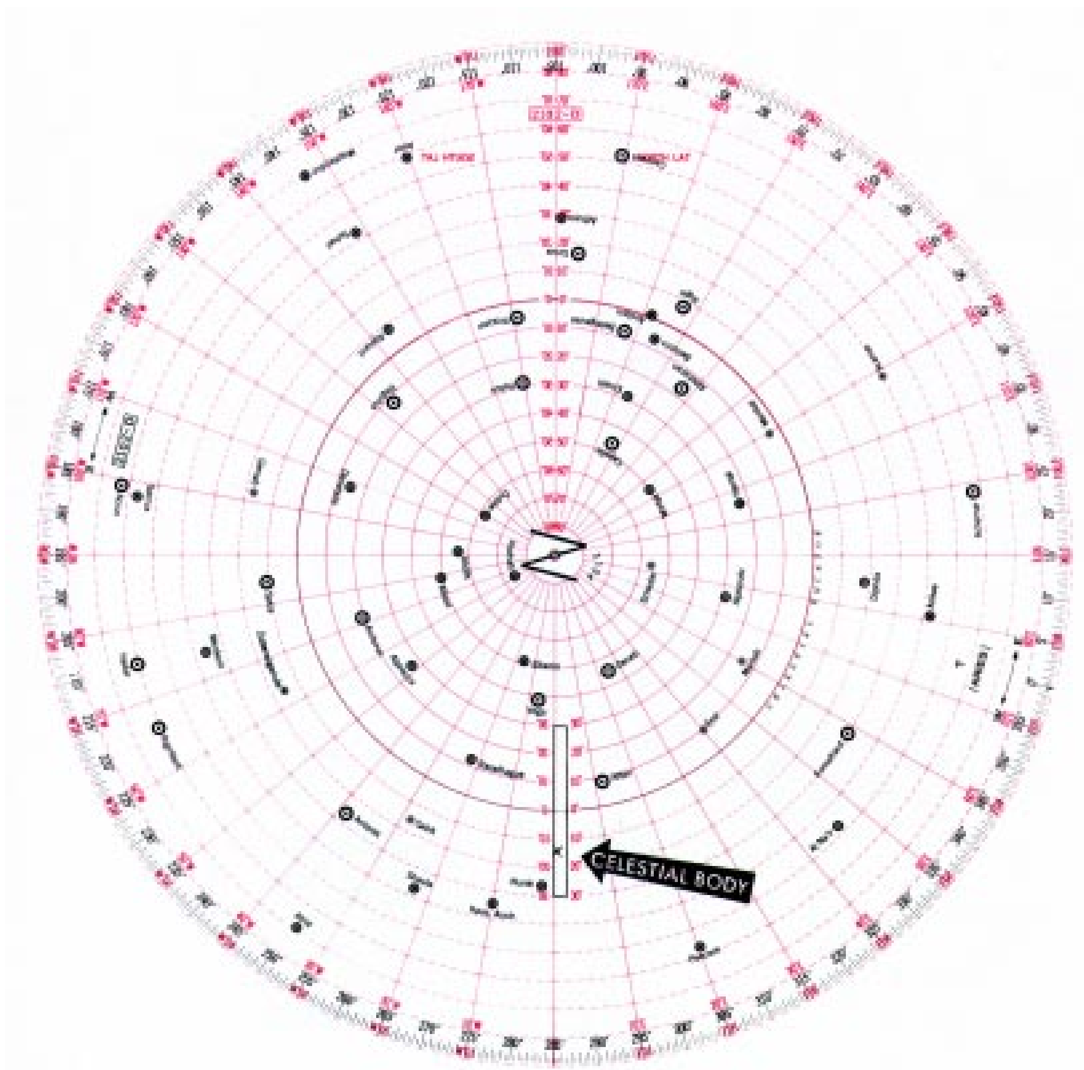

Figure 1539b. Plotting a celestial body on the star base of No. 2102D.

idly moving ones more often than others. The satisfactory interval for each body can be determined by experience. It is good practice to record the date of each plotted position of a body of the solar system, to serve later as an indication of the interval since it was plotted.

To orient the template properly for any given time, proceed as follows: enter the almanac with GMT, and determine GHA ♈ at this time. Apply the longitude to GHA ♈, subtracting if west, or adding if east, to determine LHA ♈. If LMT is substituted for GMT in entering the almanac, LHA ♈ can be taken directly from the almanac, to sufficient accuracy for orienting the star finder template. Select the template for the latitude nearest that of the observer, and center it over the star base, being careful that the correct sides (north or south to agree with the latitude) of both template and star base are used. Rotate the template relative to the star base, until the arrow on the celestial meridian (the north-south azimuth line) is over LHA ♈ on the star based graduations. The small cross at the origin of both families of curves now represents the zenith of the observer. The approximate altitude and azimuth of the celestial bodies above the horizon can be visually interpolated from the star finder. Consider Polaris (not shown) as at the north celestial pole. For more accurate results, the template can be lifted clear of the center peg of the star base, and shifted along the celestial meridian until the latitude, on the altitude scale, is over the pole. This refinement is not needed for normal use of the device. It should not be used for a latitude differing more than 5° from that for which the curves were drawn. If the altitude and azimuth of an identified body shown on the star base are known, the template can be oriented by rotating it until it is in correct position relative to that body.

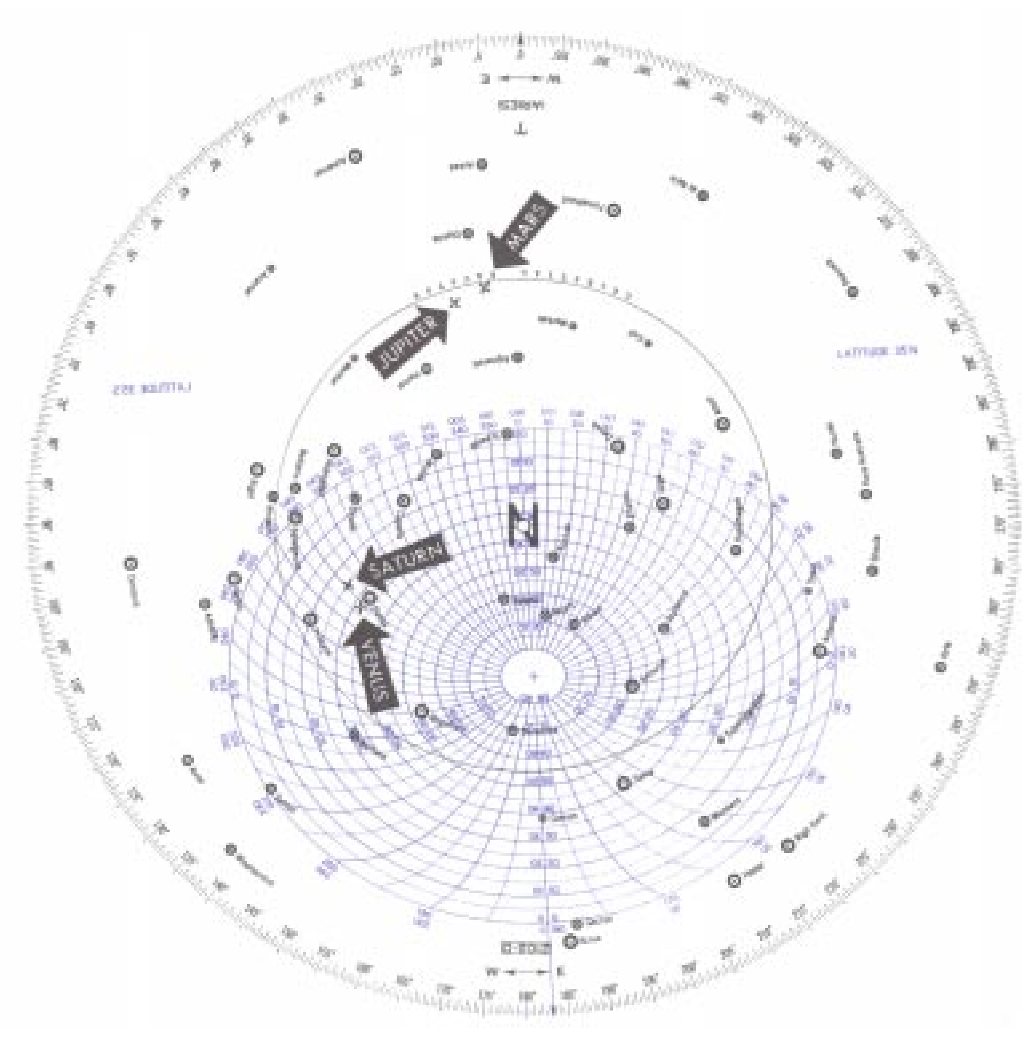

Figure 1539c. A template in place over the star base of No. 2102D.

1540. *Sight Reduction Tables for Air Navigation (Pub. No. 249)*

Volume I of *Pub. No. 249* can be used as a star finder for the stars tabulated at any given time. For these bodies the altitude and azimuth are tabulated for each 1° of latitude and 1° of LHA ♈ (2° beyond latitude 69°). The principal limitation is the small number of stars listed.

1541. Air Almanac Sky Diagram

Near the back of the Air Almanac are a number of sky diagrams. These are azimuthal equidistant projections of the celestial sphere on the plane of the horizon, at latitudes 75°N, 50°N, 25°N, 0°, 25°S, and 50°S, at intervals of 2 hours of local mean time each month. A number of the brighter stars, the visible planets, and several positions of the moon are shown at their correct altitude and azimuth. These are of limited value to marine navigators because of their small scale; the large increments of latitude, time, and date; and the limited number of bodies shown. However, in the absence of other methods, particularly a star finder, these diagrams can be useful. Allowance can be made for variations from the conditions for which each diagram is constructed. Instructions for use of the diagrams are included in the Air Almanac.

1542. Identification By Computation

If the altitude and azimuth of the celestial body, and the approximate latitude of the observer, are known, the navigational triangle can be solved for meridian angle and declination. The meridian angle can be converted to LHA, and this to GHA. With this and GHA ♈ at the time of observation, the SHA of the body can be determined. With SHA and declination, one can identify the body by reference to an almanac. Any method of solving a spherical triangle, with two sides and the included angle being given, is suitable for this purpose. A large-scale, carefully-drawn diagram on the plane of the celestial meridian, using the refinement shown in Figure 1529f, should yield satisfactory results.

Although no formal star identification tables are included in *Pub. No. 229*, a simple approach to star identification is to scan the pages of the appropriate latitudes, and observe the combination of arguments which give the altitude and azimuth angle of the observation. Thus the declination and LHA Z are determined directly. The star's SHA is found from SHA ★ = LHA ★ – LHA ♈. From these quantities the star can be identified from the Nautical Almanac.

Another solution is available through an interchange of arguments using the nearest integral values. The procedure consists of entering *Pub. No. 229* with the observer's latitude (same name as declination), with the observed azimuth angle (converted from observed true azimuth as required) as LHA and the observed altitude as declination, and extracting from the tables the altitude and azimuth angle respondents. The extracted altitude becomes the body's declination; the extracted azimuth angle (or its supplement) is the meridian angle of the body. Note that the tables are always entered with latitude of same name as declination. In north latitudes the tables can be entered with true azimuth as LHA.

If the respondents are extracted from above the C-S Line on a right-hand page, the name of the latitude is actually contrary to the declination. Otherwise, the declination of the body has the same name as the latitude. If the azimuth angle respondent is extracted from above the C-S Line, the supplement of the tabular value is the meridian angle, t, of the body. If the body is east of the observer's meridian, LHA = 360° – t; if the body is west of the meridian, LHA = t.

CHAPTER 16

INSTRUMENTS FOR CELESTIAL NAVIGATION

THE MARINE SEXTANT

1600. Description And Use

The marine sextant measures the angle between two points by bringing the direct ray from one point and a double-reflected ray from the other into coincidence. Its principal use is to measure the altitudes of celestial bodies above the visible sea horizon. It may also be used to measure vertical angles to find the range from an object of known height. Sometimes it is turned on its side and used for measuring the angular distance between two terrestrial objects.

A marine sextant can measure angles up to approximately 120°. Originally, the term "sextant" was applied to the navigator's double-reflecting, altitude-measuring instrument only if its arc was 60° in length, or 1/6 of a circle, permitting measurement of angles from 0° to 120°. In modern usage the term is applied to all modern navigational altitude-measuring instruments regardless of angular range or principles of operation.

1601. Optical Principles Of A Sextant

When a plane surface reflects a light ray, the angle of reflection equals the angle of incidence. The angle between the first and final directions of a ray of light that has undergone double reflection in the same plane is twice the angle the two reflecting surfaces make with each other (Figure 1601).

In Figure 1601, AB is a ray of light from a celestial body.

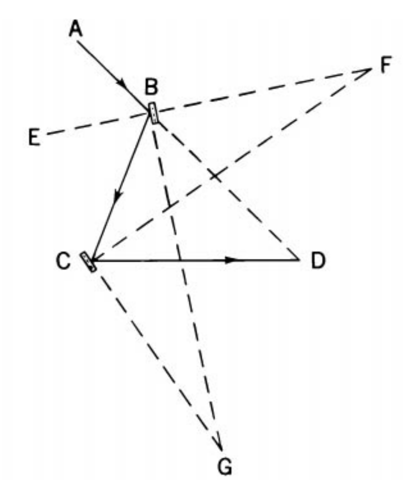

Figure 1601. Optical principle of the marine sextant.

The index mirror of the sextant is at B, the horizon glass at C, and the eye of the observer at D. Construction lines EF and CF are perpendicular to the index mirror and horizon glass, respectively. Lines BG and CG are parallel to these mirrors. Therefore, angles BFC and BGC are equal because their sides are mutually perpendicular. Angle BGC is the inclination of the two reflecting surfaces. The ray of light AB is reflected at mirror B, proceeds to mirror C, where it is again reflected, and then continues on to the eye of the observer at D. Since the angle of reflection is equal to the angle of incidence,

ABE = EBC, and ABC = 2EBC.
BCF = FCD, and BCD = 2BCF.

Since an exterior angle of a triangle equals the sum of the two non adjacent interior angles,

ABC = BDC+BCD, and EBC = BFC+BCF.
Transposing,
BDC = ABC-BCD, and BFC = EBC-BCF.

Substituting 2EBC for ABC, and 2BCF for BCD in the first of these equations,

BDC = 2EBC-2BCF, or BDC=2 (EBC-BCF).

Since BFC=EBC - BCF, and BFC = BGC, therefore

BDC = 2BFC = 2BGC.

That is, BDC, the angle between the first and last directions of the ray of light, is equal to 2BGC, twice the angle of inclination of the reflecting surfaces. Angle BDC is the altitude of the celestial body.

If the two mirrors are parallel, the incident ray from any observed body must be parallel to the observer's line of sight through the horizon glass. In that case, the body's altitude would be zero. The angle that these two reflecting surfaces make with each other is one-half the observed angle. The graduations on the arc reflect this half angle relationship between the angle observed and the mirrors' angle.

1602. Micrometer Drum Sextant

Figure 1602 shows a modern marine sextant, called a **micrometer drum sextant**. In most marine sextants, brass or aluminum comprise the **frame**, A. Frames come in various designs; most are similar to this. Teeth mark the outer edge of the **limb**, B; each tooth marks one degree of altitude. The altitude graduations, C, along the limb, mark the **arc**. Some sextants have an arc marked in a strip of brass, silver, or platinum inlaid in the limb.

The **index arm**, D, is a movable bar of the same material as the frame. It pivots about the center of curvature of the limb. The **tangent screw**, E, is mounted perpendicularly on the end of the index arm, where it engages the teeth of the limb. Because the observer can move the index arm through the length of the arc by rotating the tangent screw, this is sometimes called an "endless tangent screw." Contrast this with the limited-range device on older instruments. The **release**, F, is a spring-actuated clamp that keeps the tangent screw engaged with the limb's teeth. The observer can disengage the tangent screw and move the index arm along the limb for rough adjustment. The end of the tangent screw mounts a **micrometer drum**, G, graduated in minutes of altitude. One complete turn of the drum moves the index arm one degree along the arc. Next to the micrometer drum and fixed on the index arm is a **vernier**, H, that reads in fractions of a minute. The vernier shown is graduated into ten parts, permitting readings to $^{1}/_{10}$ of a minute of arc (0.1'). Some sextants (generally of European manufacture) have verniers graduated into only five parts, permitting readings to 0.2'.

The **index mirror**, I, is a piece of silvered plate glass mounted on the index arm, perpendicular to the plane of the instrument, with the center of the reflecting surface directly over the pivot of the index arm. The **horizon glass**, J, is a piece of optical glass silvered on its half nearer the frame. It is mounted on the frame, perpendicular to the plane of the sextant. The index mirror and horizon glass are mounted so that their surfaces are parallel when the micrometer drum is set at 0°, if the instrument is in perfect adjustment. **Shade glasses**, K, of varying darkness are mounted on the sextant's frame in front of the index mirror and horizon glass. They can be moved into the line of sight as needed to reduce the intensity of light reaching the eye.

The **telescope**, L, screws into an adjustable collar in line with the horizon glass and parallel to the plane of the instrument. Most modern sextants are provided with only one telescope. When only one telescope is provided, it is of the "erect image type," either as shown or with a wider "object glass" (far end of telescope), which generally is shorter in length and gives a greater field of view. The second telescope, if provided, may be the "inverting type." The inverting telescope, having one lens less than the erect type, absorbs less light, but at the expense of producing an inverted image. A small colored glass cap is sometimes provided, to be placed over the "eyepiece" (near end of telescope) to reduce glare. With this in place, shade glasses are generally not needed. A "peep sight," or clear tube which serves to direct the line of sight of the observer when no telescope is used, may be fitted.

Sextants are designed to be held in the right hand. Some have a small light on the index arm to assist in reading altitudes. The batteries for this light are fitted inside a recess in the **handle**, M. Not clearly shown in Figure 1602 are the **tangent screw**, E, and the three legs.

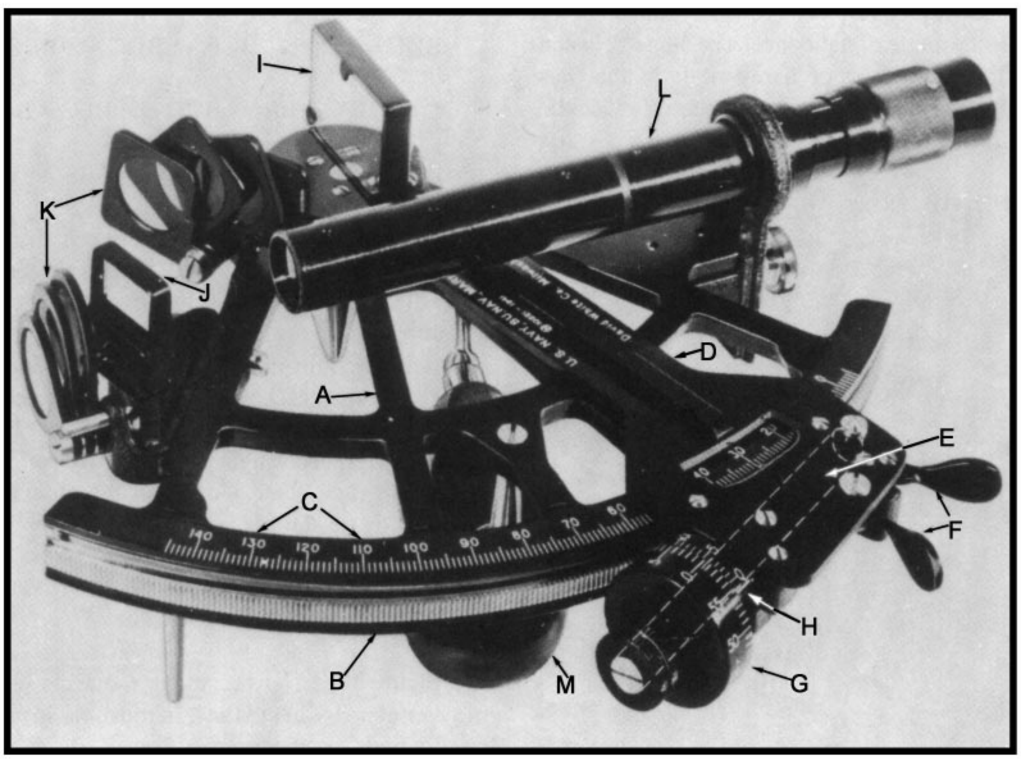

Figure 1602. U.S. Navy Mark 2 micrometer drum sextant.

There are two basic designs commonly used for mounting and adjusting mirrors on marine sextants. On the U.S. Navy Mark 3 and certain other sextants, the mirror is mounted so that it can be moved against retaining or mounting springs within its frame. Only one perpendicular adjustment screw is required. On the U.S. Navy Mark 2 and other sextants the mirror is fixed within its frame. Two perpendicular adjustment screws are required. One screw must be loosened before the other screw bearing on the same surface is tightened.

1603. Vernier Sextant

Most recent marine sextants are of the micrometer drum type, but at least two older-type sextants are still in use. These differ from the micrometer drum sextant principally in the manner in which the final reading is made. They are called **vernier sextants**.

The **clamp screw vernier sextant** is the older of the two. In place of the modern release clamp, a clamp screw is fitted on the underside of the index arm. To move the index arm, the clamp screw is loosened, releasing the arm. When the arm is placed at the approximate altitude of the body being observed, the clamp screw is tightened. Fixed to the clamp screw and engaged with the index arm is a long tangent screw. When this screw is turned, the index arm moves slowly, permitting accurate setting. Movement of the index arm by the tangent screw is limited to the length of the screw (several degrees of arc). Before an altitude is measured, this screw should be set to the approximate mid-point of its range. The final reading is made on a vernier set in the index arm below the arc. A small microscope or magnifying glass fitted to the index arm is used in making the final reading.

The **endless tangent screw vernier sextant** is identical to the micrometer drum sextant, except that it has no drum, and the fine reading is made by a vernier along the arc, as with th-eclamp screw vernier sextant. The release is the same as on the micrometer drum sextant, and teeth are cut into the underside of the limb which engage with the endless tangent screw.

1604. Sextant Sun Sights

Hold the sextant vertically and direct the sight line at the horizon directly below the sun. After moving suitable shade glasses into the line of sight, move the index arm outward along the arc until the reflected image appears in the horizon glass near the direct view of the horizon. Rock the sextant slightly to the right and left to ensure it is perpendicular. As the observer rocks the sextant, the image of the sun appears to move in an arc, and the observer may have to turn slightly to prevent the image from moving off the horizon glass.

The sextant is vertical when the sun appears at the bottom of the arc. This is the correct position for making the observation. The sun's reflected image appears at the center of the horizon glass; one half appears on the silvered part, and the other half appears on the clear part. Move the index arm with the drum or vernier slowly until the sun appears to be resting *exactly* on the horizon, tangent to the lower limb. The novice observer needs practice to determine the exact point of tangency. Beginners often err by bringing the image down too far.

Some navigators get their most accurate observations by letting the body contact the horizon by its own motion, bringing it slightly below the horizon if rising, and above if setting. At the instant the horizon is tangent to the disk, the navigator notes the time. The sextant altitude is the uncorrected reading of the sextant.

1605. Sextant Moon Sights

When observing the moon, follow the same procedure as for the sun. Because of the phases of the moon, the upper limb of the moon is observed more often than that of the sun. When the terminator (the line between light and dark areas) is nearly vertical, be careful in selecting the limb to shoot. Sights of the moon are best made during either daylight hours or that part of twilight in which the moon is least luminous. At night, false horizons may appear below the moon because the moon illuminates the water below it.

1606. Sextant Star And Planet Sights

Use one of these three methods when making the initial altitude approximation on a star or planet:

Method 1. Set the index arm and micrometer drum on 0° and direct the line of sight at the body to be observed. Then, while keeping the reflected image of the body in the mirrored half of the horizon glass, swing the index arm out and rotate the frame of the sextant down. Keep the reflected image of the body in the mirror until the horizon appears in the clear part of the horizon glass. Then, make the observation. When there is little contrast between brightness of the sky and the body, this procedure is difficult. If the body is "lost" while it is being brought down, it may not be recovered without starting over again.

Method 2. Direct the line of sight at the body while holding the sextant upside down. Slowly move the index-arm out until the horizon appears in the horizon glass. Then invert the sextant and take the sight in the usual manner.

Method 3. Determine in advance the approximate altitude and azimuth of the body by a star finder such as No. 2102D. Set the sextant at the indicated altitude and face in the direction of the azimuth. The image of the body should appear in the horizon glass with a little searching.

When measuring the altitude of a star or planet, bring its *center* down to the horizon. Stars and planets have no discernible upper or lower limb; observe the center of the point of light. Because stars and planets have no discernible limb and because their visibility may be limited, the method of letting a star or planet intersect the horizon by its own motion is not recommended. As with the sun and moon, however, "rock the sextant" to establish perpendicularity.

1607. Taking A Sight

Predict expected altitudes and azimuths for up to eight bodies when preparing to take celestial sights. Choose the stars and planets that give the best bearing spread. Try to select bodies with a predicted altitude between 30° and 70°. Take sights of the brightest stars first in the evening; take sights of the brightest stars last in the morning.

Occasionally, fog, haze, or other ships in a formation may obscure the horizon directly below a body which the navigator wishes to observe. If the arc of the sextant is sufficiently long, a **back sight** might be obtained, using the opposite point of the horizon as the reference. For this the observer faces away from the body and observes the supplement of the altitude. If the sun or moon is observed in this manner, what appears in the horizon glass to be the lower limb is in fact the upper limb, and vice versa. In the case of the sun, it is usually preferable to observe what appears to be the upper limb. The arc that appears when rocking the sextant for a back sight is inverted; that is, the highest point indicates the position of perpendicularity.

If more than one telescope is furnished with the sextant, the erecting telescope is used to observe the sun. A wider field of view is present if the telescope is not used. The collar into which the sextant telescope fits may be adjusted in or out, in relation to the frame. When moved in, more of the mirrored half of the horizon glass is visible to the navigator, and a star or planet is more easily observed when the sky is relatively bright. Near the darker limit of twilight, the telescope can be moved out, giving a broader view of the clear half of the glass, and making the less distinct horizon more easily discernible. If both eyes are kept open until the last moments of an observation, eye strain will be lessened. Practice will permit observations to be made quickly, reducing inaccuracy due to eye fatigue.

When measuring an altitude, have an assistant note and record the time if possible, with a "stand-by" warning when the measurement is almost ready, and a "mark" at the moment a sight is made. If a flashlight is needed to see the comparing watch, the assistant should be careful not to interfere with the navigator's night vision.

If an assistant is not available to time the observations, the observer holds the watch in the palm of his left hand, leaving his fingers free to manipulate the tangent screw of the sextant. After making the observation, he notes the time as quickly as possible. The delay between completing the altitude observation and noting the time should not be more than one or two seconds.

1608. Reading The Sextant

Reading a micrometer drum sextant is done in three steps. The degrees are read by noting the position of the arrow on the index arm in relation to the arc. The minutes are read by noting the position of the zero on the vernier with

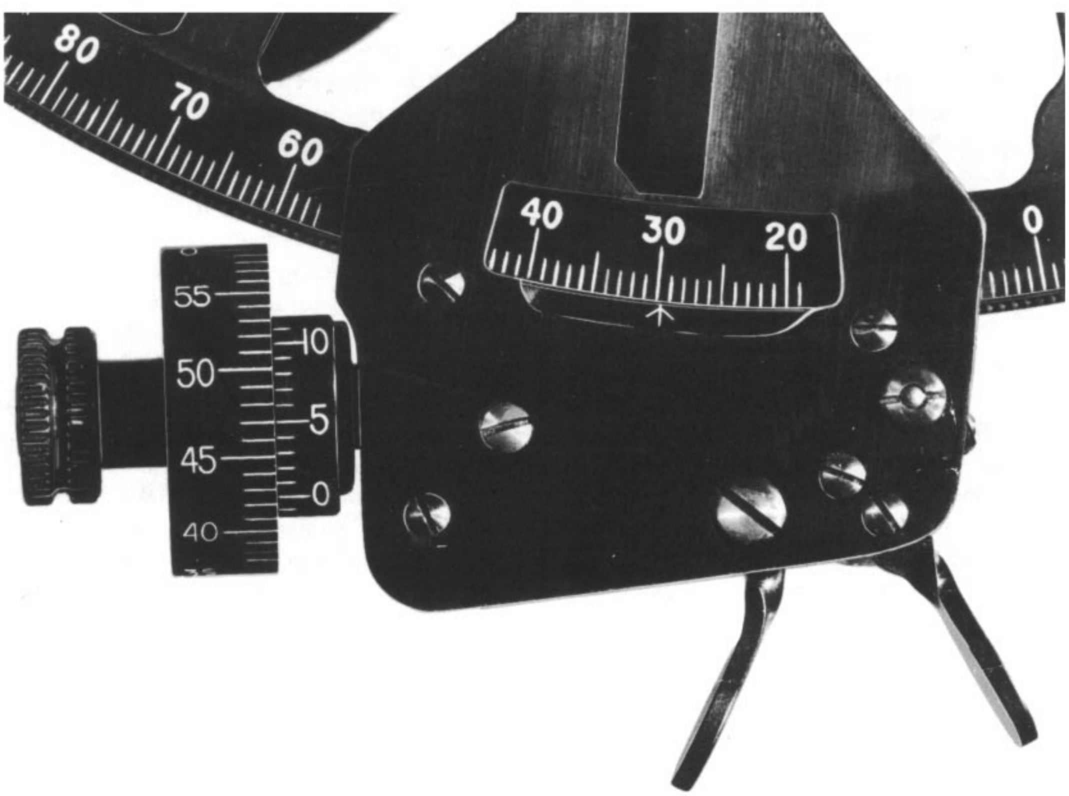

Figure 1608a. Micrometer drum sextant set at 29° 42.5'.

Figure 1608b. Vernier sextant set at 29°42'30".

relation to the graduations on the micrometer drum. The fraction of a minute is read by noting which mark on the vernier most nearly coincides with one of the graduations on the micrometer drum. This is similar to reading the time with the hour, minute, and second hands of a watch. In both, the relationship of one part of the reading to the others should be kept in mind. Thus, if the hour hand of a watch were about on "4," one would know that the time was about four o'clock. But if the minute hand were on "58," one would know that the time was 0358 (or 1558), not 0458 (or 1658). Similarly, if the arc indicated a reading of about 40°, and 58' on the micrometer drum were opposite zero on the vernier, one would know that the reading was 39° 58', not 40°58'. Similarly, any doubt as to the correct minute can be removed by noting the fraction of a minute from the position of the vernier. In Figure 1608a the reading is 29° 42.5'. The arrow on the index mark is between 29° and 30°, the zero on the vernier is between 42' and 43', and the 0.5' graduation on the vernier coincides with one of the graduations on the micrometer drum.

The principle of reading a vernier sextant is the same, but the reading is made in two steps. Figure 1608b shows a typical altitude setting. Each degree on the arc of this sextant is graduated into three parts, permitting an initial reading by the reference mark on the index arm to the nearest 20' of arc. In this illustration the reference mark lies between 29°40' and 30°00', indicating a reading between these values. The reading for the fraction of 20' is made using the vernier, which is engraved on the index arm and has the small reference mark as its zero graduation. On this vernier, 40 graduations coincide with 39 graduations on the arc. Each graduation on the vernier is equivalent to 1/40 of one graduation of 20' on the arc, or 0.5', or 30". In the illustration, the vernier graduation representing 2 1/2' (2'30") most nearly coincides with one of the graduations on the arc. Therefore, the reading is 29°42'30", or 29°42.5', as before. When a vernier of this type is used, any doubt as to which mark on the vernier coincides with a graduation on the arc can usually be resolved by noting the position of the vernier mark on each side of the one that seems to be in coincidence.

Negative readings, such as a negative index correction, are made in the same manner as positive readings; the various figures are added algebraically. Thus, if the three parts of a micrometer drum reading are (-)1°, 56' and 0.3', the total reading is (-)1° + 56' + 0.3' = (-)3.7'.

1609. Developing Observational Skill

A well-constructed marine sextant is capable of measuring angles with an instrument error not exceeding 0.1'. Lines of position from altitudes of this accuracy would not be in error by more than about 200 yards. However, there are various sources of error, other than instrumental, in altitudes measured by sextant. One of the principal sources is the observer.

The first fix a student celestial navigator plots is likely to be disappointing. Most navigators require a great amount of practice to develop the skill necessary for good observations. But practice alone is not sufficient. Good technique should be developed early and refined throughout the navigator's career. Many good pointers can be obtained from experienced navigators, but each develops his own technique, and a practice that proves successful for one observer may not help another. Also, an experienced navigator is not necessarily a good observer. Navigators have a natural tendency to judge the accuracy of their observations by the size of the figure formed when the lines of position are plotted. Although this is some indication, it is an imperfect one, because it does not indicate errors of individual observations, and may not reflect constant errors. Also, it is a compound of a number of errors, some of which are not subject to the navigator's control.

Lines of position from celestial observations can be compared with good positions obtained by electronics or piloting. Common sources of error are:

1. The sextant may not be rocked properly.
2. Tangency may not be judged accurately.
3. A false horizon may have been used.
4. Subnormal refraction (dip) might be present.
5. The height of eye may be wrong.
6. Time might be in error.
7. The index correction may have been determined incorrectly.
8. The sextant might be out of adjustment.
9. An error may have been made in the computation.

Generally, it is possible to correct observation technique errors, but occasionally a personal error will persist. This error might vary as a function of the body observed, degree of fatigue of the observer, and other factors. For this reason, a personal error should be applied with caution.

To obtain greater accuracy, take a number of closely-spaced observations. Plot the resulting altitudes versus time and fair a curve through the points. Unless the body is near the celestial meridian, this curve should be a straight line. Use this graph to determine the altitude of the body at any time covered by the graph. It is best to use a point near the middle of the line. Using a calculator to reduce the sight will also yield greater accuracy because of the rounding errors inherent in the use of sight reduction tables.

A simpler method involves making observations at equal intervals. This procedure is based upon the assumption that, unless the body is on the celestial meridian, the change in altitude should be equal for equal intervals of time. Observations can be made at equal intervals of altitude or time. If time intervals are constant, the mid time and the average altitude are used as the observation. If altitude increments are constant, the average time and mid altitude are used.

If only a small number of observations is available, reduce and plot the resulting lines of position; then adjust them to a common time. The average position of the line might be used, but it is generally better practice to use the middle line. Reject any observation considered unreliable when determining the average.

1610. Care Of The Sextant

A sextant is a rugged instrument. However, careless handling or neglect can cause it irreparable harm. If you drop it, take it to an instrument repair shop for testing and inspection. When not using the sextant, stow it in a sturdy and sufficiently padded case. Keep the sextant out of excessive heat and dampness. Do not expose it to excessive vibration. Do not leave it unattended when it is out of its case. Do not hold it by its limb, index arm, or telescope. Liftit by its frame or handle. Do not lift it by its arc or index bar.

Next to careless handling, moisture is the sextant's greatest enemy. Wipe the mirrors and the arc after each use. If the mirrors get dirty, clean them with lens paper and a small amount of alcohol. Clean the arc with ammonia; never use a polishing compound. When cleaning, do not apply excessive pressure to any part of the instrument.

Silica gel kept in the sextant case will help keep the instrument free from moisture and preserve the mirrors. Occasionally heat the silica gel to remove the absorbed moisture.

Rinse the sextant with fresh water if sea water gets on it. Wipe the sextant gently with a soft cotton cloth and dry the optics with lens paper.

Glass optics do not transmit all the light received because glass surfaces reflect a small portion of light incident on their face. This loss of light reduces the brightness of the object viewed. Viewing an object through several glass optics affects the perceived brightness and makes the image indistinct. The reflection also causes glare which obscures the object being viewed. To reduce this effect to a minimum, the glass optics are treated with a thin, fragile, anti-reflection coating. Therefore, apply only light pressure when polishing the coated optics. Blow loose dust off the lens before wiping them so grit does not scratch the lens.

Frequently oil and clean the tangent screw and the teeth on the side of the limb. Use the oil provided with the sextant or an all-purpose light machine oil. Occasionally set the index arm of an endless tangent screw at one extremity of the limb, oil it lightly, and then rotate the tangent screw over the length of the arc. This will clean the teeth and spread oil over them. When stowing a sextant for a long period, clean it thoroughly, polish and oil it, and protect its arc with a thin coat of petroleum jelly.

If the mirrors need re-silvering, take the sextant to an instrument shop.

1611. Non Adjustable Sextant Errors

The non-adjustable sextant errors are prismatic error, graduation error, and centering error.

Prismatic error occurs when the faces of the shade glasses and mirrors are not parallel. Error due to lack of parallelism in the shade glasses may be called **shade error**. The navigator can determine shade error in the shade glasses near the index mirror by comparing an angle measured when a shade glass is in the line of sight with the same angle measured when the glass is not in the line of sight. In this manner, determine and record the error for each shade glass. Before using a combination of shade glasses, determine their combined error. If certain observations require additional shading, use the colored telescope eyepiece cover. This does not introduce an error because direct and reflected rays are traveling together when they reach the cover and are, therefore, affected equally by any lack of parallelism of its two sides.

Graduation errors occur in the arc, micrometer drum, and vernier of a sextant which is improperly cut or incorrectly calibrated. Normally, the navigator cannot determine whether the arc of a sextant is improperly cut, but the principle of the vernier makes it possible to determine the existence of graduation errors in the micrometer drum or vernier. This is a useful guide in detecting a poorly made instrument. The first and last markings on any vernier should align perfectly with one less graduation on the adjacent micrometer drum.

Centering error results if the index arm does not pivot at the exact center of the arc's curvature. Calculate centering error by measuring known angles after removing all adjustable errors. Use horizontal angles accurately measured with a theodolite as references for this procedure. Several readings by both theodolite and sextant should minimize errors. If a theodolite is not available, use calculated angles between the lines of sight to stars as the reference, comparing these calculated values with the values determined by the sextant. To minimize refraction errors, select stars at about the same altitude and avoid stars near the horizon. The same shade glasses, if any, used for determining index error should be used for measuring centering error.

The manufacturer normally determines the magnitude of all three non-adjustable errors and reports them to the user as **instrument error**. The navigator should apply the correction for this error to each sextant reading.

1612. Adjustable Sextant Error

The navigator should measure and remove the following adjustable sextant errors in the order listed:

1. **Perpendicularity Error:** Adjust first for perpendicularity of the index mirror to the frame of the sextant. To test for perpendicularity, place the index arm at about 35° on the arc and hold the sextant on its side with the index mirror up and toward the eye. Observe the direct and reflected views of the sextant arc, as illustrated in Figure 1612a. If the two views are not joined in a straight line, the index mirror is not perpendicular. If the reflected image is above the direct view, the mirror is inclined forward. If the reflected image is below the direct view, the mirror is inclined backward. Make the adjustment using two screws behind the index mirror.

2. **Side Error:** An error resulting from the horizon glass not being perpendicular is called **side error**. To test for side error, set the index arm at zero and direct the line of sight at a star. Then rotate the tangent screw back and forth so that the reflected image passes alternately above and below the direct view. If, in changing from one position to the other, the reflected image passes directly over the unreflected image, no side error exists. If it passes to one side, side error exists. Figure 1612b illustrates observations without side error (left) and with side error (right). Whether the sextant reads zero when the true and reflected images are in coincidence is immaterial for this test. An alternative method is to observe a vertical line, such as one edge of the mast of another vessel (or the sextant can be held on its side and the horizon used). If the direct and reflected portions do not form a continuous line, the horizon glass is not perpendicular to the

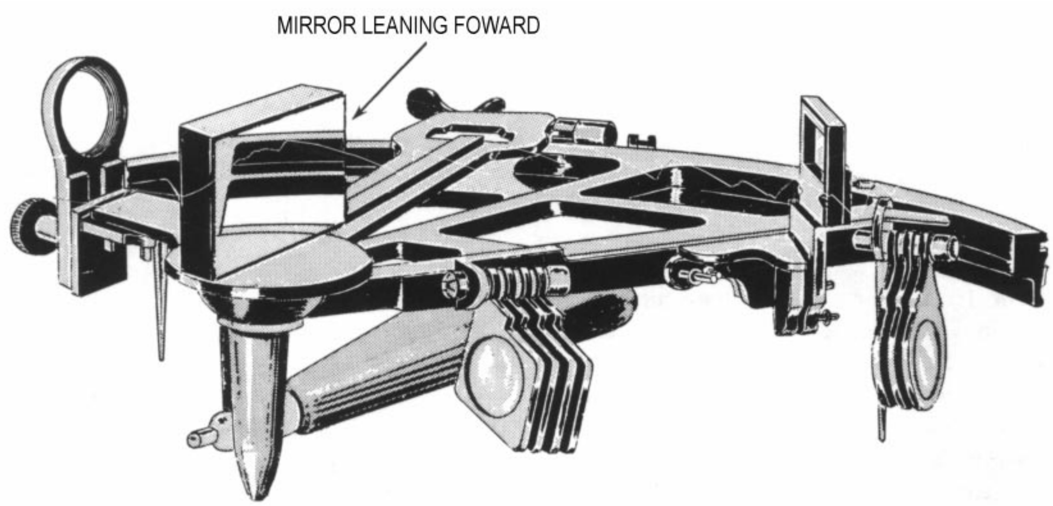

Figure 1612a. Testing the perpendicularity of the index mirror. Here the mirror is not perpendicular.

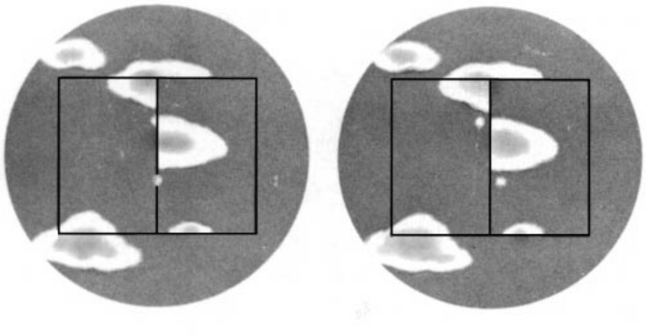

Figure 1612b. Testing the perpendicularity of the horizon glass. On the left, side error does not exist. At the right, side error does exist.

frame of the sextant. A third method involves holding the sextant vertically, as in observing the altitude of a celestial body. Bring the reflected image of the horizon into coincidence with the direct view until it appears as a continuous line across the horizon glass. Then tilt the sextant right or left. If the horizon still appears continuous, the horizon glass is perpendicular to the frame, but if the reflected portion appears above or below the part seen directly, the glass is not perpendicular. Make the appropriate adjustment using two screws behind the horizon glass.

3. **Collimation Error:** If the line of sight through the telescope is not parallel to the plane of the instrument, a **collimation error** will result. Altitudes measured will be greater than their actual values. To check for parallelism of the telescope, insert it in its collar and observe two stars 90° or more apart. Bring the reflected image of one into coincidence with the direct view of the other near either the right or left edge of the field of view (the upper or lower edge if the sextant is horizontal). Then tilt the sextant so that the stars appear near the opposite edge. If they remain in coincidence, the telescope is parallel to the frame; if they separate, it is not. An alternative method involves placing the telescope in its collar and then laying the sextant on a flat table. Sight along the frame of the sextant and have an assistant place a mark on the opposite bulkhead, in line with the frame. Place another mark above the first, at a distance equal to the distance from the center of the telescope to the frame. This second line should be in the center of the field of view of the telescope if the telescope is parallel to the frame. Adjust the collar to correct for non-parallelism.

4. **Index Error:** Index error is the error remaining after the navigator has removed perpendicularity error, side error, and collimation error. The index mirror and horizon glass not being parallel when the index arm is set exactly at zero is the major cause of index error. To test for parallelism of the mirrors, set the instrument at zero and direct the line of sight at the horizon. Adjust the sextant reading as necessary to cause both images of the horizon to come into line. The sextant's reading when the horizon comes into line is the index error. If the index error is positive, subtract it from each sextant reading. If the index error is negative, add it to each sextant reading.

1613. Selecting A Sextant

Carefully match the selected sextant to its required uses. For occasional small craft or student use, a plastic sextant may be adequate. A plastic sextant may also be appropriate for an emergency navigation kit. Accurate offshore navigation requires a quality metal instrument. For ordinary use in measuring altitudes of celestial bodies, an arc of 90° or slightly more is sufficient. If using a sextant for back sights or determining horizontal angles, purchase one with a longer arc. If necessary, have an experienced mariner examine the sextant and test it for non adjustable errors before purchase.

1614. The Artificial Horizon

Measurement of altitude requires an exact horizontal reference. At sea, the visible sea horizon normally provides this reference. If the horizon is not clearly visible, however, a different horizontal reference is required. Such a reference is commonly termed an **artificial horizon**. If it is attached to, or part of, the sextant, altitudes can be measured at sea, on land, or in the air, whenever celestial bodies are available for observations. Any horizontal reflecting surface will work. A pan of any liquid sheltered from the wind will serve. Foreign material on the surface of the liquid is likely to distort the image and introduce an error in the reading.

To use an external artificial horizon, stand or sit in such a position that the celestial body to be observed is reflected in the liquid, and is also visible in direct view. With the sextant, bring the double-reflected image into coincidence with the image appearing in the liquid. For a lower limb observation of the sun or the moon, bring the bottom of the double-reflected image into coincidence with the top of the image in the liquid. For an upper-limb observation, bring the opposite sides into coincidence. If one image covers the other, the observation is of the center of the body.

After the observation, apply the index correction and any other instrumental correction. Then take *half* the remaining angle and apply all other corrections except dip (height of eye) correction, since this is not applicable. If the center of the sun or moon is observed, omit the correction for semidiameter.

1615. Artificial Horizon Sextants

Various types of artificial horizons have been used, including a bubble, gyroscope, and pendulum. Of these, the bubble has been most widely used. This type of instrument is fitted as a backup system to inertial and other positioning systems in a few aircraft, fulfilling the requirement for a self-contained, non-emitting system. On land, a skilled observer using a 2-minute averaging bubble or pendulum sextant can measure altitudes to an accuracy of perhaps 2', (2 miles). This, of course, refers to the accuracy of measurement only, and does not include additional errors such as abnormal refraction, deflection of the vertical, computing and plotting errors, etc. In steady flight through smooth air the error of a 2-minute observation is increased to perhaps 5 to 10 miles.

At sea, with virtually no roll or pitch, results should approach those on land. However, even a gentle roll causes large errors. Under these conditions observational errors of 10-16 miles are not unreasonable. With a moderate sea, errors of 30 miles or more are common. In a heavy sea, any useful observations are virtually impossible to obtain. Single altitude observations in a moderate sea can be in error by a matter of degrees.

When the horizon is obscured by ice or haze, polar navigators can sometimes obtain better results with an artificial-horizon sextant than with a marine sextant. Some artificial-horizon sextants have provision for making observations with the natural horizon as a reference, but results are not generally as satisfactory as by marine sextant. Because of their more complicated optical systems, and the need for providing a horizontal reference, artificial-horizon sextants are generally much more costly to manufacture than marine sextants.

Altitudes observed by artificial-horizon sextants are subject to the same errors as those observed by marine sextant, except that the dip (height of eye) correction does not apply. Also, when the center of the sun or moon is observed, no correction for semidiameter is required.

CHRONOMETERS

1616. The Marine Chronometer

The spring-driven **marine chronometer** is a precision timepiece. It is used aboard ship to provide accurate time for timing celestial observations. A chronometer differs from a spring-driven watch principally in that it contains a variable lever device to maintain even pressure on the mainspring, and a special balance designed to compensate for temperature variations.

A spring-driven chronometer is set approximately to Greenwich mean time (GMT) and is not reset until the instrument is overhauled and cleaned, usually at three-year intervals. The difference between GMT and chronometer time (C) is carefully determined and applied as a correction to all chronometer readings. This difference, called chronometer error (CE), is **fast** (F) if chronometer time is later than GMT, and **slow** (S) if earlier. The amount by which chronometer error changes in 1 day is called **chronometer rate**. An erratic rate indicates a defective instrument requiring repair.

The principal maintenance requirement is regular winding at about the same time each day. At maximum intervals of about three years, a spring-driven chronometer should be sent to a chronometer repair shop for cleaning and overhaul.

1617. Quartz Crystal Marine Chronometers

Quartz crystal marine chronometers have replaced spring-driven chronometers aboard many ships because of their greater accuracy. They are maintained on GMT directly from radio time signals. This eliminates chronometer error (CE) and watch error (WE) corrections. Should the second hand be in error by a readable amount, it can be reset electrically.

The basic element for time generation is a quartz crystal oscillator. The quartz crystal is temperature compensated and is hermetically sealed in an evacuated envelope. A calibrated adjustment capability is provided to adjust for the aging of the crystal.

The chronometer is designed to operate for a minimum of 1 year on a single set of batteries. A good marine chronometer has a built-in push button battery test meter. The meter face is marked to indicate when the battery should be replaced. The chronometer continues to operate and keep the correct time for at least 5 minutes while the batteries are changed. The chronometer is designed to accommodate the gradual voltage drop during the life of the batteries while maintaining accuracy requirements.

1618. Watches

A chronometer should not be removed from its case to time sights. Observations may be timed and ship's clocks set with a **comparing watch**, which is set to chronometer time (GMT) and taken to the bridge wing for recording sight times. In practice, a wrist watch coordinated to the nearest second with the chronometer will be adequate.

A stop watch, either spring wound or digital, may also be used for celestial observations. In this case, the watch is started at a known GMT by chronometer, and the elapsed time of each sight added to this to obtain GMT of the sight.

CHAPTER 17

AZIMUTHS AND AMPLITUDES

INTRODUCTION

1700. Compass Checks

At sea, the mariner is constantly concerned about the accuracy of the gyro compass. There are several ways to check the accuracy of the gyro. He can, for example, compare it with an accurate electronic navigator such as an inertial navigaton system. Lacking a sophisticated electronic navigation suite, he can use the celestial techniques of comparing the measured and calculated azimuths and amplitudes of celestial bodies. The difference between the calculated value and the value determined by gyro measurement is gyro error. This chapter discusses these procedures.

Theoretically, these procedures work with any celestial body. However, the sun and Polaris are used most often when measuring azimuths, and the sun when measuring amplitudes.

AZIMUTHS

1701. Compass Error By Azimuth Of The Sun

Mariners use *Pub 229, Sight Reduction Tables for Marine Navigation* to compute the sun's azimuth. They compare the computed azimuth to the azimuth measured with the compass to determine compass error. In computing an azimuth, interpolate the tabular azimuth angle for the difference between the table arguments and the actual values of declination, latitude, and local hour angle. Do this triple interpolation of the azimuth angle as follows:

1. Enter the *Sight Reduction Tables* with the nearest integral values of declination, latitude, and local hour angle. For each of these arguments, extract a base azimuth angle.
2. Reenter the tables with the same latitude and LHA arguments but with the declination argument 1° greater or less than the base declination argument, depending upon whether the actual declination is greater or less than the base argument. Record the difference between the respondent azimuth angle and the base azimuth angle and label it as the azimuth angle difference (Z Diff.).
3. Reenter the tables with the base declination and LHA arguments, but with the latitude argument 1° greater or less than the base latitude argument, depending upon whether the actual (usually DR) latitude is greater or less than the base argument. Record the Z Diff. for the increment of latitude.
4. Reenter the tables with the base declination and latitude arguments, but with the LHA argument 1° greater or less than the base LHA argument, depending upon whether the actual LHA is greater or less than the base argument. Record the Z Diff. for the increment of LHA.
5. Correct the base azimuth angle for each increment.

Example:

In DR latitude 33° 24.0'N, the azimuth of the sun is 096.5° pgc. At the time of the observation, the declination of the sun is 20° 13.8'N; the local hour angle of the sun is 316° 41.2'. Determine compass error.

Solution:

See Figure 1701 Enter the actual value of declination, DR latitude, and LHA. Round each argument to the nearest whole degree. In this case, round the declination and the latitude down to the nearest whole degree. Round the LHA up to the nearest whole degree. Enter the Sight Reduction Tables with these whole degree arguments and extract the base azimuth value for these rounded off arguments. Record the base azimuth value in the table.

As the first step in the triple interpolation process, increase the value of declination by 1° to 21° because the actual declination value was greater than the base declination. Enter the Sight Reduction Tables with the following arguments: (1) Declination = 21°; (2) DR Latitude = 33°; (3) LHA = 317°. Record the tabulated azimuth for these arguments.

As the second step in the triple interpolation process, increase the value of latitude by 1° to 34° because the actual DR latitude was greater than the base latitude. Enter the Sight Reduction Tables with the following arguments: (1) Declination = 20°; (2) DR Latitude = 34°; (3) LHA = 317°.

	Actual	Base Arguments	Base Z	Tab* Z	Z Diff.	Increments	Correction (Z Diff x Inc.÷ 60)
Dec.	20°13.8' N	20°	97.8°	96.4°	–1.4°	13.8'	–0.3°
DR Lar.	33°24.0' N	33°(Same)	97.8°	98.9°	+1.1°	24.0'	+0.4°
LHA	316°41.2'	317°	97.8°	97.1°	– 0.7°	18.8'	–0.2°

Base Z	97.8°
Corr.	(–) 0.1°
Z	N 97.7° E
Zn	097.7°
Zn pgc	096.5°
Gyro Error	1.2° E

Total Corr.	–0.1°

*Respondent for the two base arguments and 1° change from third base argument, in vertical order of Dec., DR Lat., and LHA.

Figure 1701. Azimuth by *Pub. No. 229*.

Record the tabulated azimuth for these arguments.

As the third and final step in the triple interpolation process, decrease the value of LHA to 316° because the actual LHA value was smaller than the base LHA. Enter the Sight Reduction Tables with the following arguments: (1) Declination = 20°; (2) DR Latitude = 33°; (3) LHA = 316°. Record the tabulated azimuth for these arguments.

Calculate the Z Difference by subtracting the base azimuth from the tabulated azimuth. Be careful to carry the correct sign.

Z Difference = Tab Z - Base Z

Next, determine the increment for each argument by taking the difference between the actual values of each argument and the base argument. Calculate the correction for each of the three argument interpolations by multiplying the increment by the Z difference and dividing the resulting product by 60.

The sign of each correction is the same as the sign of the corresponding Z difference used to calculate it. In the above example, the total correction sums to -0.1'. Apply this value to the base azimuth of 97.8° to obtain the true azimuth 97.7°. Compare this to the compass reading of 096.5° pgc. The compass error is 1.2°E.

AZIMUTH OF POLARIS

1702. Compass Error By Azimuth Of Polaris

The Polaris tables in the *Nautical Almanac* list the azimuth of Polaris for latitudes between the equator and 65° N. Figure 2011 in Chapter 20 shows this table. Compare a compass bearing of Polaris to the tabular value of Polaris to determine compass error. The entering arguments for the table are LHA of Aries and observer latitude.

Example:

On March 17, 1994, at L 33° 15.0' N and 045° 00.0'W, at 02-00-00 GMT, Polaris bears 358.6°T by compass. Calculate the compass error.

Date	*17 March 1994*
Time (GMT)	*02-00-00*
GHA Aries	*204° 25.4'*
Longitude	*045° 00.0'W*
LHA Aries	*161° 25.4'*

Solution:

Enter the azimuth section of the Polaris table with the calculated LHA of Aries. In this case, go to the column for LHA Aries between 160° and 169°. Follow that column down and extract the value for the given latitude. Since the increment between tabulated values is so small, visual interpolation is sufficient. In this case, the azimuth for Polaris for the given LHA of Aries and the given latitude is 359.3°.

Tabulated Azimuth	*359.3°T*
Compass Bearing	*358.6°T*
Error	*0.7°E*

AMPLITUDES

1703. Amplitudes

A celestial body's **amplitude** is the arc between the observed body on the horizon and the point where the observer's horizon intersects the celestial equator. See Figure 1703.

Calculate an amplitude after observing a body on either the celestial or visual horizon. Compare a body's measured

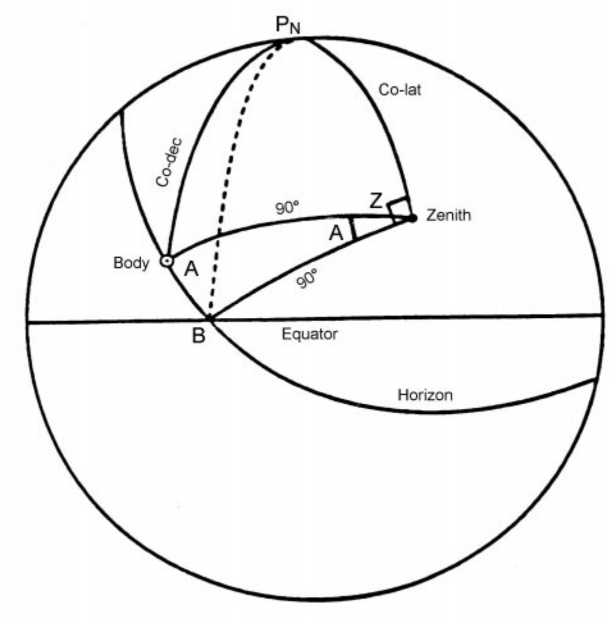

Figure 1703. The amplitude is the arc (A) between the observed body on the horizon and the point where the observer's horizon intersects the celestial equator.

amplitude with an amplitude extracted from the Amplitude table. The difference between the two values represents compass error.

Give amplitudes the suffix N if the body from which it was determined has a northern declination and S if it has a southern declination. Give the amplitudes the prefix E if the body is rising and W if the body is setting.

The values in the *Amplitude* table assume that the body is on the *celestial* horizon. The sun is on the celestial horizon when its lower limb is about two-thirds of a diameter above the visible horizon. The moon is on the celestial horizon when its upper limb is on the visible horizon. Planets and stars are on the celestial horizon when they are approximately one sun diameter above the visible horizon.

When using a body on the visible, not celestial, horizon, correct the observed amplitude from Table 23 Apply this table's correction to the *observed* amplitude and *not* to the amplitude extracted from the *Amplitude* table. For the sun, a planet, or a star, apply this correction to the observed amplitude in the direction *away from* the elevated pole. If using the moon, apply one-half of the Table 23 correction in the direction *towards* the elevated pole.

Navigators most often use the sun when determining amplitudes. The rule for applying the Table 23 corrections to a sun's observed amplitude is summarized as follows. If the DR latitude is north and the sun is rising, or if the DR latitude is south and the sun is setting, add the Table 23 correction to the observed amplitude. Conversely, if the DR latitude is north and the sun is setting, or the DR latitude is south and the sun is rising, then subtract the Table 23 correction from the observed amplitude.

The following two sections demonstrate the procedure for obtaining the amplitude of the sun on both the celestial and visible horizons.

1704. Amplitude Of The Sun On The Celestial Horizon

Example:

The DR latitude of a ship is 51° 24.6' N. The navigator observes the setting sun on the celestial horizon. Its declination is N 19° 40.4'. Its observed amplitude is W 32.9° N. (32.9° "north of west," or 302.9°).

Required:

Compass error.

Solution:

Interpolate in Table 22 for the sun's calculated amplitude as follows. See Figure 1704. The actual values for latitude and declination are L = 51.4° N and dec. = N 19.67°. Find the tabulated values of latitude and declination closest to these actual values. In this case, these tabulated values are L = 51° and dec. = 19.5°. Record the amplitude corresponding to these base values, 32.0°, as the base amplitude.

Next, holding the base declination value constant at 19.5°, increase the value of latitude to the next tabulated value: N 52°. Note that this value of latitude was increased because the actual latitude value was greater than the base value of latitude. Record the tabulated amplitude for L = 52° and dec. = 19.5°: 32.8°. Then, holding the base latitude value constant at 51°, increase the declination value to the next tabulated value: 20°. Record the tabulated amplitude for L = 51° and dec. = 20°: 32.9°.

The latitude's actual value (51.4°) is 0.4 of the way between the base value (51°) and the value used to determine the tabulated amplitude (52°). The declination's actual value (19.67°) is 0.3 of the way between the base value (19.5°) and the value used to determine the tabulated amplitude (20.0°). To determine the total correction to base amplitude, multiply these increments (0.4 and 0.3) by the respective difference between the base and tabulated values (+0.8 and +0.9, respectively) and sum the products. The total correction is +0.6°. Add the total correction (+0.6°) to the base amplitude (32.0°) to determine the final amplitude (32.6°).

Calculate the gyro error as follows:

Amplitude (observed) pgc	=	*W 32.9° N*
Amplitude (from Table 22)	=	*W 32.6° N*
Compass Error		*0.3°W*

1705. Amplitude Of The Sun On The Visible Horizon

Example:

The same problem as section 1704, except that the sun is setting on the visible horizon.

Required:
Compass error.

Solution:

Interpolate in Table 23 to determine the correction for the sun on the visible horizon as follows. See Figure 1705.. Choose as base values of latitude and declination the tabular values of latitude and declination closest to the actual values. In this case, these tabulated values are L = 51° N and dec. = 20°. Record the correction corresponding to these base values, 1.1°, as the base correction.

Completing the interpolation procedure indicates that the base correction (1.1°) is the actual correction.

Apply this correction in accordance with the rules discussed in section 1703. Since the vessel's latitude was north and the sun was setting, subtract the correction from the observed amplitude. The observed amplitude was W 32.9 N. Subtracting the 1.1° correction yields a corrected observed amplitude of W 31.8° N. From section 1704, the tabular amplitude was W 32.6° N.

Calculate the gyro error as follows:

Amplitude (from Table 22)	=	*W 32.6° N*
Amplitude (observed)	=	*W 31.8° N*
Compass Error		*0.8° E*

1706. Amplitude By Calculation

As an alternative to using Table 22 and Table 23, use the following formulas to calculate amplitudes:

a) Body on the celestial horizon:

$$\text{Amplitude} = \sin^{-1}\left[\frac{\sin d}{\cos L}\right]$$

where d = celestial body's declination and L = observer's latitude.

b) Body on the visible horizon:

$$\text{Amplitude} = \sin^{-1}\left[\frac{\sin d - \sin L \sin h}{\cos L \cos h}\right]$$

where d = celestial body's declination, L = observer's latitude, and h = – 0.7°.

Using the same example as in section 1704, d = 19.67° N and L = N 51.4°. If the sun is on the celestial horizon, its amplitude is:

$$\text{Amplitude} = \sin^{-1}\left[\frac{\sin 19.67°}{\cos 51.4°}\right] = \text{W } 32.6° \text{ N.}$$

If the sun is on the visible horizon, its amplitude is:

$$\text{Amplitude} = \sin^{-1}\left[\frac{\sin 19.67° - \sin 51.4° \sin - 0.7°}{\cos 51.4° \cos - 0.7°}\right]$$

=W 33.7° N

Actual	Base	Base Amp.	Tab. Amp.	Diff.	Inc.	Correction
L=51.4°N	51°	32.0°	32.8°	+0.8°	0.4	+0.3°
dec=19.67°N	19.5°	32.0°	32.9°	+0.9°	0.3	+0.3°
					Total	+0.6°

Figure 1704. Interpolation in Table 22 for Amplitude.

Actual	Base	Base Corr.	Tab. Corr.	Diff.	Inc.	Correction
L=51.4°N	51°	1.1°	1.1°	0.0°	0.4	0.0°
dec=19.67°N	20°	1.1°	1.0°	-0.1°	0.2	0.0°

Figure 1705. Interpolation in Table 23 for Amplitude Correction.

CHAPTER 18

TIME

TIME IN NAVIGATION

1800. Solar Time

The earth's rotation on its axis causes the sun and other celestial bodies to appear to move across the sky from east to west each day. If a person located on the earth's equator measured the time interval between two successive transits overhead of a very distant star, he would be measuring the period of the earth's rotation. If he then made a similar measurement of the sun, the resulting time would be about 4 minutes longer. This is due to the earth's motion around the sun, which continuously changes the apparent place of the sun among the stars. Thus, during the course of a day the sun appears to move a little to the east among the stars so that the earth must rotate on its axis through more than 360° in order to bring the sun overhead again.

See Figure 1800. If the sun is on the observer's meridian when the earth is at point A in its orbit around the sun, it will not be on the observer's meridian after the earth has rotated through 360° because the earth will have moved along its orbit to point B. Before the sun is again on the observer's meridian, the earth must turn still more on its axis. The sun will be on the observer's meridian again when the earth has moved to point C in its orbit. Thus, during the course of a day the sun appears to move eastward with respect to the stars.

The apparent positions of the stars are commonly reckoned with reference to an imaginary point called the **vernal equinox**, the intersection of the celestial equator and the ecliptic. The period of the earth's rotation measured with respect to the vernal equinox is called a **sidereal day**. The period with respect to the sun is called an **apparent solar day**.

When measuring time by the earth's rotation, using the actual position of the sun results in **apparent solar time**.

Use of the apparent sun as a time reference results in time of non-constant rate for at least three reasons. First, revolution of the earth in its orbit is not constant. Second, time is measured along the celestial equator and the path of the real sun is not along the celestial equator. Rather, its path is along the ecliptic, which is tilted at an angle of 23° 27' with respect to the celestial equator. Third, rotation of the earth on its axis is not constant.

To obtain a constant rate of time, the apparent sun is replaced by a fictitious **mean sun**. This mean sun moves eastward along the celestial equator at a uniform speed equal

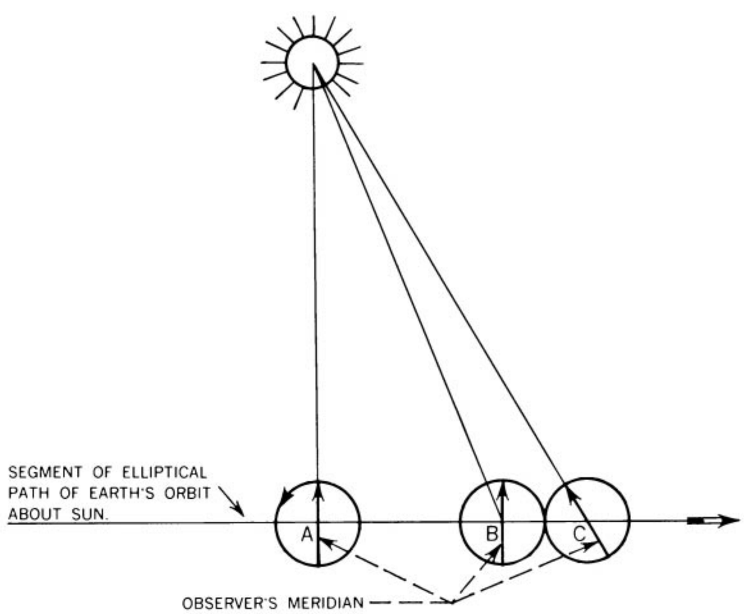

Figure 1800. Apparent eastward movement of the sun with respect to the stars.

to the average speed of the apparent sun along the ecliptic. This mean sun, therefore, provides a uniform measure of time which approximates the average apparent time. The speed of the mean sun along the celestial equator is 15° per hour of mean solar time.

1801. Equation Of Time

Mean solar time, or **mean time** as it is commonly called, is sometimes ahead of and sometimes behind apparent solar time. This difference, which never exceeds about 16.4 minutes, is called the **equation of time**.

The navigator most often deals with the equation of time when determining the time of **upper meridian passage** of the sun. The sun transits the observer's upper meridian at **local apparent noon**. Were it not for the difference in rate between the mean and apparent sun, the sun would be on the observer's meridian when the mean sun indicated 1200 local time. The apparent solar time of upper meridian passage, however, is offset from exactly 1200 mean solar time. This time difference, the equation of time at meridian transit, is listed on the right hand daily pages of the *Nautical Almanac*.

The sign of the equation of time is positive if the time of sun's meridian passage is earlier than 1200 and negative if later than 1200. Therefore: Apparent Time = Mean Time – (equation of time).

Example 1: *Determine the time of the sun's meridian passage (Local Apparent Noon) on June 16, 1994.*

Solution: *See Figure 2007 in Chapter 20, the Nautical Almanac's right hand daily page for June 16, 1994. The equation of time is listed in the bottom right hand corner of the page. There are two ways to solve the problem, depending on the accuracy required for the value of meridian passage. The time of the sun at meridian passage is given to the nearest minute in the "Mer. Pass."column. For June 16, 1994, this value is 1201.*

To determine the exact time of meridian passage, use the value given for the equation of time. This value is listed immediately to the left of the "Mer. Pass." column on the daily pages. For June 16, 1994, the value is given as 00^m37^s. Use the "12^h" column because the problem asked for meridian passage at LAN. The value of meridian passage from the "Mer. Pass." column indicates that meridian passage occurs <u>after</u> 1200; therefore, add the 37 second correction to 1200 to obtain the exact time of meridian passage. The exact time of meridian passage for June 16, 1994, is $12^h00^m37^s$.

The equation of time's maximum value approaches 16^m22^s in November.

If the Almanac lists the time of meridian passage as 1200, proceed as follows. Examine the equations of time listed in the Almanac to find the dividing line marking where the equation of time changes between positive and negative values. Examine the trend of the values near this dividing line to determine the correct sign for the equation of time.

Example 2: *See Figure 1801. Determine the time of the upper meridian passage of the sun on April 16, 1995.*

Solution: *From Figure 1801, upper meridian passage of the sun on April 16, 1995, is given as 1200. The dividing line between the values for upper and lower meridian passage on April 16th indicates that the sign of the equation of time changes between lower meridian passage and upper meridian passage on this date; the question, therefore, becomes: does it become positive or negative? Note that on April 18, 1995, upper meridian passage is given as 1159, indicating that on April 18, 1995, the equation of time is positive. All values for the equation of time on the same side of the dividing line as April 18th are positive. Therefore, the equation of time for upper meridian passage of the sun on April 16, 1995 is (+) 00^m05^s. Upper meridian passage, therefore, takes place at $11^h59^m55^s$.*

Day	SUN						MOON					
	Eqn. of Time				Mer. Pass.		Mer. Pass.				Age	Phase
	00^h		12^h				Upper		Lower			
	m	s	m	s	h	m	h	m	h	m	d	
16	00	02	00	05	12	00	00	26	12	55	16	
17	00	13	00	20	12	00	01	25	13	54	17	
18	00	27	00	33	11	59	02	25	14	55	18	

Figure 1801. The equation of time for April 16, 17, 18, 1995.

To calculate latitude and longitude at LAN, the navigator seldom requires the time of meridian passage to accuracies greater than one minute. Therefore, use the time listed under the "Mer. Pass." column to estimate LAN unless extraordinary accuracy is required.

1802. Fundamental Systems Of Time

The first fundamental system of time is **Ephemeris Time (ET)**. Ephemeris Time is used by astronomers in calculating the fundamental ephemerides of the sun, moon, and planets. It is not used by navigators.

The fundamental system of time of most interest to navigators is **Universal Time (UT)**. UT is the mean solar time on the Greenwich meridian, reckoned in days of 24 mean solar hours beginning with 0^h at midnight. Universal Time, in principle, is determined by the average rate of the apparent daily motion of the sun relative to the meridian of Greenwich; but in practice the numerical measure of Universal Time at any instant is computed from sidereal time. Universal Time is the standard in the application of astronomy to navigation. Observations of Universal Times are made by observing the times of transit of stars.

The Universal Time determined directly from astronomical observations is denoted **UT0**. Since the earth's rotation is nonuniform, corrections must be applied to UT0 to obtain a more uniform time. This more uniform time is obtained by correcting for two known periodic motions.

One motion, the motion of the geographic poles, is the result of the axis of rotation continuously moving with respect to the earth's crust. The corrections for this motion are quite small (± 15 milliseconds for Washington, D.C.). On applying the correction to UT0, the result is **UT1**, which is the same as Greenwich mean time (GMT) used in celestial navigation.

The second known periodic motion is the variation in the earth's speed of rotation due to winds, tides, and other phenomena. As a consequence, the earth suffers an annual variation in its speed of rotation, of about ± 30 milliseconds. When UT1 is corrected for the mean seasonal variations in the earth's rate of rotation, the result is **UT2**.

Although UT2 was at one time believed to be a uniform time system, it was later determined that there are variations in the earth's rate of rotation, possibly caused by random accumulations of matter in the convection core of the earth. Such accumulations would change the earth's moment of inertia and thus its rate of rotation.

The third fundamental system of time, **Atomic Time (AT)**, is based on transitions in the atom. The basic principle of the atomic clock is that electromagnetic waves of a particular frequency are emitted when an atomic transition occurs. The frequency of the cesium beam atomic clock is 9,192,631,770 cycles per second of Ephemeris Time.

The advent of atomic clocks having accuracies better than 1 part in 10^{-13} led in 1961 to the coordination of time and frequency emissions of the U. S. Naval Observatory and the Royal Greenwich Observatory. The master oscillators controlling the signals were calibrated in terms of the cesium standard, and corrections determined at the U. S. Naval Observatory and the Royal Greenwich Observatory were made simultaneously at all transmitting stations. The result is **Coordinated Universal Time (UTC)**.

1803. Time And Arc

One day represents one complete rotation of the earth. Each day is divided into 24 hours of 60 minutes; each minute has 60 seconds.

Time of day is an indication of the phase of rotation of the earth. That is, it indicates how much of a day has elapsed, or what part of a rotation has been completed. Thus, at zero hours the day begins. One hour later, the earth has turned through 1/24 of a day, or 1/24 of 360°, or 360° ÷ 24 = 15°

Smaller intervals can also be stated in angular units; since 1 hour or 60 minutes is equivalent to 15°, 1 minute of time is equivalent to 15° ÷ 60 = 0.25° = 15', and 1 second of time is equivalent to 15' ÷ 60 = 0.25' = 15".

Summarizing in table form:

	Time	*Arc*
1^d	$=24^h$	=360°
60^m	$=1^h$	=15°
4^m	= 1°	=60'
60^s	$= 1^m$	= 15'
4^s	= 1'	= 60"
1^s	= 15"	= 0.25'

Therefore any time interval can be expressed as an equivalent amount of rotation, and vice versa. Interconversion of these units can be made by the relationships indicated above.

To convert time to arc:

1. Multiply the hours by 15 to obtain degrees of arc.
2. Divide the minutes of time by four to obtain degrees.
3. Multiply the remainder of step 2 by 15 to obtain minutes of arc.
4. Divide the seconds of time by four to obtain minutes of arc
5. Multiply the remainder by 15 to obtain seconds of arc.
6. Add the resulting degrees, minutes, and seconds.

Example 1: *Convert $14^h21^m39^s$ to arc.*

Solution:

(1)	$14^h \times 15$	=	*210° 00' 00"*
(2)	$21^m \div 4$	=	*005° 00' 00" (remainder 1)*
(3)	1×15	=	*000° 15' 00"*
(4)	$39^s \div 4$	=	*000° 09' 00" (remainder 3)*
(5)	3×15	=	*000° 00' 45"*
(6)	$14^h21^m39^s$	=	*215° 24' 45"*

To convert arc to time:

1. Divide the degrees by 15 to obtain hours.
2. Multiply the remainder from step 1 by four to obtain minutes of time.
3. Divide the minutes of arc by 15 to obtain minutes of time.
4. Multiply the remainder from step 3 by four to obtain seconds of time.
5. Divide the seconds of arc by 15 to obtain seconds of time.
6. Add the resulting hours, minutes, and seconds.

Example 2: *Convert 215° 24' 45" to time units.*

Solution:

(1)	215° ÷ 15	=	$14^h00^m00^s$	*remainder 5*
(2)	5×4	=	$00^h20^m00^s$	
(3)	24' ÷ 15	=	$00^h01^m00^s$	*remainder 9*
(4)	9×4	=	$00^h00^m36^s$	

(5) $45'' \div 15 = 00^h 00^m 03^s$

(6) $215° 24' 45'' = 14^h 21^m 39^s$

Solutions can also be made using arc to time conversion tables in the almanacs. In the *Nautical Almanac*, the table given near the back of the volume is in two parts, permitting separate entries with degrees, minutes, and quarter minutes of arc. This table is arranged in this manner because the navigator converts arc to time more often than the reverse.

Example 3: *Convert 334°18'22" to time units, using the Nautical Almanac arc to time conversion table.*

Solution:

Convert the 22" to the nearest quarter minute of arc for solution to the nearest second of time. Interpolate if more precise results are required.

$334° 00.00^m = 22^h 16^m 00^s$
$000° 18.25^m = 00^h 01^m 13^s$

$334° 18' 22'' = 22^h 17^m 13^s$

1804. Time And Longitude

Suppose a celestial reference point were directly over a certain point on the earth. An hour later the earth would have turned through 15°, and the celestial reference would be directly over a meridian 15° farther west. Any difference of longitude between two points is a measure of the angle through which the earth must rotate to separate them. Therefore, places east of an observer have later time, and those west have earlier time, and the difference is exactly equal to the difference in longitude, expressed in *time* units. The difference in time between two places is equal to the difference of longitude between their meridians, expressed in time units instead of arc.

1805. The Date Line

Since time is later toward the east and earlier toward the west of an observer, time at the lower branch of one's meridian is 12 hours earlier or later depending upon the direction of reckoning. A traveler making a trip around the world gains or loses an entire day. To prevent the date from being in error, and to provide a starting place for each day, a **date line** is fixed by international agreement. This line coincides with the 180th meridian over most of its length. In crossing this line, the date is altered by one day. If a person is traveling eastward from east longitude to west longitude, time is becoming later, and when the date line is crossed the date becomes 1 day earlier. At any moment the date immediately to the west of the date line (east longitude) is 1 day later than the date immediately to the east of the line. When solving problems, convert local time to Greenwich time and then convert this to local time on the opposite side of the date line.

1806. Zone Time

At sea, as well as ashore, watches and clocks are normally set to some form of **zone time (ZT)**. At sea the nearest meridian exactly divisible by 15° is usually used as the **time meridian** or **zone meridian**. Thus, within a time zone extending 7.5' on each side of the time meridian the time is the same, and time in consecutive zones differs by exactly one hour. The time is changed as convenient, usually at a whole hour, when crossing the boundary between zones. Each time zone is identified by the number of times the longitude of its zone meridian is divisible by 15°, *positive in west longitude* and *negative in east longitude*. This number and its sign, called the **zone description (ZD)**, is the number of whole hours that are added to or subtracted from the zone time to obtain Greenwich mean time (GMT). The mean sun is the celestial reference point for zone time. See Figure 1806.

Converting ZT to GMT, a positive ZT is added and a negative one subtracted; converting GMT to ZT, a positive ZD is subtracted, and a negative one added.

Example: *The GMT is* $15^h 27^m 09^s$.

Required: *(1) ZT at long. 156°24.4' W.*
(2) ZT at long. 039°04.8' E.

Solutions:

(1)	*GMT*	$15^h 27^m 09^s$
	ZD	$+10^h$ *(rev.)*
	ZT	$05^h 27^m 09^s$
(2)	*GMT*	$15^h 27^m 09^s$
	ZD	-03^h *(rev.)*
	ZT	$18^h 27^m 09^s$

1807. Chronometer Time

Chronometer time (C) is time indicated by a chronometer. Since a chronometer is set approximately to GMT and not reset until it is overhauled and cleaned about every 3 years, there is nearly always a **chronometer error (CE)**, either fast (F) or slow (S). The change in chronometer error in 24 hours is called **chronometer rate**, or **daily rate**, and designated gaining or losing. With a consistent rate of 1^s per day for three years, the chronometer error would be approximately 18^m. Since chronometer error is subject to change, it should be determined from time to time, preferably daily at sea. Chronometer error is found by radio time signal, by

TIME ZONE CHART

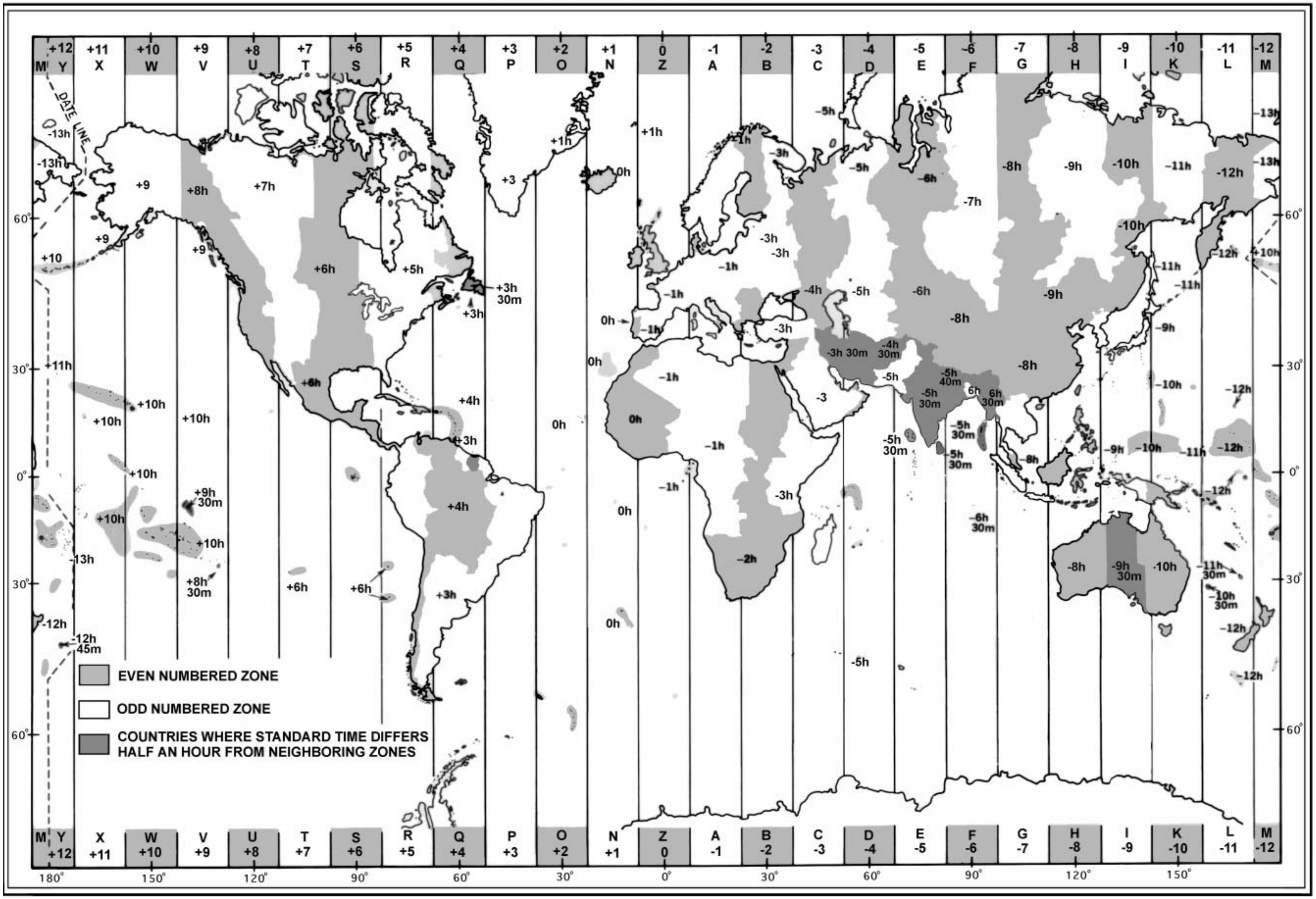

Figure 1806. Time Zone Chart.

comparison with another timepiece of known error, or by applying chronometer rate to previous readings of the same instrument. It is recorded to the nearest whole or half second. Chronometer rate is recorded to the nearest 0.1 second.

Example: *At GMT 1200 on May 12 the chronometer reads* $12^h04^m21^s$. *At GMT 1600 on May 18 it reads* $4^h04^m25^s$.

Required: *1. Chronometer error at 1200 GMT May 12.*
2. Chronometer error at 1600 GMT May 18.
3. Chronometer rate.
4. Chronometer error at GMT 0530, May 27.

Solutions:

1.	GMT	$12^h00^m00^s$	May 12
	C	$12^h04^m21^s$	
	CE	(F)4^m21^s	
2.	GMT	$16^h00^m00^s$	May 18
	C	04 04 25	
	CE	(F)4^m25^s	
3.	GMT	18^d16^h	
	GMT	12^d12h	
	diff.	$06^d04^h = 6.2^d$	
	CE	(F)4^m21^s	1200 May 12
	CE	(F)4^m25^s	1600 May 18
	diff.	4^s (gained)	
	daily rate	0.6^s (gain)	
4.	GMT	$27^d05^h30^m$	
	GMT	$18^d16^h00^m$	
	diff.	$08^d13^h30^m$ (8.5^d)	
	CE	(F)4^m25^s	1600 May 18
	corr.	(+)0^m05^s	diff. × rate
	CE	(F)4^m30^s	0530 May 27

Because GMT is on a 24-hour basis and chronometer time on a 12-hour basis, a 12-hour ambiguity exists. This is ignored in finding chronometer error. However, if chronometer error is applied to chronometer time to find GMT, a 12-hour error can result. This can be resolved by mentally applying the zone description to local time to obtain approximate GMT. A time diagram can be used for resolving doubt as to approximate GMT and Greenwich date. If the sun for the kind of time used (mean or apparent) is between the lower branches of two time meridians (as the standard meridian for local time, and the Greenwich meridian for GMT), the date at the place farther east is one day later than at the place farther west.

1808. Watch Time

Watch time (WT) is usually an approximation of zone time, except that for timing celestial observations it is easiest to set a comparing watch to GMT. If the watch has a second-setting hand, the watch can be set exactly to ZT or GMT, and the time is so designated. If the watch is not set exactly to one of these times, the difference is known as **watch error (WE)**, labeled fast (F) or slow (S) to indicate whether the watch is ahead of or behind the correct time.

If a watch is to be set exactly to ZT or GMT, set it to some whole minute slightly ahead of the correct time and stopped. When the set time arrives, start the watch and check it for accuracy.

The GMT may be in error by 12^h, but if the watch is graduated to 12 hours, this will not be reflected. If a watch with a 24-hour dial is used, the actual GMT should be determined.

To determine watch error compare the reading of the watch with that of the chronometer at a selected moment. This may also be at some selected GMT. Unless a watch is graduated to 24 hours, its time is designated am before noon and pm after noon.

Even though a watch is set to zone time approximately, its error on GMT can be determined and used for timing observations. In this case the 12-hour ambiguity in GMT should be resolved, and a time diagram used to avoid error. This method requires additional work, and presents a greater probability of error, without compensating advantages.

If a stopwatch is used for timing observations, it should be started at some convenient GMT, such as a whole 5^m or 10^m. The time of each observation is then the GMT plus the watch time. Digital stopwatches and wristwatches are ideal for this purpose, as they can be set from a convenient GMT and read immediately after the altitude is taken.

1809. Local Mean Time

Local mean time (LMT), like zone time, uses the mean sun as the celestial reference point. It differs from zone time in that the local meridian is used as the terrestrial reference, rather than a zone meridian. Thus, the local mean time at each meridian differs from every other meridian, the difference being equal to the difference of longitude expressed in time units. At each zone meridian, including 0°, LMT and ZT are identical.

In navigation the principal use of LMT is in rising, setting, and twilight tables. The problem is usually one of converting the LMT taken from the table to ZT. At sea, the difference between the times is normally not more than 30^m, and the conversion is made directly, without finding GMT as an intermediate step. This is done by applying a correction equal to the difference of longitude. If the observer is west of the time meridian, the correction is added, and if east of it, the correction is subtracted. If Greenwich time is desired, it is found from ZT.

Where there is an irregular zone boundary, the longitude may differ by more than 7.5° (30^m) from the time meridian.

If LMT is to be corrected to daylight saving time, the difference in longitude between the local and time meridian can be used, or the ZT can first be found and then increased by one hour.

Conversion of ZT (including GMT) to LMT is the same as conversion in the opposite direction, except that the sign of difference of longitude is reversed. This problem is not normally encountered in navigation.

1810. Sidereal Time

Sidereal time uses the first point of Aries (vernal equinox) as the celestial reference point. Since the earth revolves around the sun, and since the direction of the earth's rotation and revolution are the same, it completes a rotation with respect to the stars in less time (about $3^m56.6^s$ of mean solar units) than with respect to the sun, and during one revolution about the sun (1 year) it makes one complete rotation more with respect to the stars than with the sun. This accounts for the daily shift of the stars nearly 1° westward each night. Hence, sidereal days are shorter than solar days, and its hours, minutes, and seconds are correspondingly shorter. Because of nutation, sidereal time is not quite constant in rate. Time based upon the average rate is called **mean sidereal time**, when it is to be distinguished from the slightly irregular sidereal time. The ratio of mean solar time units to mean sidereal time units is 1:1.00273791.

A navigator very seldom uses sidereal time. Astronomers use it to regulate mean time because its celestial reference point remains almost fixed in relation to the stars.

1811. Time And Hour Angle

Both time and hour angle are a measure of the phase of rotation of the earth, since both indicate the angular distance of a celestial reference point west of a terrestrial reference meridian. Hour angle, however, applies to any point on the celestial sphere. Time might be used in this respect, but only the apparent sun, mean sun, the first point of Aries, and occasionally the moon, are commonly used.

Hour angles are usually expressed in arc units, and are measured from the upper branch of the celestial meridian. Time is customarily expressed in time units. Sidereal time is measured from the upper branch of the celestial meridian, like hour angle, but solar time is measured from the lower branch. Thus, LMT = LHA mean sun plus or minus 180°, LAT = LHA apparent sun plus or minus 180°, and LST = LHA Aries.

As with time, local hour angle (LHA) at two places differs by their difference in longitude, and LHA at longitude 0° is called Greenwich hour angle (GHA). In addition, it is often convenient to express hour angle in terms of the shorter arc between the local meridian and the body. This is similar to measurement of longitude from the Greenwich meridian. Local hour angle measured in this way is called meridian angle (t), which is labeled east or west, like longitude, to indicate the direction of measurement. A westerly meridian angle is numerically equal to LHA, while an easterly meridian angle is equal to 360° – LHA. LHA = t (W), and LHA = 360° – t (E). Meridian angle is used in the solution of the navigational triangle.

Example: *Find LHA and t of the sun at GMT $3^h24^m16^s$ on June 1, 1975, for long. 118°48.2' W.*

Solution:

GMT	$3^h24^m16^s$	*June 1*
3^h	*225°35.7'*	
24^m16^s	*6°04.0'*	
GHA	*231°39.7'*	
λ	*118°48.2'* W	
LHA	*112°51.5'*	
t	*112°51.5' W*	

RADIO DISSEMINATION OF TIME SIGNALS

1812. Dissemination Systems

Of the many systems for time and frequency dissemination, the majority employ some type of radio transmission, either in dedicated time and frequency emissions or established systems such as radionavigation systems. The most accurate means of time and frequency dissemination today is by the mutual exchange of time signals through communication (commonly called Two-Way) and by the mutual observation of navigation satellites (commonly called Common View).

Radio time signals can be used either to perform a clock's function or to set clocks. When using a radio wave instead of a clock, however, new considerations evolve. One is the delay time of approximately 3 microseconds per kilometer it takes the radio wave to propagate and arrive at the reception point. Thus, a user 1,000 kilometers from a transmitter receives the time signal about 3 milliseconds later than the on-time transmitter signal. If time is needed to better than 3 milliseconds, a correction must be made for the time it takes the signal to pass through the receiver.

In most cases standard time and frequency emissions as received are more than adequate for ordinary needs. However, many systems exist for the more exacting scientific requirements.

1813. Characteristic Elements Of Dissemination Systems

A number of common elements characterize most time and frequency dissemination systems. Among the more important elements are accuracy, ambiguity, repeatability, coverage, availability of time signal, reliability, ease of use, cost to the user, and the number of users served. No single system incorporates all desired characteristics. The relative importance of these characteristics will vary from one user to the next, and the solution for one user may not be satisfactory to another. These common elements are discussed in the following examination of a hypothetical radio signal.

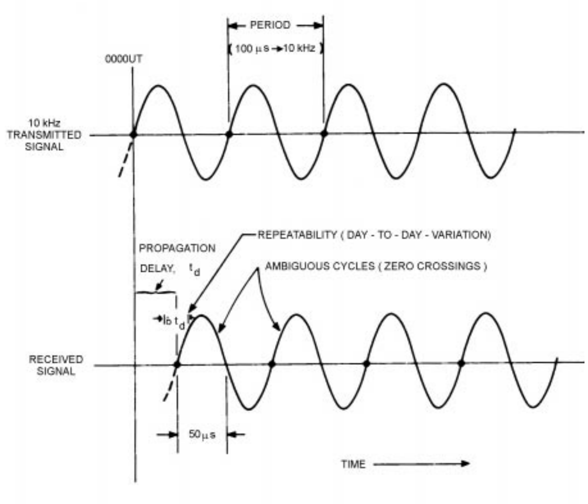

Figure 1813. Single tone time dissemination.

Consider a very simple system consisting of an unmodulated 10-kHz signal as shown in Figure 1813. This signal, leaving the transmitter at 0000 UTC, will reach the receiver at a later time equivalent to the propagation delay. The user must know this delay because the accuracy of his knowledge of time can be no better than the degree to which the delay is known. Since all cycles of the signal are identical, the signal is ambiguous and the user must somehow decide which cycle is the "on time" cycle. This means, in the case of the hypothetical 10-kHz signal, that the user must know the time to ± 50 microseconds (half the period of the signal). Further, the user may desire to use this system, say once a day, for an extended period of time to check his clock or frequency standard. However, if the delay varies from one day to the next without the user knowing, accuracy will be limited by the lack of repeatability.

Many users are interested in making time coordinated measurements over large geographic areas. They would like all measurements to be referenced to one time system to eliminate corrections for different time systems used at scattered or remote locations. This is a very important practical consideration when measurements are undertaken in the field. In addition, a one-reference system, such as a single time broadcast, increases confidence that all measurements can be related to each other in some known way. Thus, the coverage of a system is an important concept. Another important characteristic of a timing system is the percent of time available. The man on the street who has to keep an appointment needs to know the time perhaps to a minute or so. Although requiring only coarse time information, he wants it on demand, so he carries a wristwatch that gives the time 24 hours a day. On the other hand, a user who needs time to a few microseconds employs a very good clock which only needs an occasional update, perhaps only once or twice a day. An additional characteristic of time and frequency dissemination is reliability, i.e., the likelihood that a time signal will be available when scheduled. Propagation fadeout can sometimes prevent reception of HF signals.

1814. Radio Propagation Factors

Radio has been used to transmit standard time and frequency signals since the early 1900's. As opposed to the physical transfer of time via portable clocks, the transfer of information by radio entails propagation of electromagnetic energy through some propagation medium from a transmitter to a distant receiver.

In a typical standard frequency and time broadcast, the signals are directly related to some master clock and are transmitted with little or no degradation in accuracy. In a vacuum and with a noise free background, the signals should be received at a distant point essentially as transmitted, except for a constant path delay with the radio wave propagating near the speed of light (299,773 kilometers per second). The propagation media, including the earth, atmosphere, and ionosphere, as well as physical and electrical characteristics of transmitters and receivers, influence the stability and accuracy of received radio signals, dependent upon the frequency of the transmission and length of signal path. Propagation delays are affected in varying degrees by extraneous radiations in the propagation media, solar disturbances, diurnal effects, and weather conditions, among others.

Radio dissemination systems can be classified in a number of different ways. One way is to divide those carrier frequencies low enough to be reflected by the ionosphere (below 30 MHz) from those sufficiently high to penetrate the ionosphere (above 30 MHz). The former can be observed at great distances from the transmitter but suffer from ionospheric propagation anomalies that limit accuracy; the latter are restricted to line-of-sight applications but show little or no signal deterioration caused by propagation anomalies. The most accurate systems tend to be those which use the higher, line-of-sight frequencies, while broadcasts of the lower carrier frequencies show the greatest number of users.

1815. Standard Time Broadcasts

The World Administrative Radio Council (WARC) has allocated certain frequencies in five bands for standard frequency and time signal emission. For such dedicated standard frequency transmissions, the International Radio Consultative Committee (CCIR) recommends that carrier frequencies be maintained so that the average daily fractional frequency deviations from the internationally designated standard for measurement of time interval should not exceed 1 X 10^{-10}. The U. S. Naval Observatory Time Service Announcement Series 1, No. 2, gives characteristics of standard time signals assigned to allocated bands, as reported by the CCIR.

1816. Time Signals

The usual method of determining chronometer error and daily rate is by radio time signals, popularly called **time ticks**. Most maritime nations broadcast time signals several times daily from one or more stations, and a vessel equipped with radio receiving equipment normally has no difficulty in obtaining a time tick anywhere in the world. Normally, the time transmitted is maintained virtually uniform with respect to atomic clocks. The Coordinated Universal Time (UTC) as received by a vessel may differ from (GMT) by as much as 0.9 second.

The majority of radio time signals are transmitted automatically, being controlled by the standard clock of an astronomical observatory or a national measurement standards laboratory. Absolute reliance may be had in these signals because they are required to be accurate to at least 0.001^s as transmitted.

Other radio stations, however, have no automatic transmission system installed, and the signals are given by hand. In this instance the operator is guided by the standard clock at the station. The clock is checked by astronomical observations or radio time signals and is normally correct to 0.25 second.

At sea, a spring-driven chronometer should be checked daily by radio time signal, and in port daily checks should be maintained, or begun at least three days prior to departure, if conditions permit. Error and rate are entered in the chronometer record book (or record sheet) each time they are determined.

The various time signal systems used throughout the world are discussed in Pub. No. 117, Radio Navigational Aids, and volume 5 of Admiralty List of Radio Signals. Only the United States signals are discussed here.

The National Institute of Standards and Technology (NIST) broadcasts continuous time and frequency reference signals from WWV, WWVH, WWVB, and the GOES satellite system. Because of their wide coverage and relative simplicity, the HF services from WWV and WWVH are used extensively for navigation.

Station WWV broadcasts from Fort Collins, Colorado at the internationally allocated frequencies of 2.5, 5.0, 10.0, 15.0, and 20.0 MHz; station WWVH transmits from Kauai, Hawaii on the same frequencies with the exception of 20.0 MHz. The broadcast signals include standard time and frequencies, and various voice announcements. Details of these broadcasts are given in NIST Special Publication 432, *NIST Frequency and Time Dissemination Services*. Both HF emissions are directly controlled by cesium beam frequency standards with periodic reference to the NIST atomic frequency and time standards.

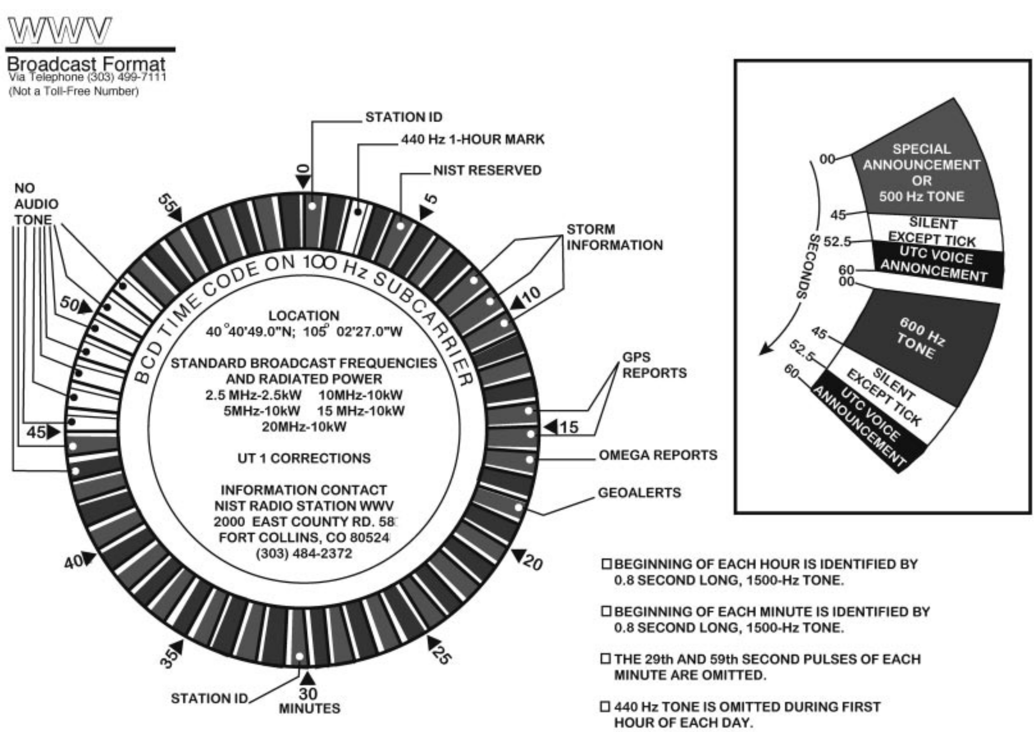

Figure 1816a. Broadcast format of station WWV.

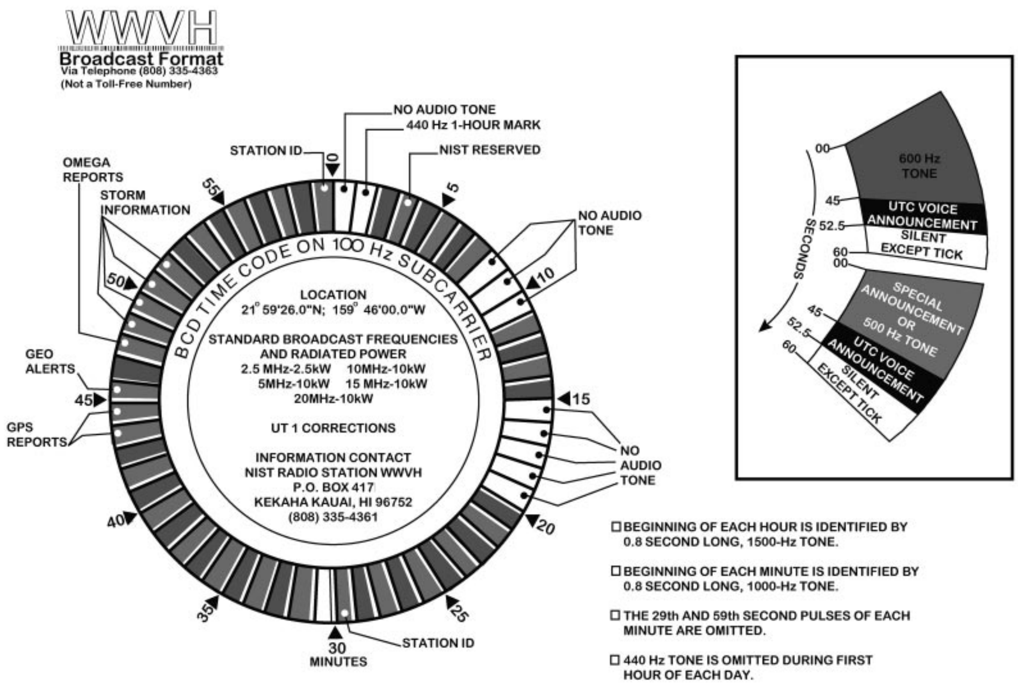

Figure 1816b. Broadcast format of station WWVH.

The time ticks in the WWV and WWVH emissions are shown in Figure 1816a and Figure 1816b. The 1-second UTC markers are transmitted continuously by WWV and WWVH, except for omission of the 29th and 59th marker each minute. With the exception of the beginning tone at each minute (800 milliseconds) all 1-second markers are of 5 milliseconds duration. Each pulse is preceded by 10 milliseconds of silence and followed by 25 milliseconds of silence. Time voice announcements are given also at 1-minute intervals. All time announcements are UTC.

Pub. No. 117, Radio Navigational Aids, should be referred to for further information on time signals.

1817. Leap-Second Adjustments

By international agreement, UTC is maintained within about 0.9 seconds of the celestial navigator's time scale, UT1. The introduction of **leap seconds** allows a good clock to keep approximate step with the sun. Because of the variations in the rate of rotation of the earth, however, the occurrences of the leap seconds are not predictable in detail.

The Central Bureau of the International Earth Rotation Service (IERS) decides upon and announces the introduction of a leap second. The IERS announces the new leap second at least several weeks in advance. A positive or negative leap

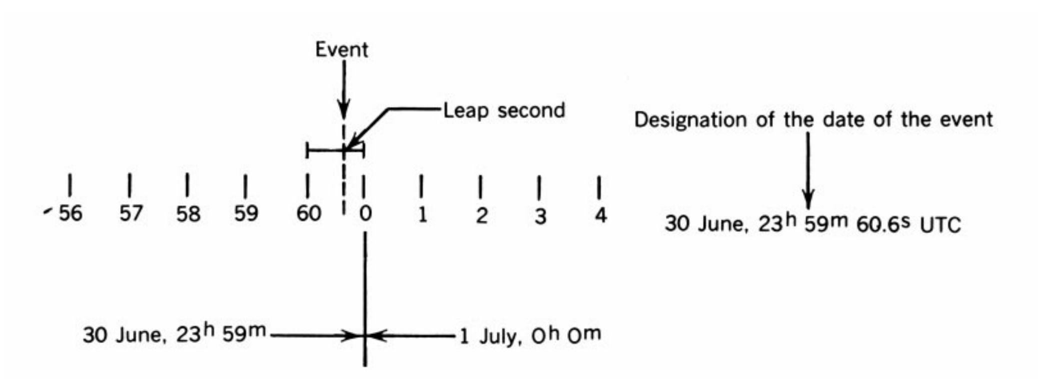

Figure 1817a. Dating of event in the vicinity of a positive leap second.

second is introduced the last second of a UTC month, but first preference is given to the end of December and June, and second preference is given to the end of March and September. A positive leap second begins at $23^h59^m60^s$ and ends at $00^h00^m00^s$ of the first day of the following month. In the case of a negative leap second, $23^h59^m58^s$ is followed one second later by $00^h00^m00^s$ of the first day of the following month.

The dating of events in the vicinity of a leap second is effected in the manner indicated in Figure 1817a and Figure 1817b.

Whenever leap second adjustments are to be made to UTC, mariners are advised by messages from the Defense Mapping Agency Hydrographic/Topographic Center.

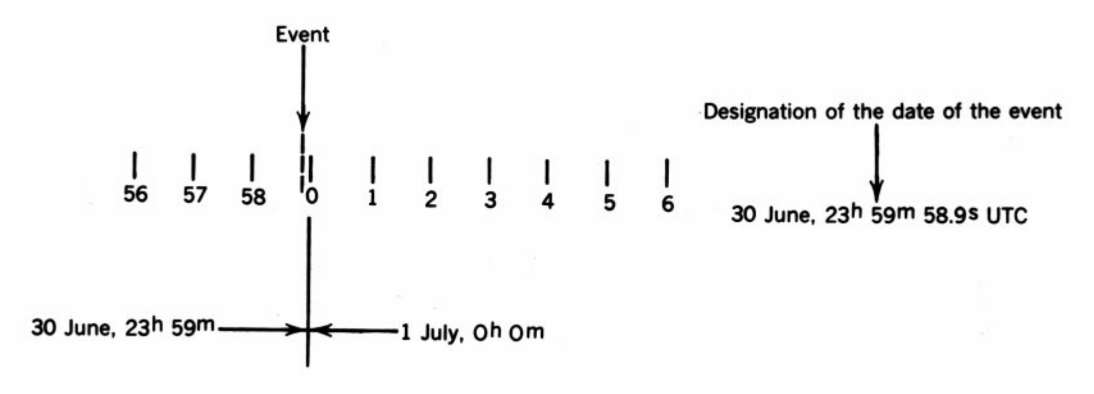

Figure 1817b. Dating of event in the vicinity of a negative leap second.

CHAPTER 19

THE ALMANACS

PURPOSE OF ALMANACS

1900. Introduction

Celestial navigation requires accurate predictions of the geographic positions of the celestial bodies observed. These predictions are available from three almanacs published annually by the United States Naval Observatory and H. M. Nautical Almanac Office, Royal Greenwich Observatory.

The ***Astronomical Almanac*** precisely tabulates celestial data for the exacting requirements found in several scientific fields. Its precision is far greater than that required by celestial navigation. Even if the *Astronomical Almanac* is used for celestial navigation, it will not necessarily result in more accurate fixes due to the limitations of other aspects of the celestial navigation process.

The ***Nautical Almanac*** contains the astronomical information specifically needed by marine navigators. Information is tabulated to the nearest 0.1' of arc and 1 second of time. GHA and declination are available for the sun, moon, planets, and 173 stars, as well as corrections necessary to reduce the observed values to true.

The ***Air Almanac*** is intended primarily for air navigators. In general, the information is similar to the *Nautical Almanac*, but is given to a precision of 1' of arc and 1 second of time, at intervals of 10 minutes (values for the sun and Aries are given to a precision of 0.1'). This publication is suitable for ordinary navigation at sea, but may lack the precision of the *Nautical Almanac*, and provides GHA and declination for only the 57 commonly used navigation stars.

The **Floppy Almanac** is a computer software program produced by the U.S. Naval Observatory which not only contains ephemeris data, but also computes rising, setting, and twilight problems; does sight planning given course and speed (this function includes a computer-generated star finder centered on the observer’s zenith); computes great circle and rumb line routes; computes compass error from celestial observations; and does complete sight reduction solutions including computer plotting and weighted analysis of the LOP’s. The Floppy Almanac is in DOS format.

FORMAT OF THE *NAUTICAL* AND *AIR ALMANACS*

1901. *Nautical Almanac*

The major portion of the *Nautical Almanac* is devoted to hourly tabulations of Greenwich Hour Angle (GHA) and declination, to the nearest 0.1' of arc. On each set of facing pages, information is listed for three consecutive days. On the left-hand page, successive columns list GHA of Aries (♈), and both GHA and declination of Venus, Mars, Jupiter, and Saturn, followed by the Sidereal Hour Angle (SHA) and declination of 57 stars. The GHA and declination of the sun and moon, and the horizontal parallax of the moon, are listed on the right-hand page. Where applicable, the quantities v and d are given to assist in interpolation. The quantity v is the difference between the actual change of GHA in 1 hour and a constant value used in the interpolation tables, while d is the change in declination in 1 hour. Both v and d are listed to the nearest 0.1'.

To the right of the moon data is listed the Local Mean Time (LMT) of sunrise, sunset, and beginning and ending of nautical and civil twilight for latitudes from 72°N to 60°S. The LMT of moonrise and moonset at the same latitudes is listed for each of the three days for which other information is given, and for the following day. Magnitude of each planet at UT 1200 of the middle day is listed at the top of the column. The UT of transit across the celestial meridian of Greenwich is listed as “Mer. Pass.”. The value for the first point of Aries for the middle of the three days is listed to the nearest 0.1' at the bottom of the Aries column. The time of transit of the planets for the middle day is given to the nearest whole minute, with SHA (at UT 0000 of the middle day) to the nearest 0.1', below the list of stars. For the sun and moon, the time of transit to the nearest whole minute is given for each day. For the moon, both upper and lower transits are given. This information is tabulated below the rising, setting, and twilight information. Also listed, are the equation of time for 0^h and 12^h, and the age and phase of the moon. Equation of time is listed, without sign, to the nearest whole second. Age is given to the nearest whole day. Phase is given by symbol.

The main tabulation is preceded by a list of religious and civil holidays, phases of the Moon, a calendar, information on eclipses occurring during the year, and notes and a diagram giving information on the planets.

The main tabulation is followed by explanations and examples. Next are four pages of standard times (zone descriptions). Star charts are next, followed by a list of 173 stars in order of increasing SHA. This list includes the stars given on the daily pages. It gives the SHA and declination-each month, and the magnitude. Stars are listed by Bayer's name and also by popular name where applicable. Following the star list are the Polaris tables. These tables give the azimuth and the corrections to be applied to the observed altitude to find the latitude.

Following the Polaris table is a section that gives formulas and examples for the entry of almanac data, the calculations that reduce a sight, and a method of solution for position, all for use with a calculator or microcomputer. This is followed by concise sight reduction tables, with instructions and examples, for use when a calculator or traditional sight reduction tables are not available. Tabular precision of the concise tables is one minute of arc.

Next is a table for converting arc to time units. This is followed by a 30-page table called "Increments and Corrections," used for interpolation of GHA and declination. This table is printed on tinted paper, for quick location. Then come tables for interpolating for times of rise, set, and twilight; followed by two indices of the 57 stars listed on the daily pages, one index in alphabetical order, and the other in order of decreasing SHA.

Sextant altitude corrections are given at the front and back of the almanac. Tables for the sun, stars, and planets, and a dip table, are given on the inside front cover and facing page, with an additional correction for nonstandard temperature and atmospheric pressure on the following page. Tables for the moon, and an abbreviated dip table, are given on the inside back cover and facing page. Corrections for the sun, stars, and planets for altitudes greater than 10°, and the dip table, are repeated on one side of a loose bookmark. The star indices are repeated on the other side.

1902. *Air Almanac*

As in the *Nautical Almanac*, the major portion of the *Air Almanac* is devoted to a tabulation of GHA and declination. However, in the *Air Almanac* values are listed at intervals of 10 minutes, to a precision of 0.1' for the sun and Aries, and to a precision of 1' for the moon and the planets. Values are given for the sun, first point of Aries (GHA only), the three navigational planets most favorably located for observation, and the moon. The magnitude of each planet listed is given at the top of its column, and the phase of the moon is given at the top of its column. Values for the first 12 hours of the day are given on the right-hand page, and those for the second half of the day on the back. In addition, each page has a table of the moon's parallax in altitude, and below this the semidiameter of the sun, and both the semidiameter and age of the moon. Each daily page includes the LMT of moonrise and moonset; and a difference column to find the time of moonrise and moonset at any longitude.

Critical tables for interpolation for GHA are given on the inside front cover, which also has an alphabetical listing of the stars, with the number, magnitude, SHA, and declination of each. The same interpolation table and star list are printed on a flap which follows the daily pages. This flap also contains a star chart, a star index in order of decreasing SHA, and a table for interpolation of the LMT of moonrise and moonset for longitude.

Following the flap are instructions for the use of the almanac; a list of symbols and abbreviations in English, French, and Spanish; a list of time differences between Greenwich and other places; sky diagrams; a planet location diagram; star recognition diagrams for periscopic sextants; sunrise, sunset, and civil twilight tables; rising, setting, and depression graphs; semiduration graphs of sunlight, twilight, and moonlight in high latitudes; percentage of the moon illuminated at 6 and 18 hours UT daily; a list of 173 stars by number and Bayer's name (also popular name where there is one), giving the SHA and declination each month (to a precision of 0.1'), and the magnitude; tables for interpolation of GHA sun and GHA ♈ ; a table for converting arc to time; a single Polaris correction table; an aircraft standard dome refraction table; a refraction correction table; a Coriolis correction table; and on the inside back cover, a correction table for dip of the horizon.

USING THE ALMANACS

1903. Entering Arguments

The time used as an entering argument in the almanacs is 12^h + GHA of the mean sun and is denoted by UT. This scale may differ from the broadcast time signals by an amount which, if ignored, will introduce an error of up to 0.2' in longitude determined from astronomical observations. The difference arises because the time argument depends on the variable rate of rotation of the earth while the broadcast time signals are now based on atomic time. Step adjustments of exactly one second are made to the time signals as required (primarily at 24h on December 31 and June 30) so that the

Correction to time signals	*Correction to longitude*
-0.7^s to -0.9^s	0.2' to east
-0.6^s to -0.3^s	0.1' to east
-0.2^s to $+0.2^s$	no correction
$+0.3^s$ to $+0.6^s$	0.1' to west
$+0.7^s$ to $+0.9^s$	0.2' to west

Table 1903. Corrections to time.

difference between the time signals and UT, as used in the almanacs, may not exceed 0.9^s. If observations to a precision of better than 1^s are required, corrections must be obtained from coding in the signal, or from other sources. The correction may be applied to each of the times of observation. Alternatively, the longitude, when determined from observations, may be corrected by the corresponding amount shown in Table 1903.

The main contents of the almanacs consist of data from which the GHA and the declination of all the bodies used for navigation can be obtained for any instant of UT. The LHA can then be obtained with the formula:

LHA = GHA + east longitude.
LHA = GHA - west longitude.

For the sun, moon, and the four navigational planets, the GHA and declination are tabulated directly in the *Nautical Almanac* for each hour of GMT throughout the year; in the *Air Almanac*, the values are tabulated for each whole 10 m of GMT. For the stars, the SHA is given, and the GHA is obtained from:

GHA Star = GHA ♈ + SHA Star.

The SHA and declination of the stars change slowly and may be regarded as constant over periods of several days or even months if lesser accuracy is required. The SHA and declination of stars tabulated in the *Air Almanac* may be considered constant to a precision of 1.5' to 2' for the period covered by each of the volumes providing the data for a whole year, with most data being closer to the smaller value. GHA ♈ , or the GHA of the first point of Aries (the vernal equinox), is tabulated for each hour in the *Nautical Almanac* and for each whole 10^m in the *Air Almanac*. Permanent tables list the appropriate increments to the tabulated values of GHA and declination for the minutes and seconds of time.

In the *Nautical Almanac*, the permanent table for increments also includes corrections for *v*, the difference between the actual change of GHA in one hour and a constant value used in the interpolation tables; and *d*, the change in declination in one hour.

In the *Nautical Almanac*, *v* is always positive unless a negative sign (-) is shown. This occurs only in the case of Venus. For the sun, the tabulated values of GHA have been adjusted to reduce to a minimum the error caused by treating *v* as negligible; there is no *v* tabulated for the sun.

No sign is given for tabulated values of *d*, which is positive if declination is increasing, and negative if decreasing. The sign of a *v* or *d* value is also given to the related correction.

In the *Air Almanac*, the tabular values of the GHA of the moon are adjusted so that use of an interpolation table based on a fixed rate of change gives rise to negligible error; no such adjustment is necessary for the sun and planets. The tabulated declination values, except for the sun, are those for the middle of the interval between the time indicated and the next following time for which a value is given, making interpolation unnecessary. Thus, it is always important to take out the GHA and declination for the time immediately *before* the time of observation.

In the *Air Almanac*, GHA ♈ and the GHA and declination of the sun are tabulated to a precision of 0.1'. If these values are extracted with the tabular precision, the "Interpolation of GHA" table on the inside front cover (and flap) should not be used; use the "Interpolation of GHA Sun" and "Interpolation of GHA Aries' tables, as appropriate. These tables are found immediately preceding the Polaris Table.

1904. Finding GHA And Declination Of The Sun

Nautical Almanac: Enter the daily page table with the whole hour before the given GMT, unless the exact time is a whole hour, and take out the tabulated GHA and declination. Also record the d value given at the bottom of the declination column. Next, enter the increments and corrections table for the number of minutes of GMT. If there are seconds, use the next earlier whole minute. On the line corresponding to the seconds of GMT, extract the value from the Sun-Planets column. Add this to the value of GHA from the daily page. This is GHA of the sun. Next, enter the correction table for the same minute with the d value and take out the correction. Give this the sign of the d value and apply it to the declination from the daily page. This is the declination.

The correction table for GHA of the Sun is based upona rate of change of 15° per hour, the average rate during a year. At most times the rate differs slightly. The slight error is minimized by adjustment of the tabular values. The d value is the amount that the declination changes between 1200 and 1300 on the middle day of the three shown.

Air Almanac: Enter the daily page with the whole 10^m preceding the given GMT, unless the time is itself a whole 10^m, and extract the GHA. The declination is extracted without interpolation from the same line as the tabulated GHA or, in the case of planets, the top line of the block of six. If the values extracted are rounded to the nearest minute, next enter the "Interpolation of GHA" table on the inside front cover (and flap), using the "Sun, etc." entry column, and take out the value for the remaining minutes and seconds of GMT. If the entry time is an exact tabulated value, use the correction listed half a line above the entry time. Add this correction to the GHA taken from the daily page. This is GHA. No adjustment of declination is needed. If the values are extracted with a precision of 0.1', the table for interpolating the GHA of the sun to a precision of 0.1' must be used. Again no adjustment of declination is needed.

1905. Finding GHA And Declination Of The Moon

Nautical Almanac: Enter the daily page table with the whole hour before the given GMT, unless this time is itself a whole hour, and extract the tabulated GHA and declination. Record the corresponding v and d values tabulated on the same line, and determine the sign of the d value. The v value of the moon is always positive (+) and is not marked in the almanac. Next, enter the increments and corrections table for the minutes of GMT, and on the line for the seconds of GMT, take the GHA correction from the moon column. Then, enter the correction table for the same minute with the v value, and extract the correction. Add both of these corrections to the GHA from the daily page. This is GHA of the moon. Then, enter the same correction table with the d value and extract the correction. Give this correction the sign of the d value and apply it to the declination from the daily page. This is declination.

The correction table for GHA of the moon is based upon the minimum rate at which the moon's GHA increases, 14°19.0' per hour. The v correction adjusts for the actual rate. The v value is the difference between the minimum rate and the actual rate during the hour following the tabulated time. The d value is the amount that the declination changes during the hour following the tabulated time.

Air Almanac: Enter the daily page with the whole 10^m next preceding the given GMT, unless this time is a whole 10^m, and extract the tabulated GHA and the declination without interpolation. Next, enter the "Interpolation of GHA" table on the inside front cover, using the "moon" entry column, and extract the value for the remaining minutes and seconds of GMT. If the entry time is an exact tabulated value, use the correction given half a line above the entry time. Add this correction to the GHA taken from the daily page to find the GHA at the given time. No adjustment of declination is needed.

The declination given in the table is correct for the time 5 minutes later than tabulated, so that it can be used for the 10-minute interval without interpolation, to an accuracy to meet most requirements. Declination changes much more slowly than GHA. If greater accuracy is needed, it can be obtained by interpolation, remembering to allow for the 5 minutes.

1906. Finding GHA And Declination Of A Planet

Nautical Almanac: Enter the daily page table with the whole hour before the given GMT, unless the time is a whole hour, and extract the tabulated GHA and declination. Record the v value given at the bottom of each of these columns. Next, enter the increments and corrections table for the minutes of GMT, and on the line for the seconds of GMT, take the GHA correction from the sun-planets column. Next, enter the correction table with the v value and extract the correction, giving it the sign of the v value. Add the first correction to the GHA from the daily page, and apply the second correction in accordance with its sign. This is GHA. Then enter the correction table for the same minute with the d value, and extract the correction. Give this correction the sign of the d value, and apply it to the declination from the daily page to find the declination at the given time.

The correction table for GHA of planets is based upon the mean rate of the sun, 15° per hour. The v value is the difference between 15° and the change of GHA of the planet between 1200 and 1300 on the middle day of the three shown. The d value is the amount the declination changes between 1200 and 1300 on the middle day. Venus is the only body listed which ever has a negative v value.

Air Almanac: Enter the daily page with the whole 10^m before the given GMT, unless this time is a whole 10^m, and extract the tabulated GHA and declination, without interpolation. The tabulated declination is correct for the time 30^m later than tabulated, so interpolation during the hour following tabulation is not needed for most purposes. Next, enter the "Interpolation of GHA" table on the inside front cover, using the "sun, etc." column, and take out the value for the remaining minutes and seconds of GMT. If the entry time is an exact tabulated value, use the correction half a line above the entry time. Add this correction to the GHA from the daily page to find the GHA at the given time. No adjustment of declination is needed.

1907. Finding GHA And Declination Of A Star

If the GHA and declination of each navigational star were tabulated separately, the almanacs would be several times their present size. But since the sidereal hour angle and the declination are nearly constant over several days (to the nearest 0.1') or months (to the nearest 1'), separate tabulations are not needed. Instead, the GHA of the first point of Aries, from which SHA is measured, is tabulated on the daily pages, and a single listing of SHA and declination is given for each double page of the Nautical Almanac, and for an entire volume of the Air Almanac. Finding the GHA ♈ is similar to finding the GHA of the sun, moon, and planets.

Nautical Almanac: Enter the daily page table with the whole hour before the given GMT, unless this time is a whole hour, and extract the tabulated GHA of Aries. Also record the tabulated SHA and declination of the star from the listing on the left-hand daily page. Next, enter the increments and corrections table for the minutes of GMT, and, on the line for the seconds of GMT, extract the GHA correction from the Aries column. Add this correction and the SHA of the star to the GHA ♈ on the daily page to find the GHA of the star at the given time. No adjustment of declination is needed.

The SHA and declination of 173 stars, including Polaris and the 57 listed on the daily pages, are given for the middle of each month. For a star not listed on the daily pages, this is the only almanac source of this information. Interpolation in this table is not necessary for ordinary purposes of navigation, but is sometimes needed for precise results.

Air Almanac: Enter the daily page with the whole 10^m before the given GMT, unless this is a whole 10^m, and extract the tabulated GHA ♈. Next, enter the "Interpolation of GHA" table on the inside front cover, using the "Sun, etc." entry column, and extract the value for the remaining minutes and seconds of GMT. If the entry time is an exact tabulated value, use the correction given half a line above the entry time. From the tabulation at the left side of the same page, extract the SHA and declination of the star. Add the GHA from the daily page and the two values taken from the inside front cover to find the GHA at the given time. No adjustment of declination is needed.

RISING, SETTING, AND TWILIGHT

1908. Rising, Setting, And Twilight

In both *Air* and *Nautical Almanacs*, the times of sunrise, sunset, moonrise, moonset, and twilight information, at various latitudes between 72°N and 60°S, is listed to the nearest whole minute. By definition, rising or setting occurs when the upper limb of the body is on the visible horizon, assuming standard refraction for zero height of eye. Because of variations in refraction and height of eye, computation to a greater precision than 1 minute of time is not justified.

In high latitudes, some of the phenomena do not occur during certain periods. Symbols are used in the almanacs to indicate:

1. Sun or moon does not set, but remains continuously above the horizon, indicated by an open rectangle.
2. Sun or moon does not rise, but remains continuously below the horizon, indicated by a solid rectangle.
3. Twilight lasts all night, indicated by 4 slashes (////).

The *Nautical Almanac* makes no provision for finding the times of rising, setting, or twilight in polar regions. The *Air Almanac* has graphs for this purpose.

In the *Nautical Almanac*, sunrise, sunset, and twilight tables are given only once for the middle of the three days on each page opening. For navigational purposes this information can be used for all three days. Both almanacs have moonrise and moonset tables for each day.

The tabulations are in LMT. On the zone meridian, this is the zone time (ZT). For every 15' of longitude the observer's position differs from the zone meridian, the zone time of the phenomena differs by 1^m, being later if the observer is west of the zone meridian, and earlier if east of the zone meridian. The LMT of the phenomena varies with latitude of the observer, declination of the body, and hour angle of the body relative to the mean sun.

The UT of the phenomenon is found from LMT by the formula:

UT = LMT + W Longitude
UT = LMT - E Longitude.

To use this formula, convert the longitude to time using the table on page i or by computation, and add or subtract as indicated. Apply the zone description (ZD) to find the zone time of the phenomena.

Sunrise and sunset are also tabulated in the tide tables (from 76°N to 60°S).

1909. Finding Times Of Sunrise And Sunset

To find the time of sunrise or sunset in the *Nautical Almanac*, enter the table on the daily page, and extract the LMT for the latitude next smaller than your own (unless it is exactly the same). Apply a correction from Table I on almanac page xxxii to interpolate for altitude, determining the sign by inspection. Then convert LMT to ZT using the difference of longitude between the local and zone meridians.

For the *Air Almanac*, the procedure is the same as for the *Nautical Almanac*, except that the LMT is taken from the tables of sunrise and sunset instead of from the daily page, and the latitude correction is by linear interpolation.

The tabulated times are for the Greenwich meridian. Except in high latitudes near the time of the equinoxes, the time of sunrise and sunset varies so little from day to day that no interpolation is needed for longitude. In high latitudes interpolation is not always possible. Between two tabulated entries, the sun may in fact cease to set. In this case, the time of rising and setting is greatly influenced by small variations in refraction and changes in height of eye.

1910. Twilight

Morning twilight ends at sunrise, and evening twilight begins at sunset. The time of the darker limit can be found from the almanacs. The time of the darker limits of both civil and nautical twilights (center of the sun 6° and 12°, respectively, below the celestial horizon) is given in the *Nautical Almanac*. The *Air Almanac* provides tabulations of civil twilight from 60°S to 72°N. The brightness of the sky at any given depression of the sun below the horizon may vary considerably from day to day, depending upon the amount of cloudiness, haze, and other atmospheric conditions. In general, the most effective period for observing stars and planets occurs when the center of the sun is between about 3° and 9° below the celestial horizon. Hence, the darker limit of civil twilight occurs at about the midpoint of this period. At the darker limit of nautical twilight, the horizon is generally too dark for good observations.

At the darker limit of astronomical twilight (center of the sun 18° below the celestial horizon), full night has set in. The time of this twilight is given in the *Astronomical Almanac*. Its approximate value can be determined by extrapolation in the *Nautical Almanac*, noting that the duration of the different kinds of twilight is not proportional to the number of degrees of depression at the darker limit.

More precise determination of the time at which the center of the sun is any given number of degrees below the celestial horizon can be determined by a large-scale diagram on the plane of the celestial meridian, or by computation. Duration of twilight in latitudes higher than 65°N is given in a graph in the *Air Almanac*.

In both *Nautical* and *Air Almanacs*, the method of finding the darker limit of twilight is the same as that for sunrise and sunset.

Sometimes in high latitudes the sun does not rise but twilight occurs. This is indicated in the *Air Almanac* by a solid black rectangle symbol in the sunrise and sunset column. To find the time of beginning of morning twilight, subtract half the duration of twilight as obtained from the duration of twilight graph from the time of meridian transit of the sun; and for the time of ending of evening twilight, add it to the time of meridian transit. The LMT of meridian transit never differs by more than 16.4^m (approximately) from 1200. The actual time on any date can be determined from the almanac.

1911. Moonrise And Moonset

Finding the time of moonrise and moonset is similar to finding the time of sunrise and sunset, with one important difference. Because of the moon's rapid change of declination, and its fast eastward motion relative to the sun, the time of moonrise and moonset varies considerably from day to day. These changes of position on the celestial sphere are continuous, as moonrise and moonset occur successively at various longitudes around the earth. Therefore, the change in time is distributed over all longitudes. For precise results, it would be necessary to compute the time of the phenomena at any given place by lengthy complex calculation. For ordinary purposes of navigation, however, it is sufficiently accurate to interpolate between consecutive moonrises or moonsets at the Greenwich meridian. Since apparent motion of the moon is westward, relative to an observer on the earth, interpolation in west longitude is between the phenomenon on the given date and the following one. In east longitude it is between the phenomenon on the given date and the preceding one.

To find the time of moonrise or moonset in the *Nautical Almanac*, enter the daily-page table with latitude, and extract the LMT for the tabulated latitude next smaller than the observer's latitude (unless this is an exact tabulated value). Apply a correction from table I of almanac page xxxii to interpolate for latitude, determining the sign of the correction by inspection. Repeat this procedure for the day following the given date, if in west longitude; or for the day preceding, if in east longitude. Using the difference between these two times, and the longitude, enter table II of the almanac on the same page and take out the correction. Apply this correction to the LMT of moonrise or moonset at the Greenwich meridian on the given date to find the LMT at the position of the observer. The sign to be given the correction is such as to make the corrected time fall between the times for the two dates between which interpolation is being made. This is nearly always positive (+) in west longitude and negative (-) in east longitude. Convert the corrected LMT to ZT.

To find the time of moonrise or moonset by the *Air Almanac* for the given date, determine LMT for the observer's latitude at the Greenwich meridian in the same manner as with the *Nautical Almanac*, except that linear interpolation is made directly from the main tables, since no interpolation table is provided. Extract, also, the value from the "Diff." column to the right of the moonrise and moonset column, interpolating if necessary. This "Diff." is one-fourth of one-half of the daily difference. The error introduced by this approximation is generally not more than a few minutes, although it increases with latitude. Using this difference, and the longitude, enter the "Interpolation of Moonrise, Moonset" table on flap F4 of the *Air Almanac* and extract the correction. The *Air Almanac* recommends taking the correction from this table without interpolation. The results thus obtained are sufficiently accurate for ordinary purposes of navigation. If greater accuracy is desired, the correction can be taken by interpolation. However, since the "Diff." itself is an approximation, the *Nautical Almanac* or computation should be used if accuracy is a consideration. Apply the correction to the LMT of moonrise or moonset at the Greenwich meridian on the given date to find the LMT at the position of the observer. The correction is positive (+) for west longitude, and negative (-) for east longitude, unless the "Diff." on the daily page is preceded by the negative sign (-), when the correction is negative (-) for west longitude, and positive (+) for east longitude. If the time is near midnight, record the date at each step, as in the *Nautical Almanac* solution.

As with the sun, there are times in high latitudes when interpolation is inaccurate or impossible. At such periods, the times of the phenomena themselves are uncertain, but an approximate answer can be obtained by the moonlight graph in the *Air Almanac*, or by computation. With the moon, this condition occurs when the moon rises or sets at one latitude, but not at the next higher tabulated latitude, as with the sun. It also occurs when the moon rises or sets on one day, but not on the preceding or following day. This latter condition is indicated in the *Air Almanac* by the symbol * in the "Diff." column.

Because of the eastward revolution of the moon around the earth, there is one day each synodical month (29 $^1/_2$ days) when the moon does not rise, and one day when it does not set. These occur near last quarter and first quarter, respectively. Since this day is not the same at all latitudes or at all longitudes, the time of moonrise or moonset found from the almanac may occasionally be the preceding or succeeding one to that desired. When interpolating near midnight, caution will prevent an error.

The effect of the revolution of the moon around the earth is to cause the moon to rise or set later from day to day. The daily retardation due to this effect does not differ greatly from 50^m. However, the change in declination of the moon may increase or decrease this effect. This effect increases with latitude, and in extreme conditions it may be greater than the effect due to revolution of the moon. Hence, the interval between successive moonrises or moonsets is more erratic in high latitudes than in low latitudes. When the two effects act in the same direction, daily differences can be quite large. When they act in opposite directions, they are small, and when the effect due to change in declination is larger than that due to revolution, the moon sets *earlier* on succeeding days. This condition is reflected in the *Air Almanac* by a negative "Diff." If this happens near the last quarter or first quarter, two moonrises or moonsets might occur on the same day, one a few minutes after the day begins, and the other a few minutes before it ends, as on June 19, where two times are listed in the same space.

Interpolation for longitude is always made between consecutive moonrises or moonsets, regardless of the days on which they fall.

Beyond the northern limits of the almanacs the values can be obtained from a series of graphs given near the back of the *Air Almanac*. For high latitudes, graphs are used instead of tables because graphs give a clearer picture of conditions, which may change radically with relatively little change in position or date. Under these conditions interpolation to practical precision is simpler by graph than by table. In those parts of the graph which are difficult to read, the times of the phenomena's occurrence are uncertain, being altered considerably by a relatively small change in refraction or height of eye.

On all of these graphs, any given latitude is represented by a horizontal line and any given date by a vertical line. At the intersection of these two lines the duration is read from the curves, interpolating by eye between curves.

The "Semiduration of Sunlight" graph gives the number of hours between sunrise and meridian transit or between meridian transit and sunset. The dot scale near the top of the graph indicates the LMT of meridian transit, the time represented by the minute dot nearest the vertical dateline being used. If the intersection occurs in the area marked "sun above horizon," the sun does not set; and if in the area marked "sun below horizon," the sun does not rise.

The "Duration of Twilight" graph gives the number of hours between the beginning of morning civil twilight (center of sun 6° below the horizon) and sunrise, or between sunset and the end of evening civil twilight. If the sun does not rise, but twilight occurs, the time taken from the graph is half the total length of the single twilight period, or the number of hours from beginning of morning twilight to LAN, or from LAN to end of evening twilight. If the intersection occurs in the area marked "continuous twilight or sunlight," the center of the sun does not move more than 6° below the horizon, and if in the area marked "no twilight nor sunlight," the sun remains more than 6° below the horizon throughout the entire day.

The "Semiduration of Moonlight" graph gives the number of hours between moonrise and meridian transit or between meridian transit and moonset. The dot scale near the top of the graph indicates the LMT of meridian transit, each dot representing one hour. The phase symbols indicate the date on which the principal moon phases occur, the open circle indicating full moon and the dark circle indicating new moon. If the intersection of the vertical dateline and the horizontal latitude line falls in the "moon above horizon" or "moon below horizon" area, the moon remains above or below the horizon, respectively, for the entire 24 hours of the day.

If approximations of the times of moonrise and moonset are sufficient, the semiduration of moonlight is taken for the time of meridian passage and can be used without adjustment. When as estimated time of rise falls on the preceding day, that phenomenon may be recalculated using the meridian passage and semiduration for the day following. When an estimated time of set falls on the following day, that phenomenon may be recalculated using meridian passage and semiduration for the preceding day. For more accurate results (seldom justified), the times on the required date and the adjacent date (the following date in W longitude and the preceding date in E longitude) should be determined, and an interpolation made for longitude, as in any latitude, since the intervals given are for the Greenwich meridian.

Sunlight, twilight, and moonlight graphs are not given for south latitudes. Beyond latitude 65°S, the northern hemisphere graphs can be used for determining the semiduration or duration, by using the vertical dateline for a day when the declination has the same numerical value but opposite sign. The time of meridian transit and the phase of the moon are determined as explained above, using the correct date. Between latitudes 60°S and 65°S, the solution is made by interpolation between the tables and the graphs.

Other methods of solution of these phenomena are available. The Tide Tables tabulate sunrise and sunset from latitude 76°N to 60°S. Semiduration or duration can be determined graphically using a diagram on the plane of the celestial meridian, or by computation. When computation is used, solution is made for the meridian angle at which the required negative altitude occurs. The meridian angle expressed in time units is the semiduration in the case of sunrise, sunset, moonrise, and moonset; and the semiduration of the combined sunlight and twilight, or the time from meridian transit at which morning twilight begins or evening twilight ends. For sunrise and sunset the altitude used is (-)50'. Allowance for height of eye can be made by algebraically subtracting (numerically adding) the dip correction from this altitude. The altitude used for twilight is (-)6°, (-)12°, or (-)18° for civil, nautical, or astronomical twilight, respectively. The altitude used for moonrise and moonset is -34' - SD + HP, where SD is semidiameter and HP is horizontal parallax, from the daily pages of the *Nautical Almanac*.

1912. Rising, Setting, And Twilight On A Moving Craft

Instructions to this point relate to a fixed position on the earth. Aboard a moving craft the problem is complicated somewhat by the fact that time of occurrence depends upon position of the craft, which itself depends on the time. At ship speeds, it is generally sufficiently accurate to make an approximate mental solution and use the position of the vessel at this time to make a more accurate solution. If greater accuracy is required, the position at the time indicated in the second solution can be used for a third solution. If desired, this process can be repeated until the same answer is obtained from two consecutive solutions. However, it is generally sufficient to alter the first solution by 1^m for each 15' of longitude that the position of the craft differs from that used in the solution, adding if west of the estimated position, and subtracting if east of it. In applying this rule, use both longitudes to the nearest 15'. The first solution is the **first estimate**; the second solution is the **second estimate**.

CHAPTER 20

SIGHT REDUCTION

BASIC PRINCIPLES

2000. Introduction

Reducing a celestial sight to obtain a line of position consists of six steps:

1. Correcting sextant altitude (hs) to obtain observed altitude (ho).
2. Determining the body's GHA and declination.
3. Selecting an assumed position and finding that position's local hour angle.
4. Computing altitude and azimuth for the assumed position.
5. Comparing computed and observed altitudes.
6. Plotting the line of position.

This chapter concentrates on using the *Nautical Almanac* and *Pub. No. 229, Sight Reduction Tables for Marine Navigation.*

The introduction to each volume of the *Sight Reduction Tables* contains information: (1) discussing use of the publication in a variety of special celestial navigation techniques; (2) discussing interpolation, explaining the double second difference interpolation required in some sight reductions, and providing tables to facilitate the interpolation process; and (3) discussing the publication's use in solving problems of great circle sailings. Prior to using the *Sight Reduction Tables*, carefully read this introductory material.

Celestial navigation involves determining a circular line of position based on an observer's distance from a celestial body's geographic position (GP). Should the observer determine both a body's GP and his distance from the GP, he would have enough information to plot a line of position; he would be somewhere on a circle whose center was the GP and whose radius equaled his distance from that GP. That circle, from all points on which a body's measured altitude would be equal, is a **circle of equal altitude**. There is a direct proportionality between a body's altitude as measured by an observer and the distance of its GP from that observer; the lower the altitude, the farther away the GP. Therefore, when an observer measures a body's altitude he obtains an indirect measure of the distance between himself and the body's GP. Sight reduction is the process of converting that indirect measurement into a line of position.

Sight reduction reduces the problem scale to manageable size. Depending on a body's altitude, its GP could be thousands of miles from the observer's position. The size of a chart required to plot this large distance would be impractical. To eliminate this problem, the navigator does not plot this line of position directly. Indeed, he does not plot the GP at all. Rather, he chooses an **assumed position (AP)** near, but usually not coincident with, his DR position. The navigator chooses the AP's latitude and longitude to correspond to the entering arguments of LHA and latitude used in the *Sight Reduction Tables*. From the *Sight Reduction Tables*, the navigator computes what the body's altitude *would have been* had it been measured from the AP. This yields the **computed altitude (h_c)**. He then compares this computed value with the **observed altitude (h_o)** obtained at his actual position. The difference between the computed and observed altitudes is directly proportional to the distance between the circles of equal altitude for the assumed position and the actual position. The *Sight Reduction Tables* also give the *direction* from the GP to the AP. Having selected the assumed position, calculated the distance between the circles of equal altitude for that AP and his actual position, and determined the direction from the assumed position to the body's GP, the navigator has enough information to plot a line of position (LOP).

To plot an LOP, plot the assumed position on either a chart or a plotting sheet. From the *Sight Reduction Tables*, determine: 1) the altitude of the body for a sight taken at the AP and 2) the direction from the AP to the GP. Then, determine the difference between the body's calculated altitude at this AP and the body's measured altitude. This difference represents the difference in radii between the equal altitude circle passing through the AP and the equal altitude circle passing through the actual position. Plot this difference from the AP either *towards* or *away from* the GP along the axis between the AP and the GP. Finally, draw the circle of equal altitude representing the circle with the body's GP at the center and with a radius equal to the distance between the GP and the navigator's actual position.

One final consideration simplifies the plotting of the equal altitude circle. Recall that the GP is usually thousands of miles away from the navigator's position. The equal altitude circle's radius, therefore, can be extremely large. Since this radius is so large, the navigator can approximate the section close to his position with a straight line drawn perpendicular to the line connecting the AP and the GP. This straight line approximation is good only for sights of relatively low altitudes. The higher the altitude, the shorter the distance between the GP and the actual position, and the smaller the circle of equal altitude. The shorter this distance, the greater the inaccuracy introduced by this approximation.

2001. Selection Of The Assumed Position (AP)

Use the following arguments when entering the *Sight Reduction Tables* to compute altitude (h_c) and azimuth:

1. Latitude (L).
2. Declination (d or Dec.).
3. Local hour angle (LHA).

Latitude and LHA are functions of the assumed position. Select an AP longitude resulting in a whole degree of LHA and an AP latitude equal to that whole degree of latitude closest to the DR position. Selecting the AP in this manner eliminates interpolation for LHA and latitude in the *Sight Reduction Tables*.

Reducing the sight using a computer or calculator simplifies this AP selection process. Simply choose any convenient position such as the vessel's DR position as the assumed position. Enter the information required by the specific celestial program in use. Using a calculator reduces the math and interpolation errors inherent in using the *Sight Reduction* tables. Enter the required calculator data carefully.

2002. Comparison Of Computed And Observed Altitudes

The difference between the computed altitude (h_c) and the observed altitude (h_o) is the **altitude intercept** (a).

The altitude intercept is the difference in the length of the radii of the circles of equal altitude passing through the AP and the observers actual position. The position having the greater altitude is on the circle of smaller radius and is closer to the observed body's GP. In Figure 2003, the AP is shown on the inner circle. Therefore, h_c is greater than h_o.

Express the altitude intercept in nautical miles and label it T or A to indicate whether the line of position is toward or away from the GP, as measured from the AP.

A useful aid in remembering the relation between h_o, h_c, and the altitude intercept is: $\underline{H}_o$ $\underline{M}_o$ $\underline{T}_o$ for H_o <u>More</u> <u>Toward</u>. Another is C-G-A: <u>C</u>omputed <u>G</u>reater <u>A</u>way, remembered as <u>C</u>oast <u>G</u>uard <u>A</u>cademy. In other words, if h_o is greater than h_c, the line of position intersects a point measured from the AP towards the GP a distance equal to the altitude intercept. Draw the LOP through this intersection point perpendicular to the axis between the AP and GP.

2003. Plotting The Line Of Position

Plot the line of position as shown in Figure 2003. Plot the AP first; then plot the azimuth line from the AP toward or away from the GP. Then, measure the altitude intercept along this line. At the point on the azimuth line equal to the intercept distance, draw a line perpendicular to the azimuth line. This perpendicular represents that section of the circle of equal altitude passing through the navigator's actual position. This is the line of position.

A navigator often takes sights of more than one celestial body when determining a celestial fix. After plotting the lines of position from these several sights, advance the resulting LOP's along the track to the time of the last sight and label the resulting fix with the time of this last sight.

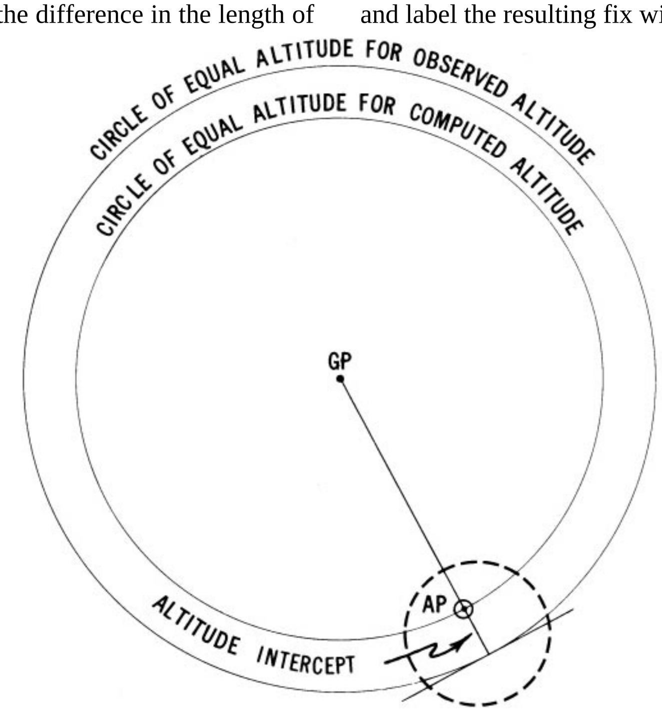

Figure 2003. The basis for the line of position from a celestial observation.

2004. Recommended Sight Reduction Procedure

Just as it is important to understand the theory of sight reduction, it is also important to develop a working procedure to reduce celestial sights accurately. Sight reduction involves several consecutive steps, the accuracy of each completely dependent on the accuracy of the steps that went before. Sight reduction tables have, for the most part, reduced the mathematics involved to simple addition and subtraction. However, careless errors will render even the most skillfully measured sights inaccurate. The navigator must work methodically to reduce these careless errors.

Naval navigators will most likely use OPNAV 3530, U.S. Navy Navigation Workbook, which contains pre-formatted pages with “strip forms” to guide the navigator through sight reduction. A variety of commercially-produced forms are also available. Pick a form and learn its method *thoroughly*. With familiarity will come increasing understanding.

Figure 2004 represents a functional and complete worksheet designed to ensure a methodical approach to any sight reduction problem. The recommended procedure discussed below is not the only one available; however, the navigator who uses it can be assured that he has considered *every* correction required to obtain an accurate fix.

SECTION ONE consists of two parts: (1) Correcting sextant altitude to obtain apparent altitude; and (2) Correcting the apparent altitude to obtain the observed altitude.

Body: Enter the name of the body whose altitude you have measured. If using the sun or the moon, indicate which limb was measured.

Index Correction: This is determined by the characteristics of the individual sextant used. Chapter 16 discusses determining its magnitude and algebraic sign.

Dip: The dip correction is a function of the height of eye of the observer. It is always negative; its magnitude is determined from the Dip Table on the inside front covert of the *Nautical Almanac*.

Sum: Enter the algebraic sum of the dip correction and the index correction.

Sextant Altitude: Enter the altitude of the body measured by the sextant.

Apparent Altitude: Apply the sum correction determined above to the measured altitude and enter the result as the apparent altitude.

Altitude Correction: Every observation requires an altitude correction. This correction is a function of the apparent altitude of the body. The *Almanac* contains tables for determining these corrections. For the sun, planets, and stars, these tables are located on the inside front cover and facing page. For the moon, these tables are located on the back inside cover and preceding page.

Mars or Venus Additional Correction: As the name implies, this correction is applied to sights of Mars and Venus. The correction is a function of the planet measured, the time of year, and the apparent altitude. The inside front cover of the *Almanac* lists these corrections.

Additional Correction: Enter this additional correction from Table A 4 located at the front of the *Almanac* when obtaining a sight under non-standard atmospheric temperature and pressure conditions. This correction is a function of atmospheric pressure, temperature, and apparent altitude.

Horizontal Parallax Correction: This correction is unique to reducing moon sights. Obtain the H.P. correction value from the daily pages of the *Almanac*. Enter the H.P correction table at the back of the *Almanac* with this value. The H.P correction is a function of the limb of the moon used (upper or lower), the apparent altitude, and the H.P. correction factor. The H.P. correction is always added to the apparent altitude.

Moon Upper Limb Correction: Enter -30' for this correction if the sight was of the upper limb of the moon.

Correction to Apparent Altitude: Sum the altitude correction, the Mars or Venus additional correction, the additional correction, the horizontal parallax correction, and the moon’s upper limb correction. Be careful to determine and carry the algebraic sign of the corrections and their sum correctly. Enter this sum as the correction to the apparent altitude.

Observed Altitude: Apply the Correction to Apparent Altitude algebraically to the apparent altitude. The result is the observed altitude.

SECTION TWO determines the Greenwich Mean Time (GMT) and GMT date of the sight.

Date: Enter the local time zone date of the sight.

DR Latitude: Enter the dead reckoning latitude of the vessel.

DR Longitude: Enter the dead reckoning longitude of the vessel.

Observation Time: Enter the local time of the sight as recorded on the ship’s chronometer or other timepiece.

Watch Error: Enter a correction for any known watch error.

Zone Time: Correct the observation time with watch error to determine zone time.

Zone Description: Enter the zone description of the time zone indicated by the DR longitude. If the longitude is west of the Greenwich Meridian, the zone description is positive. Conversely, if the longitude is east of the Greenwich Meridian, the zone description is negative. The zone description represents the correction necessary to convert local time to Greenwich Mean Time.

Greenwich Mean Time: Add to the zone description the zone time to determine Greenwich Mean Time.

Date: Carefully evaluate the time correction applied above and determine if the correction has changed the date. Enter the GMT date.

SECTION THREE determines two of the three arguments required to enter the *Sight Reduction Tables*: Local Hour Angle (LHA) and Declination. This section employs the principle that a celestial body’s LHA is the algebraic sum of its Greenwich Hour Angle (GHA) and the observer’s lon-

SECTION ONE: OBSERVED ALTITUDE

Body	....	....
Index Correction	....	....
Dip (height of eye)	....	....
Sum	....	....
Sextant Altitude (h_s)	....	....
Apparent Altitude (h_a)	....	....
Altitude Correction	....	....
Mars or Venus Additional Correction	....	....
Additional Correction	....	....
Horizontal Parallax Correction	....	....
Moon Upper Limb Correction	....	....
Correction to Apparent Altitude (h_a)	....	....
Observed Altitude (h_o)	....	....

SECTION TWO: GMT TIME AND DATE

Date	....	....
DR Latitude	....	....
DR Longitude	....	....
Observation Time	....	....
Watch Error	....	....
Zone Time	....	....
Zone Description	....	....
Greenwich Mean Time	....	....
Date GMT	....	....

SECTION THREE: LOCAL HOUR ANGLE AND DECLINATION

Tabulated GHA and *v* Correction Factor	....	....
GHA Increment	....	....
Sidereal Hour Angle (SHA) or *v* Correction	....	....
GHA	....	....
+ or - 360° if needed	....	....
Assumed Longitude (-W, +E)	....	....
Local Hour Angle (LHA)	....	....
Tabulated Declination and *d* Correction Factor	....	....
d Correction	....	....
True Declination	....	....
Assumed Latitude	....	....

SECTION FOUR: ALTITUDE INTERCEPT AND AZIMUTH

Declination Increment and *d* Interpolation Factor	....	....
Computed Altitude (Tabulated)	....	....
Double Second Difference Correction	....	....
Total Correction	....	....
Computed Altitude (h_c)	....	....
Observed Altitude (h_o)	....	....
Altitude Intercept	....	....
Azimuth Angle	....	....
True Azimuth	....	....

Figure 2004. Complete sight reduction form.

gitude. Therefore, the basic method employed in this section is: (1) Determine the body's GHA; (2) Determine an assumed longitude; (3) Algebraically combine the two quantities, remembering to subtract a western assumed longitude from GHA and to add an eastern longitude to GHA; and (4) Extract the declination of the body from the appropriate Almanac table, correcting the tabular value if required.

(1) Tabulated GHA and (2) *v* Correction Factor:

(1) For the sun, the moon, or a planet, extract the value for the whole hour of GHA corresponding to the sight. For example, if the sight was obtained at 13-50-45 GMT, extract the GHA value for 1300. For a star sight reduction, extract the value of the GHA of Aries (GHA ♈), again using the value corresponding to the whole hour of the time of the sight.

(2) For a planet or moon sight reduction, enter the *v* correction value. This quantity is not applicable to a sun or star sight. The *v* correction for a planet sight is found at the bottom of the column for each particular planet. The *v* correction factor for the moon is located directly beside the tabulated hourly GHA values. The *v* correction factor for the moon is always positive. If a planet's *v* correction factor is listed without sign, it is positive. If listed with a negative sign, the planet's *v* correction factor is negative. This *v* correction factor is not the magnitude of the *v* correction; it is used later to enter the Increments and Correction table to determine the magnitude of the correction.

GHA Increment: The GHA increment serves as an interpolation factor, correcting for the time that the sight differed from the whole hour. For example, in the sight at 13-50-45 discussed above, this increment correction accounts for the 50 minutes and 45 seconds after the whole hour at which the sight was taken. Obtain this correction value from the Increments and Corrections tables in the *Almanac*. The entering arguments for these tables are the minutes and seconds after the hour at which the sight was taken and the body sighted. Extract the proper correction from the applicable table and enter the correction here.

Sidereal Hour Angle or *v* Correction: If reducing a star sight, enter the star's Sidereal Hour Angle (SHA). The SHA is found in the star column of the daily pages of the *Almanac*. The SHA combined with the GHA of Aries results in the star's GHA. The SHA entry is applicable only to a star. If reducing a planet or moon sight, obtain the *v* correction from the Increments and Corrections Table. The correction is a function of only the *v* correction factor; its magnitude is the same for both the moon and the planets.

GHA: A star's GHA equals the sum of the Tabulated GHA of Aries, the GHA Increment, and the star's SHA. The sun's GHA equals the sum of the Tabulated GHA and the GHA Increment. The GHA of the moon or a planet equals the sum of the Tabulated GHA, the GHA Increment, and the *v* correction.

+ or – 360° (if needed): Since the LHA will be determined from subtracting or adding the assumed longitude to the GHA, adjust the GHA by 360° if needed to facilitate the addition or subtraction.

Assumed Longitude: If the vessel is west of the prime meridian, the assumed longitude will be subtracted from the GHA to determine LHA. If the vessel is east of the prime meridian, the assumed longitude will be added to the GHA to determine the LHA. Select the assumed longitude to meet the following two criteria: (1) When added or subtracted (as applicable) to the GHA determined above, a whole degree of LHA will result; and (2) It is the longitude closest to that DR longitude that meets criterion (1) above.

Local Hour Angle (LHA): Combine the body's GHA with the assumed longitude as discussed above to determine the body's LHA.

(1) Tabulated Declination and *d* Correction factor: (1) Obtain the tabulated declination for the sun, the moon, the stars, or the planets from the daily pages of the *Almanac*. The declination values for the stars are given for the entire three day period covered by the daily page of the *Almanac*. The values for the sun, moon, and planets are listed in hourly increments. For these bodies, enter the declination value for the whole hour of the sight. For example, if the sight is at 12-58-40, enter the tabulated declination for 1200. (2) There is no *d* correction factor for a star sight. There are *d* correction factors for sun, moon, and planet sights. Similar to the v correction factor discussed above, the *d* correction factor does not equal the magnitude of the *d* correction; it provides the argument to enter the Increments and Corrections tables in the *Almanac*. The sign of the *d* correction factor, which determines the sign of the *d* correction, is determined by the trend of declination values, *not* the trend of *d* values. The *d* correction factor is simply an interpolation factor; therefore, to determine its sign, look at the declination values for the hours that frame the time of the sight. For example, suppose the sight was taken on a certain date at 12-30-00. Compare the declination value for 1200 and 1300 and determine if the declination has increased or decreased. If it has increased, the *d* correction factor is positive. If it has decreased, the *d* correction factor is negative.

***d* correction:** Enter the Increments and Corrections table with the *d* correction factor discussed above. Extract the proper correction, being careful to retain the proper sign.

True Declination: Combine the tabulated declination and the *d* correction to obtain the true declination.

Assumed Latitude: Choose as the assumed latitude that whole value of latitude closest to the vessel's DR latitude. If the assumed latitude and declination are both north or both south, label the assumed latitude *same*. If one is north and the other is south, label the assumed latitude *contrary*.

SECTION FOUR uses the arguments of assumed latitude, LHA, and declination determined in Section Three to enter the *Sight Reduction Tables* to determine azimuth and computed altitude. Then, Section Four compares computed and observed altitudes to calculate the altitude intercept. The navigator then has enough information to plot the line of position.

(1) Declination Increment and (2) *d* Interpolation Factor: Note that two of the three arguments used to enter the *Sight Reduction Tables*, LHA and latitude, are whole degree values. Section Three does not determine the third argument, declination, as a whole degree. Therefore, the navigator must interpolate in the *Sight Reduction Tables* for declination, given whole degrees of LHA and latitude. The first steps of Section Four involve this interpolation for declination. Since declination values are tabulated every whole degree in the *Sight Reduction Tables*, the declination increment is the minutes and tenths of the true declination. For example, if the true declination is 13° 15.6', then the declination increment is 15.6'. (2) The *Sight Reduction Tables* also list a *d* Interpolation Factor. This is the magnitude of the difference between the two successive tabulated values for declination that frame the true declination. Therefore, for the hypothetical declination listed above, the tabulated *d* interpolation factor listed in the table would be the difference between declination values given for 13° and 14°. If the declination increases between these two values, *d* is positive. If the declination decreases between these two values, *d* is negative.

Computed Altitude (Tabulated): Enter the *Sight Reduction Tables* with the following arguments: (1) LHA from Section Three; (2) assumed latitude from Section Three; (3) the whole degree value of the true declination. For example, if the true declination were 13° 15.6', then enter the *Sight Reduction Tables* with 13° as the value for declination. Record the tabulated computed altitude.

Double Second Difference Correction: Use this correction when linear interpolation of declination for computed altitude is not sufficiently accurate due to the non linear change in the computed altitude as a function of declination. The need for double second difference interpolation is indicated by the *d* interpolation factor appearing in italic type followed by a small dot. When this procedure must be employed, refer to detailed instructions in the *Sight Reduction Tables* introduction.

Total Correction: The total correction is the sum of the double second difference (if required) and the interpolation corrections. Calculate the interpolation correction by dividing the declination increment by 60' and multiply the resulting quotient by the *d* interpolation factor.

Computed Altitude (h_c): Apply the total correction, being careful to carry the correct sign, to the tabulated computed altitude. This yields the computed altitude.

Observed Altitude (h_o): Enter the observed altitude from Section One.

Altitude Intercept: Compare h_c and h_o. Subtract the smaller from the larger. The resulting difference is the magnitude of the altitude intercept. If h_o is greater than h_c, then label the altitude intercept *toward*. If h_c is greater than h_o, then label the altitude intercept *away*.

Azimuth Angle: Obtain the azimuth angle (Z) from the *Sight Reduction Tables*, using the same arguments which determined tabulated computed altitude. Visual interpolation is sufficiently accurate.

True Azimuth: Calculate the true azimuth (Z_n) from the azimuth angle (Z) as follows:

a) If in northern latitudes:

$$\text{LHA} > 180°\text{, then } Z_n = Z$$
$$\text{LHA} < 180°\text{, then } Z_n = 360° - Z$$

b) If in southern latitudes:

$$\text{LHA} > 180°\text{, then } Z_n = 180° - Z$$
$$\text{LHA} < 180°\text{, then } Z_n = 180° + Z$$

SIGHT REDUCTION

The section above discussed the basic theory of sight reduction and proposed a method to be followed when reducing sights. This section puts that method into practice in reducing sights of a star, the sun, the moon, and planets.

2005. Reducing Star Sights To A Fix

On May 16, 1995, at the times indicated, the navigator takes and records the following sights:

Star	Sextant Altitude	Zone Time
Kochab	47° 19.1'	20-07-43
Spica	32° 34.8'	20-11-26

Height of eye is 48 feet and index correction (IC) is +2.1'. The DR latitude for both sights is 39° N. The DR longitude for the Spica sight is 157° 10'W. The DR longitude for the Kochab sight is 157° 08.0'W. Determine the intercept and azimuth for both sights. See Figure 2005.

First, convert the sextant altitudes to observed altitudes. Reduce the Spica sight first:

Body	Spica
Index Correction	+2.1'
Dip (height 48 ft)	-6.7'
Sum	-4.6'
Sextant Altitude (h_s)	32° 34.8'
Apparent Altitude (h_a)	32° 30.2'
Altitude Correction	-1.5'
Additional Correction	0
Horizontal Parallax	0
Correction to h_a	-1.5'
Observed Altitude (h_o)	32° 28.7'

Determine the sum of the index correction and the dip correction. Go to the inside front cover of the Nautical Almanac to the table entitled DIP. This table lists dip corrections as a function of height of eye measured in either feet or meters. In the above problem, the observer's height of eye is 48 feet. The heights of eye are tabulated in intervals, with the correction corresponding to each interval listed between the interval's endpoints. In this case, 48 feet lies between the tabulated 46.9 to 48.4 feet interval; the corresponding correction for this interval is -6.7'. Add the IC and the dip correction, being careful to carry the correct sign. The sum of the corrections here is -4.6'. Apply this correction to the sextant altitude to obtain the apparent altitude (h_a).

Next, apply the altitude correction. Find the altitude correction table on the inside front cover of the *Nautical Almanac* next to the dip table. The altitude correction varies as a function of both the type of body sighted (sun, star, or planet) and the body's apparent altitude. For the problem above, enter the star altitude correction table. Again, the correction is given within an altitude interval; h_a in this case was 32° 30.2'. This value lies between the tabulated endpoints 32° 00.0' and 33° 45.0'. The correction corresponding to this interval is -1.5'. Applying this correction to h_a yields an observed altitude of 32° 28.7'.

Having calculated the observed altitude, determine the time and date of the sight in Greenwich Mean Time:

Date	16 May 1995
DR Latitude	39° N
DR Longitude	157° 10' W
Observation Time	20-11-26
Watch Error	0
Zone Time	20-11-26
Zone Description	+10
GMT	06-11-26
GMT Date	17 May 1995

Record the observation time and then apply any watch error to determine zone time. Then, use the DR longitude at the time of the sight to determine time zone description. In this case, the DR longitude indicates a zone description of +10 hours. Add the zone description to the zone time to obtain GMT. It is important to carry the correct date when applying this correction. In this case, the +10 correction made it 06-11-26 GMT on May 17, when the date in the local time zone was May 16.

After calculating both the observed altitude and the GMT time, enter the daily pages of the *Nautical Almanac* to calculate the star's Greenwich Hour Angle (GHA) and declination.

Tab GHA ♈	324° 28.4'
GHA Increment	2° 52.0'
SHA	158° 45.3'
GHA	486° 05.7'
+/- 360°	not required
Assumed Longitude	157° 05.7'
LHA	329°
Tabulated Dec/*d*	S 11° 08.4'/n.a.
d Correction	—
True Declination	S 11° 08.4'
Assumed Latitude	N 39° contrary

First, record the GHA of Aries from the May 17, 1995 daily page: 324° 28.4'.

Next, determine the incremental addition for the minutes and seconds after 0600 from the Increments and Corrections table in the back of the *Nautical Almanac*. The increment for 11 minutes and 26 seconds is 2° 52'.

Then, calculate the GHA of the star. Remember:

GHA (star) = GHA ♈ + SHA (star)

The *Nautical Almanac* lists the SHA of selected stars on each daily page. The SHA of Spica on May 17, 1995:158° 45.3'.

The *Sight Reduction Tables*' entering arguments are whole degrees of LHA and assumed latitude. Remember that LHA = GHA - west longitude or GHA + east longitude. Since in this example the vessel is in west longitude, subtract its assumed longitude from the GHA of the body to obtain the LHA. Assume a longitude meeting the criteria listed in section 2004.

From those criteria, the assumed longitude must end in 05.7 minutes so that, when subtracted from the calculated GHA, a whole degree of LHA will result. Since the DR longitude was 157° 10.0', then the assumed longitude ending in 05.7' closest to the DR longitude is 157° 05.7'. Subtracting this assumed longitude from the calculated GHA of the star yields an LHA of 329°.

The next value of concern is the star's true declination. This value is found on the May 17th daily page next to the star's SHA. Spica's declination is S 11° 08.4'. There is no d correction for a star sight, so the star's true declination equals its tabulated declination. The assumed latitude is determined from the whole degree of latitude closest to the DR latitude at the time of the sight. In this case, the assumed latitude is N 39°. It is marked "contrary" because the DR latitude is north while the star's declination is south.

The following information is known: (1) the assumed position's LHA (329°) and assumed latitude (39°N contrary name); and (2) the body's declination (S11° 08.4').

Find the page in the *Sight Reduction Table* corresponding to an LHA of 329° and an assumed latitude of N 39°, with latitude contrary to declination. Enter this table with the body's whole degree of declination. In this case, the body's whole degree of declination is 11°. This declination corresponds to a tabulated altitude of 32° 15.9'. This value is for a declination of 11°; the true declination is 11° 08.4'. Therefore, interpolate to determine the correction to add to the tabulated altitude to obtain the computed altitude.

The difference between the tabulated altitudes for 11° and 12° is given in the *Sight Reduction Tables* as the value d; in this case, d = -53.0. Express as a ratio the declination increment (in this case, 8.4') and the total interval between the tabulated declination values (in this case, 60') to obtain the percentage of the distance between the tabulated declination values represented by the declination increment. Next, multiply that percentage by the increment between the two values for computed altitude. In this case:

$$\frac{8.4}{60} \times (-53.0) = -7.4$$

Subtract 7.4' from the tabulated altitude to obtain the final computed altitude: H_c = 32° 08.5'.

Dec Inc / + or - d	8.4' / -53.0
h_c (tabulated)	32° 15.9'
Correction (+ or -)	-7.4'
h_c (computed)	32° 08.5'

It will be valuable here to review exactly what h_o and h_c represent. Recall the methodology of the altitude-intercept method. The navigator first measures and corrects an altitude for a celestial body. This corrected altitude, h_o, corresponds to a circle of equal altitude passing through the navigator's actual position whose center is the geographic position (GP) of the body. The navigator then determines an assumed position (AP) near, but not coincident with, his actual position; he then calculates an altitude for an observer at that assumed position (AP).The circle of equal altitude passing through this assumed position is concentric with the circle of equal altitude passing through the navigator's actual position. The difference between the body's altitude at the assumed position (h_c) and the body's observed altitude (h_o) is equal to the differences in radii length of the two corresponding circles of equal altitude. In the above problem, therefore, the navigator knows that the equal altitude circle passing through his actual position is:

$$\begin{array}{rl} h_o = & 32°28.7' \\ -h_c = & \underline{32°08.5'} \\ & 20.2 \text{ NM} \end{array}$$

away from the equal altitude circle passing through his assumed position. Since h_o is greater than h_c, the navigator knows that the radius of the equal altitude circle passing through his actual position is less than the radius of the equal altitude circle passing through the assumed position. The only remaining question is: in what direction from the assumed and actual position is the body's geographic position. The *Sight Reduction Tables* also provide this final piece of information. This is the value for Z tabulated with the h_c and d values discussed above. In this case, enter the *Sight Reduction Tables* as before, with LHA, assumed latitude, and declination. Visual interpolation is sufficient. Extract the value Z = 143.3°. The relation between Z and Z_n, the true azimuth, is as follows:

In northern latitudes:

$$\text{LHA} > 180°, \text{ then } Z_n = Z$$
$$\text{LHA} < 180°, \text{ then } Z_n = 360° - Z$$

In southern latitudes:

$$\text{LHA} > 180°, \text{ then } Z_n = 180° - Z$$
$$\text{LHA} < 180°, \text{ then } Z_n = 180° + Z$$

In this case, LHA > 180° and the vessel is in northern latitude. Therefore, Z_n = Z = 143.3°T. The navigator now has enough information to plot a line of position.

The values for the reduction of the Kochab sight follow:

Body	Kochab
Index Correction	+2.1'
Dip Correction	-6.7'
Sum	-4.6'
h_s	47° 19.1'
h_a	47° 14.5'
Altitude Correction	-.9'
Additional Correction	not applicable
Horizontal Parallax	not applicable
Correction to h_a	-9'
h_o	47° 13.6'
Date	16 May 1995
DR latitude	39°N
DR longitude	157° 08.0' W
Observation Time	20-07-43
Watch Error	0
Zone Time	20-07-43
Zone Description	+10
GMT	06-07-43
GMT Date	17 May 1995
Tab GHA ♈	324° 28.4'
GHA Increment	1° 56.1'
SHA	137° 18.5'
GHA	463° 43.0'
+/- 360°	not applicable
Assumed Longitude	156° 43.0'
LHA	307°
Tab Dec / *d*	N74° 10.6' / n.a.
d Correction	not applicable
True Declination	N74° 10.6'
Assumed Latitude	39°N (same)
Dec Inc / + or - d	10.6' / -24.8
h_c	47° 12.6'
Total Correction	-4.2'

1995 MAY 16, 17, 18 (TUES., WED., THURS.)

UT (GMT)	ARIES	VENUS −3.9		MARS +0.7		JUPITER −2.5		SATURN +1.3		STARS		
d h	G.H.A. ° ′	G.H.A. ° ′	Dec. ° ′	G.H.A. ° ′	Dec. ° ′	G.H.A. ° ′	Dec. ° ′	G.H.A. ° ′	Dec. ° ′	Name	S.H.A. ° ′	Dec. ° ′
16 00	233 14.4	205 51.6	N 9 30.5	84 34.3	N14 31.2	342 02.6	S21 28.7	239 13.9	S 4 40.8	Acamar	315 29.1	S40 19.4
01	248 16.9	220 51.2	31.6	99 35.8	30.8	357 05.3	28.7	254 16.2	40.7	Achernar	335 37.4	S57 15.5
02	263 19.4	235 50.8	32.7	114 37.3	30.3	12 08.1	28.7	269 18.5	40.6	Acrux	173 24.0	S63 04.7
03	278 21.8	250 50.4	33.8	129 38.8	29.9	27 10.9	28.6	284 20.7	40.6	Adhara	255 23.5	S28 58.3
04	293 24.3	265 50.0	34.9	144 40.3	29.5	42 13.7	28.6	299 23.0	40.5	Aldebaran	291 05.3	N16 29.9
05	308 26.8	280 49.6	36.0	159 41.7	29.1	57 16.4	28.5	314 25.3	40.4			
06	323 29.2	295 49.2	N 9 37.1	174 43.2	N14 28.7	72 19.2	S21 28.5	329 27.6	S 4 40.4	Alioth	166 32.3	N55 59.2
07	338 31.7	310 48.8	38.2	189 44.7	28.3	87 22.0	28.5	344 29.9	40.3	Alkaid	153 09.2	N49 20.3
T 08	353 34.2	325 48.4	39.2	204 46.2	27.9	102 24.7	28.4	359 32.1	40.2	Al Na'ir	28 00.8	S46 58.7
U 09	8 36.6	340 48.0	40.3	219 47.7	27.5	117 27.5	28.4	14 34.4	40.2	Alnilam	276 00.5	S 1 12.5
E 10	23 39.1	355 47.6	41.4	234 49.2	27.1	132 30.3	28.4	29 36.7	40.1	Alphard	218 09.5	S 8 38.6
S 11	38 41.5	10 47.1	42.5	249 50.6	26.6	147 33.1	28.3	44 39.0	40.0			
D 12	53 44.0	25 46.7	N 9 43.6	264 52.1	N14 26.2	162 35.8	S21 28.3	59 41.3	S 4 40.0	Alphecca	126 22.2	N26 43.8
A 13	68 46.5	40 46.3	44.7	279 53.6	25.8	177 38.6	28.3	74 43.6	39.9	Alpheratz	357 57.8	N29 03.8
Y 14	83 48.9	55 45.9	45.8	294 55.1	25.4	192 41.4	28.2	89 45.8	39.8	Altair	62 21.3	N 8 51.4
15	98 51.4	70 45.5	46.9	309 56.6	25.0	207 44.2	28.2	104 48.1	39.8	Ankaa	353 29.4	S42 19.7
16	113 53.9	85 45.1	47.9	324 58.0	24.6	222 46.9	28.2	119 50.4	39.7	Antares	112 42.6	S26 25.3
17	128 56.3	100 44.7	49.0	339 59.5	24.2	237 49.7	28.1	134 52.7	39.6			
18	143 58.8	115 44.3	N 9 50.1	355 01.0	N14 23.8	252 52.5	S21 28.1	149 55.0	S 4 39.6	Arcturus	146 07.8	N19 12.4
19	159 01.3	130 43.9	51.2	10 02.5	23.3	267 55.3	28.1	164 57.3	39.5	Atria	107 56.1	S69 01.0
20	174 03.7	145 43.5	52.3	25 03.9	22.9	282 58.0	28.0	179 59.5	39.4	Avior	234 23.8	S59 30.1
21	189 06.2	160 43.1	53.4	40 05.4	22.5	298 00.8	28.0	195 01.8	39.4	Bellatrix	278 46.9	N 6 20.6
22	204 08.7	175 42.7	54.5	55 06.9	22.1	313 03.6	28.0	210 04.1	39.3	Betelgeuse	271 16.3	N 7 24.2
23	219 11.1	190 42.3	55.5	70 08.4	21.7	328 06.3	27.9	225 06.4	39.2			
17 00	234 13.6	205 41.9	N 9 56.6	85 09.8	N14 21.3	343 09.1	S21 27.9	240 08.7	S 4 39.1	Canopus	264 02.6	S52 41.9
01	249 16.0	220 41.5	57.7	100 11.3	20.9	358 11.9	27.8	255 11.0	39.1	Capella	280 55.0	N45 59.5
02	264 18.5	235 41.1	58.8	115 12.8	20.5	13 14.7	27.8	270 13.2	39.0	Deneb	49 40.6	N45 15.7
03	279 21.0	250 40.7	9 59.9	130 14.3	20.0	28 17.4	27.8	285 15.5	38.9	Denebola	182 47.4	N14 35.8
04	294 23.4	265 40.3	10 01.0	145 15.7	19.6	43 20.2	27.7	300 17.8	38.9	Diphda	349 09.8	S18 00.7
05	309 25.9	280 39.8	02.0	160 17.2	19.2	58 23.0	27.7	315 20.1	38.8			
06	324 28.4	295 39.4	N10 03.1	175 18.7	N14 18.8	73 25.8	S21 27.7	330 22.4	S 4 38.7	Dubhe	194 08.2	N61 46.7
W 07	339 30.8	310 39.0	04.2	190 20.2	18.4	88 28.6	27.6	345 24.7	38.7	Elnath	278 30.2	N28 36.1
E 08	354 33.3	325 38.6	05.3	205 21.6	18.0	103 31.3	27.6	0 26.9	38.6	Eltanin	90 52.0	N51 29.3
D 09	9 35.8	340 38.2	06.4	220 23.1	17.5	118 34.1	27.6	15 29.2	38.5	Enif	34 00.5	N 9 51.2
N 10	24 38.2	355 37.8	07.4	235 24.6	17.1	133 36.9	27.5	30 31.5	38.5	Fomalhaut	15 39.1	S29 38.6
E 11	39 40.7	10 37.4	08.5	250 26.0	16.7	148 39.7	27.5	45 33.8	38.4			
S 12	54 43.1	25 37.0	N10 09.6	265 27.5	N14 16.3	163 42.4	S21 27.5	60 36.1	S 4 38.3	Gacrux	172 15.6	S57 05.5
D 13	69 45.6	40 36.6	10.7	280 29.0	15.9	178 45.2	27.4	75 38.4	38.3	Gienah	176 06.1	S17 31.2
A 14	84 48.1	55 36.2	11.8	295 30.5	15.5	193 48.0	27.4	90 40.7	38.2	Hadar	149 06.6	S60 21.2
Y 15	99 50.5	70 35.7	12.8	310 31.9	15.0	208 50.8	27.4	105 42.9	38.1	Hamal	328 16.4	N23 26.3
16	114 53.0	85 35.3	13.9	325 33.4	14.6	223 53.5	27.3	120 45.2	38.1	Kaus Aust.	84 01.5	S34 23.0
17	129 55.5	100 34.9	15.0	340 34.9	14.2	238 56.3	27.3	135 47.5	38.0			
18	144 57.9	115 34.5	N10 16.1	355 36.3	N14 13.8	253 59.1	S21 27.2	150 49.8	S 4 37.9	Kochab	137 18.5	N74 10.6
19	160 00.4	130 34.1	17.2	10 37.8	13.4	269 01.9	27.2	165 52.1	37.9	Markab	13 52.0	N15 10.8
20	175 02.9	145 33.7	18.2	25 39.3	13.0	284 04.6	27.2	180 54.4	37.8	Menkar	314 29.6	N 4 04.2
21	190 05.3	160 33.3	19.3	40 40.7	12.5	299 07.4	27.1	195 56.7	37.7	Menkent	148 23.3	S36 21.0
22	205 07.8	175 32.8	20.4	55 42.2	12.1	314 10.2	27.1	210 58.9	37.7	Miaplacidus	221 42.6	S69 42.4
23	220 10.3	190 32.4	21.5	70 43.7	11.7	329 13.0	27.1	226 01.2	37.6			
18 00	235 12.7	205 32.0	N10 22.5	85 45.1	N14 11.3	344 15.8	S21 27.0	241 03.5	S 4 37.5	Mirfak	309 00.4	N49 50.6
01	250 15.2	220 31.6	23.6	100 46.6	10.9	359 18.5	27.0	256 05.8	37.5	Nunki	76 14.9	S26 18.0
02	265 17.6	235 31.2	24.7	115 48.1	10.5	14 21.3	27.0	271 08.1	37.4	Peacock	53 40.4	S56 44.7
03	280 20.1	250 30.8	25.8	130 49.5	10.0	29 24.1	26.9	286 10.4	37.3	Pollux	243 44.6	N28 02.2
04	295 22.6	265 30.4	26.8	145 51.0	09.6	44 26.9	26.9	301 12.7	37.3	Procyon	245 14.1	N 5 14.0
05	310 25.0	280 29.9	27.9	160 52.5	09.2	59 29.6	26.9	316 15.0	37.2			
06	325 27.5	295 29.5	N10 29.0	175 53.9	N14 08.8	74 32.4	S21 26.8	331 17.2	S 4 37.1	Rasalhague	96 18.8	N12 33.8
07	340 30.0	310 29.1	30.0	190 55.4	08.4	89 35.2	26.8	346 19.5	37.1	Regulus	207 58.0	N11 59.3
T 08	355 32.4	325 28.7	31.1	205 56.9	07.9	104 38.0	26.8	1 21.8	37.0	Rigel	281 25.5	S 8 12.6
H 09	10 34.9	340 28.3	32.2	220 58.3	07.5	119 40.8	26.7	16 24.1	36.9	Rigil Kent.	140 09.6	S60 49.0
U 10	25 37.4	355 27.9	33.3	235 59.8	07.1	134 43.5	26.7	31 26.4	36.9	Sabik	102 27.8	S15 43.1
R 11	40 39.8	10 27.4	34.3	251 01.2	06.7	149 46.3	26.6	46 28.7	36.8			
S 12	55 42.3	25 27.0	N10 35.4	266 02.7	N14 06.3	164 49.1	S21 26.6	61 31.0	S 4 36.8	Schedar	349 56.4	N56 30.5
D 13	70 44.8	40 26.6	36.5	281 04.2	05.8	179 51.9	26.6	76 33.3	36.7	Shaula	96 40.0	S37 05.9
A 14	85 47.2	55 26.2	37.5	296 05.6	05.4	194 54.7	26.5	91 35.6	36.6	Sirius	258 45.9	S16 42.8
Y 15	100 49.7	70 25.8	38.6	311 07.1	05.0	209 57.4	26.5	106 37.8	36.6	Spica	158 45.3	S11 08.4
16	115 52.1	85 25.3	39.7	326 08.6	04.6	225 00.2	26.5	121 40.1	36.5	Suhail	223 02.5	S43 25.2
17	130 54.6	100 24.9	40.7	341 10.0	04.2	240 03.0	26.4	136 42.4	36.4			
18	145 57.1	115 24.5	N10 41.8	356 11.5	N14 03.7	255 05.8	S21 26.4	151 44.7	S 4 36.4	Vega	80 47.8	N38 46.7
19	160 59.5	130 24.1	42.9	11 12.9	03.3	270 08.6	26.4	166 47.0	36.3	Zuben'ubi	137 20.2	S16 01.4
20	176 02.0	145 23.6	44.0	26 14.4	02.9	285 11.3	26.3	181 49.3	36.2		S.H.A.	Mer. Pass.
21	191 04.5	160 23.2	45.0	41 15.9	02.5	300 14.1	26.3	196 51.6	36.2		° ′	h m
22	206 06.9	175 22.8	46.1	56 17.3	02.0	315 16.9	26.2	211 53.9	36.1	Venus	331 28.3	10 17
23	221 09.4	190 22.4	47.2	71 18.8	01.6	330 19.7	26.2	226 56.2	36.0	Mars	210 56.3	18 18
Mer. Pass.	h m 8 21.7	v −0.4	d 1.1	v 1.5	d 0.4	v 2.8	d 0.0	v 2.3	d 0.1	Jupiter	108 55.5	1 07
										Saturn	5 55.1	7 58

Figure 2005. Left hand daily page of the *Nautical Almanac* for May 17, 1995.

h_c (computed)	47° 08.2'
h_o	47° 13.6'
a (intercept)	5.4 towards
Z	018.9°
Z_n	018.9°

2006. Reducing A Sun Sight

The example below points out the similarities between reducing a sun sight and reducing a star sight. It also demonstrates the additional corrections required for low altitude (<10°) sights and sights taken during non-standard temperature and pressure conditions.

On June 16, 1994, at 05-15-23 local time, at DR position L 30°N λ 45°W, a navigator takes a sight of the sun's upper limb. The navigator has a height of eye of 18 feet, the temperature is 88° F, and the atmospheric pressure is 982 mb. The sextant altitude is 3° 20.2'. There is no index error. Determine the observed altitude. See Figure 2007.

Body	Sun UL
Index Correction	0
Dip Correction (18 ft)	-4.1'
Sum	-4.1'
h_s	3° 20.2'
h_a	3° 16.1'
Altitude Correction	-29.4'
Additional Correction	+1.4'
Horizontal Parallax	0
Correction to h_a	-28.0'
h_o	2° 48.1'

Apply the index and dip corrections to h_s to obtain h_a. Because h_a is less than 10°, use the special altitude correction table for sights between 0° and 10° located on the right inside front page of the *Nautical Almanac*.

Enter the table with the apparent altitude, the limb of the sun used for the sight, and the period of the year. Interpolation for the apparent altitude is not required. In this case, the table yields a correction of -29.4'. The correction's algebraic sign is found at the head of each group of entries and at every change of sign.

The additional correction is required because of the non-standard temperature and atmospheric pressure under which the sight was taken. The correction for these non-standard conditions is found in the *Additional Corrections* table located on page A4 in the front of the *Nautical Almanac*.

First, enter the *Additional Corrections* table with the temperature and pressure to determine the correct zone letter: in this case, zone L. Then, locate the correction in the L column corresponding to the apparent altitude of 3° 16.1'. Interpolate between the table arguments of 3° 00.0' and 3° 30.0' to determine the additional correction: +1.4'. The total correction to the apparent altitude is the sum of the altitude and additional corrections: -28.0'. This results in an h_o of 2° 48.1'.

Next, determine the sun's GHA and declination. Again, this process is similar to the star sights reduced above. Notice, however, that SHA, a quantity unique to star sight reduction, is not used in sun sight reduction.

Date	June 16, 1994
DR Latitude	N30° 00.0'
DR Longitude	W045° 00.0'
Observation Time	05-15-23
Watch Error	0
Zone Time	05-15-23
Zone Description	+03
GMT	08-15-23
Date GMT	June 16, 1994
Tab GHA / *v*	299° 51.3' / n.a.
GHA Increment	3° 50.8'
SHA or *v* correction	not applicable
GHA	303°42.1'
Assumed Longitude	44° 42.1' W
LHA	259°
Tab Declination / *d*	N23° 20.5' / +0.1'
d Correction	0.0
True Declination	N23° 20.5'
Assumed Latitude	N30° (same)

Determining the sun's GHA is less complicated than determining a star's GHA. The *Nautical Almanac's* daily pages list the sun's GHA in hourly increments. In this case, the sun's GHA at 0800 GMT on June 16, 1994 is 299° 51.3'. The *v* correction is not applicable for a sun sight; therefore, applying the increment correction yields the sun's GHA. In this case, the GHA is 303° 42.1'.

Determining the sun's LHA is similar to determining a star's LHA. In determining the sun's declination, however, an additional correction not encountered in the star sight, the *d* correction, must be considered. The bottom of the sun column on the daily pages of the *Nautical Almanac* lists the *d* value. This is an interpolation factor for the sun's declination. The sign of the *d* factor is not given; it must be determined by noting from the *Almanac* if the sun's declination is increasing or decreasing throughout the day. If it is increasing, the factor is positive; if it is decreasing, the factor is negative. In the above problem, the sun's declination is increasing throughout the day. Therefore, the *d* factor is +0.1.

Having obtained the *d* factor, enter the 15 minute increment and correction table. Under the column labeled "*v* or *d* corr^n," find the value for *d* in the left hand column. The corresponding number in the right hand column is the correction; apply it to the tabulated declination. In this case, the correction corresponding to a *d* value of +0.1 is 0.0'.

The final step will be to determine h_c and Z_n. Enter the *Sight Reduction Tables* with an LHA of 259°, a declination of N23° 20.5', and an assumed latitude of 30°N.

Declination Increment / + or - *d*	20.5' / +31.5
Tabulated Altitude	2° 28.8'

1994 JUNE 15, 16, 17 (WED., THURS., FRI.)

UT (GMT) d h	ARIES G.H.A. ° ′	VENUS −4.0 G.H.A. ° ′	VENUS Dec. ° ′	MARS +1.2 G.H.A. ° ′	MARS Dec. ° ′	JUPITER −2.3 G.H.A. ° ′	JUPITER Dec. ° ′	SATURN +1.0 G.H.A. ° ′	SATURN Dec. ° ′
15 00	263 03.0	140 48.0	N22 09.1	218 59.0	N16 08.6	49 42.0	S12 03.8	278 39.3	S 8 31.9
01	278 05.4	155 47.4	08.5	233 59.7	09.1	64 44.6	03.8	293 41.7	31.9
02	293 07.9	170 46.7	07.9	249 00.3	09.7	79 47.2	03.7	308 44.1	31.9
03	308 10.4	185 46.1	· · 07.3	264 01.0	· · 10.2	94 49.7	· · 03.7	323 46.6	· · 31.9
04	323 12.8	200 45.5	06.7	279 01.6	10.8	109 52.3	03.7	338 49.0	31.9
05	338 15.3	215 44.8	06.0	294 02.2	11.3	124 54.9	03.6	353 51.4	31.9
06	353 17.8	230 44.2	N22 05.4	309 02.9	N16 11.9	139 57.5	S12 03.6	8 53.9	S 8 31.9
W 07	8 20.2	245 43.6	04.8	324 03.5	12.4	155 00.1	03.6	23 56.3	31.9
E 08	23 22.7	260 42.9	04.2	339 04.2	13.0	170 02.7	03.5	38 58.7	31.9
D 09	38 25.2	275 42.3	· · 03.5	354 04.8	· · 13.5	185 05.3	· · 03.5	54 01.1	· · 31.9
N 10	53 27.6	290 41.7	02.9	9 05.5	14.0	200 07.9	03.5	69 03.6	31.9
E 11	68 30.1	305 41.0	02.3	24 06.1	14.6	215 10.4	03.4	84 06.0	31.9
S 12	83 32.6	320 40.4	N22 01.6	39 06.8	N16 15.1	230 13.0	S12 03.4	99 08.4	S 8 31.9
D 13	98 35.0	335 39.8	01.0	54 07.4	15.7	245 15.6	03.4	114 10.9	31.9
A 14	113 37.5	350 39.2	22 00.4	69 08.1	16.2	260 18.2	03.3	129 13.3	31.9
Y 15	128 39.9	5 38.5	21 59.7	84 08.7	· · 16.8	275 20.8	· · 03.3	144 15.7	· · 31.9
16	143 42.4	20 37.9	59.1	99 09.4	17.3	290 23.4	03.3	159 18.2	31.9
17	158 44.9	35 37.3	58.5	114 10.0	17.8	305 26.0	03.3	174 20.6	31.9
18	173 47.3	50 36.7	N21 57.8	129 10.7	N16 18.4	320 28.5	S12 03.2	189 23.0	S 8 31.9
19	188 49.8	65 36.0	57.2	144 11.3	18.9	335 31.1	03.2	204 25.5	31.9
20	203 52.3	80 35.4	56.6	159 12.0	19.5	350 33.7	03.2	219 27.9	31.9
21	218 54.7	95 34.8	· · 55.9	174 12.6	· · 20.0	5 36.3	· · 03.1	234 30.3	· · 31.9
22	233 57.2	110 34.2	55.3	189 13.3	20.6	20 38.9	03.1	249 32.8	31.9
23	248 59.7	125 33.5	54.6	204 13.9	21.1	35 41.5	03.1	264 35.2	31.9
16 00	264 02.1	140 32.9	N21 54.0	219 14.6	N16 21.6	50 44.1	S12 03.0	279 37.6	S 8 31.9
01	279 04.6	155 32.3	53.4	234 15.2	22.2	65 46.6	03.0	294 40.1	31.9
02	294 07.1	170 31.7	52.7	249 15.9	22.7	80 49.2	03.0	309 42.5	31.9
03	309 09.5	185 31.1	· · 52.1	264 16.5	· · 23.2	95 51.8	· · 03.0	324 44.9	· · 31.9
04	324 12.0	200 30.4	51.4	279 17.2	23.8	110 54.4	02.9	339 47.4	31.9
05	339 14.4	215 29.8	50.8	294 17.8	24.3	125 57.0	02.9	354 49.8	31.8
06	354 16.9	230 29.2	N21 50.1	309 18.5	N16 24.9	140 59.5	S12 02.9	9 52.2	S 8 31.8
07	9 19.4	245 28.6	49.5	324 19.1	25.4	156 02.1	02.8	24 54.7	31.8
T 08	24 21.8	260 28.0	48.8	339 19.8	25.9	171 04.7	02.8	39 57.1	31.8
H 09	39 24.3	275 27.4	· · 48.2	354 20.4	· · 26.5	186 07.3	· · 02.8	54 59.5	· · 31.8
U 10	54 26.8	290 26.8	47.5	9 21.1	27.0	201 09.9	02.7	70 02.0	31.8
R 11	69 29.2	305 26.1	46.9	24 21.7	27.6	216 12.5	02.7	85 04.4	31.8
S 12	84 31.7	320 25.5	N21 46.2	39 22.3	N16 28.1	231 15.0	S12 02.7	100 06.8	S 8 31.8
D 13	99 34.2	335 24.9	45.6	54 23.0	28.6	246 17.6	02.7	115 09.3	31.8
A 14	114 36.6	350 24.3	44.9	69 23.6	29.2	261 20.2	02.6	130 11.7	31.8
Y 15	129 39.1	5 23.7	· · 44.3	84 24.3	· · 29.7	276 22.8	· · 02.6	145 14.1	· · 31.8
16	144 41.5	20 23.1	43.6	99 24.9	30.2	291 25.3	02.6	160 16.6	31.8
17	159 44.0	35 22.5	42.9	114 25.6	30.8	306 27.9	02.5	175 19.0	31.8
18	174 46.5	50 21.9	N21 42.3	129 26.2	N16 31.3	321 30.5	S12 02.5	190 21.4	S 8 31.8
19	189 48.9	65 21.3	41.6	144 26.9	31.8	336 33.1	02.5	205 23.9	31.8
20	204 51.4	80 20.6	41.0	159 27.5	32.4	351 35.7	02.5	220 26.3	31.8
21	219 53.9	95 20.0	· · 40.3	174 28.2	· · 32.9	6 38.2	· · 02.4	235 28.7	· · 31.8
22	234 56.3	110 19.4	39.6	189 28.8	33.4	21 40.8	02.4	250 31.2	31.8
23	249 58.8	125 18.8	39.0	204 29.5	34.0	36 43.4	02.4	265 33.6	31.8
17 00	265 01.3	140 18.2	N21 38.3	219 30.1	N16 34.5	51 46.0	S12 02.4	280 36.0	S 8 31.8
01	280 03.7	155 17.6	37.6	234 30.8	35.0	66 48.5	02.3	295 38.5	31.8
02	295 06.2	170 17.0	37.0	249 31.4	35.6	81 51.1	02.3	310 40.9	31.8
03	310 08.7	185 16.4	· · 36.3	264 32.1	· · 36.1	96 53.7	· · 02.3	325 43.4	· · 31.8
04	325 11.1	200 15.8	35.6	279 32.7	36.6	111 56.3	02.2	340 45.8	31.8
05	340 13.6	215 15.2	35.0	294 33.3	37.2	126 58.8	02.2	355 48.2	31.8
06	355 16.0	230 14.6	N21 34.3	309 34.0	N16 37.7	142 01.4	S12 02.2	10 50.7	S 8 31.8
07	10 18.5	245 14.0	33.6	324 34.6	38.2	157 04.0	02.2	25 53.1	31.8
08	25 21.0	260 13.4	32.9	339 35.3	38.8	172 06.6	02.1	40 55.5	31.8
F 09	40 23.4	275 12.8	· · 32.3	354 35.9	· · 39.3	187 09.1	· · 02.1	55 58.0	· · 31.8
R 10	55 25.9	290 12.2	31.6	9 36.6	39.8	202 11.7	02.1	71 00.4	31.8
I 11	70 28.4	305 11.6	30.9	24 37.2	40.4	217 14.3	02.1	86 02.9	31.8
D 12	85 30.8	320 11.0	N21 30.2	39 37.9	N16 40.9	232 16.9	S12 02.0	101 05.3	S 8 31.8
A 13	100 33.3	335 10.4	29.6	54 38.5	41.4	247 19.4	02.0	116 07.7	31.8
Y 14	115 35.8	350 09.8	28.9	69 39.2	41.9	262 22.0	02.0	131 10.2	31.8
15	130 38.2	5 09.2	· · 28.2	84 39.8	· · 42.5	277 24.6	· · 02.0	146 12.6	· · 31.8
16	145 40.7	20 08.6	27.5	99 40.5	43.0	292 27.1	01.9	161 15.1	31.8
17	160 43.2	35 08.0	26.8	114 41.1	43.5	307 29.7	01.9	176 17.5	31.8
18	175 45.6	50 07.4	N21 26.2	129 41.7	N16 44.1	322 32.3	S12 01.9	191 19.9	S 8 31.8
19	190 48.1	65 06.8	25.5	144 42.4	44.6	337 34.9	01.9	206 22.4	31.8
20	205 50.5	80 06.2	24.8	159 43.0	45.1	352 37.4	01.8	221 24.8	31.8
21	220 53.0	95 05.6	· · 24.1	174 43.7	· · 45.6	7 40.0	· · 01.8	236 27.3	· · 31.8
22	235 55.5	110 05.1	23.4	189 44.3	46.2	22 42.6	01.8	251 29.7	31.8
23	250 57.9	125 04.5	22.7	204 45.0	46.7	37 45.1	01.8	266 32.1	31.8
Mer. Pass.	h m 6 22.8	v −0.6	d 0.7	v 0.6	d 0.5	v 2.6	d 0.0	v 2.4	d 0.0

STARS

Name	S.H.A. ° ′	Dec. ° ′
Acamar	315 29.5	S40 19.5
Achernar	335 37.6	S57 15.6
Acrux	173 25.1	S63 04.5
Adhara	255 24.1	S28 58.0
Aldebaran	291 06.1	N16 29.8
Alioth	166 33.0	N55 59.6
Alkaid	153 09.8	N49 20.6
Al Na'ir	28 01.4	S46 58.9
Alnilam	276 01.2	S 1 12.4
Alphard	218 10.3	S 8 38.3
Alphecca	126 22.7	N26 44.1
Alpheratz	357 58.3	N29 03.5
Altair	62 21.8	N 8 51.3
Ankaa	353 29.8	S42 19.9
Antares	112 43.4	S26 25.2
Arcturus	146 08.5	N19 12.7
Atria	107 57.4	S69 01.1
Avior	234 24.3	S59 29.8
Bellatrix	278 47.6	N 6 20.6
Betelgeuse	271 17.0	N 7 24.3
Canopus	264 03.0	S52 41.7
Capella	280 56.0	N45 59.5
Deneb	49 40.8	N45 15.6
Denebola	182 48.1	N14 36.2
Diphda	349 10.3	S18 00.9
Dubhe	194 09.2	N61 47.0
Elnath	278 31.0	N28 36.1
Eltanin	90 52.2	N51 29.4
Enif	34 00.9	N 9 51.0
Fomalhaut	15 39.6	S29 38.8
Gacrux	172 16.6	S57 05.3
Gienah	176 06.9	S17 30.9
Hadar	149 07.7	S60 21.1
Hamal	328 17.1	N23 26.1
Kaus Aust.	84 02.3	S34 23.1
Kochab	137 18.6	N74 10.9
Markab	13 52.4	N15 10.5
Menkar	314 30.2	N 4 04.1
Menkent	148 24.1	S36 20.8
Miaplacidus	221 43.2	S69 42.1
Mirfak	309 01.2	N49 50.3
Nunki	76 15.6	S26 18.1
Peacock	53 41.1	S56 44.9
Pollux	243 45.4	N28 02.3
Procyon	245 14.9	N 5 14.2
Rasalhague	96 19.3	N12 33.9
Regulus	207 58.8	N11 59.6
Rigel	281 26.1	S 8 12.6
Rigil Kent.	140 10.7	S60 48.9
Sabik	102 28.5	S15 43.0
Schedar	349 56.9	N56 30.2
Shaula	96 40.8	S37 05.9
Sirius	258 46.6	S16 42.6
Spica	158 46.1	S11 08.1
Suhail	223 03.2	S43 24.9
Vega	80 48.2	N38 46.8
Zuben'ubi	137 20.9	S16 01.2

	S.H.A. ° ′	Mer. Pass. h m
Venus	236 30.8	14 38
Mars	315 12.5	9 23
Jupiter	146 41.9	20 34
Saturn	15 35.5	5 21

Figure 2006. Left hand daily page of the *Nautical Almanac* for June 16, 1994.

Correction (+ or -)	+10.8'
Computed Altitude (h_c)	2° 39.6'
Observed Altitude (h_o)	2° 48.1'
Intercept	8.5 NM (towards)
Z	064.7°
Z_n	064.7°

2007. Reducing A Moon Sight

The moon is easy to identify and is often visible during the day. However, the moon's proximity to the earth requires applying additional corrections to h_a to obtain h_o. This section will cover moon sight reduction.

At 10-00-00 GMT, June 16, 1994, the navigator obtains a sight of the moon's upper limb. H_s is 26° 06.7'. Height of eye is 18 feet; there is no index error. Determine h_o, the moon's GHA, and the moon's declination. See Figure 2007.

Body	Moon (UL)
Index Correction	0.0'
Dip (18 feet)	-4.1'
Sum	-4.1'
Sextant Altitude (h_s)	26° 06.7'
Apparent Altitude (h_a)	26° 02.6'
Altitude Correction	+60.5'
Additional Correction	0.0'
Horizontal Parallax (58.4)	+4.0'
Moon Upper Limb Correction	-30.0'
Correction to h_a	+34.5'
Observed Altitude (h_o)	26° 37.1'

This procedure demonstrates the extra corrections required for obtaining h_o for a moon sight. Apply the index and dip corrections and in the same manner as for star and sun sights. The altitude correction comes from tables located on the inside back covers of the *Nautical Almanac*.

In this case, the apparent altitude was 26° 02.6'. Enter the altitude correction table for the moon with the above apparent altitude. Interpolation is not required. The correction is +60.5'. The additional correction in this case is not applicable because the sight was taken under standard temperature and pressure conditions.

The horizontal parallax correction is unique to moon sights. The table for determining this HP correction is on the back inside cover of the *Nautical Almanac*. First, go to the daily page for June 16 at 10-00-00 GMT. In the column for the moon, find the HP correction factor corresponding to 10-00-00. Its value is 58.4. Take this value to the HP correction table on the inside back cover of the *Almanac*. Notice that the HP correction columns line up vertically with the moon altitude correction table columns. Find the HP correction column directly under the altitude correction table heading corresponding to the apparent altitude. Enter that column with the HP correction factor from the daily pages. The column has two sets of figures listed under "U" and "L" for upper and lower limb, respectively. In this case, trace down the "U" column until it intersects with the HP correction factor of 58.4. Interpolating between 58.2 and 58.5 yields a value of +4.0' for the horizontal parallax correction.

The final correction is a constant -30.0' correction to h_a applied only to sights of the moon's upper limb. This correction is always negative; apply it only to sights of the moon's upper limb, not its lower limb. The total correction to h_a is the sum of all the corrections; in this case, this total correction is +34.5 minutes.

To obtain the moon's GHA, enter the daily pages in the moon column and extract the applicable data just as for a star or sun sight. Determining the moon's GHA requires an additional correction, the *v* correction.

GHA moon and *v*	245° 45.1' and +11.3
GHA Increment	0° 00.0'
v Correction	+0.1'
GHA	245° 45.2'

First, record the GHA of the moon for 10-00-00 on June 16, 1994, from the daily pages of the *Nautical Almanac*. Record also the *v* correction factor; in this case, it is +11.3. The *v* correction factor for the moon is always positive. The increment correction is, in this case, zero because the sight was recorded on the even hour. To obtain the *v* correction, go to the tables of increments and corrections. In the 0 minute table in the *v* or *d* correction columns, find the correction that corresponds to a *v* = 11.3. The table yields a correction of +0.1'. Adding this correction to the tabulated GHA gives the final GHA as 245° 45.2'.

Finding the moon's declination is similar to finding the declination for the sun or stars. Go to the daily pages for June 16, 1994; extract the moon's declination and *d* factor.

Tabulated Declination / *d*	S 00° 13.7' / +12.1
d Correction	+0.1'
True Declination	S 00° 13.8'

The tabulated declination and the *d* factor come from the *Nautical Almanac's* daily pages. Record the declination and *d* correction and go to the increment and correction pages to extract the proper correction for the given *d* factor. In this case, go to the correction page for 0 minutes. The correction corresponding to a *d* factor of +12.1 is +0.1. It is important to extract the correction with the correct algebraic sign. The *d* correction may be positive or negative depending on whether the moon's declination is increasing or decreasing in the interval covered by the *d* factor. In this case, the moon's declination at 10-00-00 GMT on 16 June was S 00° 13.7'; at 11-00-00 on the same date the moon's declination was S 00° 25.8'. Therefore, since the declination was increasing over this period, the *d* correction is positive. Do not determine the sign of this correction by noting the trend in the *d* factor. In other words, had the *d* factor for 11-00-00 been a value less than 12.1, that would not indicate that the *d* correction should be negative. Remember that the *d* factor is analogous to an interpolation

1994 JUNE 15, 16, 17 (WED., THURS., FRI.)

Day	UT (GMT) d h	SUN G.H.A. ° ′	SUN Dec. ° ′	MOON G.H.A. ° ′	MOON v ′	MOON Dec. ° ′	MOON d ′	MOON H.P. ′
	15 00	179 55.6	N23 17.2	112 24.4	11.8	N 6 28.5	11.4	57.6
	01	194 55.5	17.4	126 55.2	11.8	6 17.1	11.3	57.6
	02	209 55.4	17.5	141 26.0	11.8	6 05.8	11.4	57.6
	03	224 55.2	. . 17.6	155 56.8	11.7	5 54.4	11.4	57.7
	04	239 55.1	17.7	170 27.5	11.8	5 43.0	11.5	57.7
	05	254 55.0	17.8	184 58.3	11.8	5 31.5	11.5	57.7
WEDNESDAY	06	269 54.8	N23 17.9	199 29.1	11.7	N 5 20.0	11.6	57.7
	07	284 54.7	18.0	213 59.8	11.8	5 08.4	11.5	57.8
	08	299 54.6	18.1	228 30.6	11.7	4 56.9	11.7	57.8
	09	314 54.4	. . 18.2	243 01.3	11.8	4 45.2	11.6	57.8
	10	329 54.3	18.3	257 32.1	11.7	4 33.6	11.7	57.8
	11	344 54.2	18.5	272 02.8	11.7	4 21.9	11.7	57.9
	12	359 54.0	N23 18.6	286 33.5	11.7	N 4 10.2	11.8	57.9
	13	14 53.9	18.7	301 04.2	11.7	3 58.4	11.7	57.9
	14	29 53.8	18.8	315 34.9	11.7	3 46.7	11.8	57.9
	15	44 53.6	. . 18.9	330 05.6	11.7	3 34.9	11.9	58.0
	16	59 53.5	19.0	344 36.3	11.6	3 23.0	11.8	58.0
	17	74 53.4	19.1	359 06.9	11.6	3 11.2	11.9	58.0
	18	89 53.2	N23 19.2	13 37.5	11.7	N 2 59.3	11.9	58.0
	19	104 53.1	19.3	28 08.2	11.6	2 47.4	12.0	58.1
	20	119 53.0	19.4	42 38.8	11.6	2 35.4	11.9	58.1
	21	134 52.8	. . 19.5	57 09.4	11.5	2 23.5	12.0	58.1
	22	149 52.7	19.6	71 39.9	11.6	2 11.5	12.0	58.1
	23	164 52.6	19.7	86 10.5	11.5	1 59.5	12.0	58.2
	16 00	179 52.4	N23 19.8	100 41.0	11.5	N 1 47.5	12.1	58.2
	01	194 52.3	19.9	115 11.5	11.5	1 35.4	12.0	58.2
	02	209 52.2	20.0	129 42.0	11.5	1 23.4	12.1	58.2
	03	224 52.0	. . 20.1	144 12.5	11.5	1 11.3	12.1	58.3
	04	239 51.9	20.1	158 43.0	11.4	0 59.2	12.1	58.3
	05	254 51.7	20.2	173 13.4	11.4	0 47.1	12.1	58.3
THURSDAY	06	269 51.6	N23 20.3	187 43.8	11.4	N 0 35.0	12.2	58.3
	07	284 51.5	20.4	202 14.2	11.3	0 22.8	12.1	58.4
	08	299 51.3	20.5	216 44.5	11.3	N 0 10.7	12.2	58.4
	09	314 51.2	. . 20.6	231 14.8	11.3	S 0 01.5	12.2	58.4
	10	329 51.1	20.7	245 45.1	11.3	0 13.7	12.1	58.4
	11	344 50.9	20.8	260 15.4	11.2	0 25.8	12.2	58.5
	12	359 50.8	N23 20.9	274 45.6	11.3	S 0 38.0	12.2	58.5
	13	14 50.7	21.0	289 15.9	11.1	0 50.2	12.2	58.5
	14	29 50.5	21.1	303 46.0	11.2	1 02.4	12.2	58.5
	15	44 50.4	. . 21.1	318 16.2	11.1	1 14.6	12.2	58.6
	16	59 50.3	21.2	332 46.3	11.1	1 26.8	12.3	58.6
	17	74 50.1	21.3	347 16.4	11.0	1 39.1	12.2	58.6
	18	89 50.0	N23 21.4	1 46.4	11.0	S 1 51.3	12.2	58.6
	19	104 49.9	21.5	16 16.4	11.0	2 03.5	12.2	58.7
	20	119 49.7	21.6	30 46.4	10.9	2 15.7	12.2	58.7
	21	134 49.6	. . 21.6	45 16.3	10.9	2 27.9	12.2	58.7
	22	149 49.5	21.7	59 46.2	10.9	2 40.1	12.2	58.7
	23	164 49.3	21.8	74 16.1	10.8	2 52.3	12.2	58.8
	17 00	179 49.2	N23 21.9	88 45.9	10.8	S 3 04.5	12.2	58.8
	01	194 49.1	22.0	103 15.7	10.7	3 16.7	12.2	58.8
	02	209 48.9	22.0	117 45.4	10.7	3 28.9	12.2	58.8
	03	224 48.8	. . 22.1	132 15.1	10.7	3 41.1	12.2	58.9
	04	239 48.6	22.2	146 44.8	10.6	3 53.3	12.1	58.9
	05	254 48.5	22.3	161 14.4	10.6	4 05.4	12.2	58.9
FRIDAY	06	269 48.4	N23 22.3	175 44.0	10.5	S 4 17.6	12.1	58.9
	07	284 48.2	22.4	190 13.5	10.5	4 29.7	12.1	59.0
	08	299 48.1	22.5	204 43.0	10.4	4 41.8	12.1	59.0
	09	314 48.0	. . 22.6	219 12.4	10.4	4 53.9	12.1	59.0
	10	329 47.8	22.6	233 41.8	10.3	5 06.0	12.1	59.0
	11	344 47.7	22.7	248 11.1	10.3	5 18.1	12.1	59.1
	12	359 47.6	N23 22.8	262 40.4	10.2	S 5 30.2	12.0	59.1
	13	14 47.4	22.9	277 09.6	10.2	5 42.2	12.0	59.1
	14	29 47.3	22.9	291 38.8	10.1	5 54.2	12.0	59.1
	15	44 47.2	. . 23.0	306 07.9	10.1	6 06.2	11.9	59.2
	16	59 47.0	23.1	320 37.0	10.0	6 18.1	12.0	59.2
	17	74 46.9	23.1	335 06.0	10.0	6 30.1	11.9	59.2
	18	89 46.8	N23 23.2	349 35.0	9.9	S 6 42.0	11.9	59.2
	19	104 46.6	23.3	4 03.9	9.9	6 53.9	11.8	59.3
	20	119 46.5	23.3	18 32.8	9.8	7 05.7	11.8	59.3
	21	134 46.3	. . 23.4	33 01.6	9.7	7 17.5	11.8	59.3
	22	149 46.2	23.5	47 30.3	9.7	7 29.3	11.8	59.3
	23	164 46.1	23.5	61 59.0	9.6	7 41.1	11.7	59.4
		S.D. 15.8	*d* 0.1	S.D.	15.8	15.9		16.1

Lat.	Twilight Naut. h m	Twilight Civil h m	Sunrise h m	Moonrise 15 h m	Moonrise 16 h m	Moonrise 17 h m	Moonrise 18 h m
N 72	▭	▭	▭	09 54	11 50	13 49	15 56
N 70	▭	▭	▭	10 01	11 49	13 40	15 36
68	▭	▭	▭	10 06	11 48	13 33	15 21
66	▭	▭	▭	10 11	11 47	13 26	15 09
64	////	////	01 33	10 14	11 47	13 21	14 59
62	////	////	02 10	10 18	11 46	13 17	14 50
60	////	00 52	02 36	10 20	11 46	13 13	14 43
N 58	////	01 41	02 56	10 23	11 45	13 10	14 37
56	////	02 11	03 13	10 25	11 45	13 07	14 31
54	00 48	02 33	03 27	10 27	11 45	13 04	14 26
52	01 33	02 51	03 39	10 29	11 44	13 02	14 21
50	02 00	03 06	03 50	10 30	11 44	13 00	14 17
45	02 46	03 35	04 13	10 34	11 44	12 55	14 08
N 40	03 16	03 58	04 31	10 37	11 43	12 51	14 01
35	03 39	04 16	04 46	10 39	11 43	12 48	13 54
30	03 58	04 31	04 59	10 42	11 42	12 45	13 49
20	04 27	04 56	05 20	10 45	11 42	12 40	13 39
N 10	04 49	05 16	05 39	10 49	11 41	12 35	13 31
0	05 08	05 34	05 57	10 52	11 41	12 31	13 23
S 10	05 25	05 51	06 14	10 55	11 40	12 27	13 16
20	05 41	06 09	06 33	10 59	11 40	12 23	13 07
30	05 58	06 28	06 54	11 03	11 40	12 18	12 58
35	06 06	06 38	07 06	11 05	11 39	12 15	12 53
40	06 16	06 50	07 20	11 07	11 39	12 12	12 47
45	06 26	07 03	07 37	11 10	11 39	12 08	12 40
S 50	06 38	07 19	07 58	11 14	11 38	12 04	12 32
52	06 43	07 27	08 08	11 15	11 38	12 02	12 28
54	06 49	07 35	08 19	11 17	11 38	12 00	12 24
56	06 55	07 44	08 31	11 19	11 38	11 58	12 19
58	07 02	07 54	08 46	11 21	11 38	11 55	12 14
S 60	07 09	08 06	09 03	11 24	11 37	11 52	12 09

Lat.	Sunset h m	Twilight Civil h m	Twilight Naut. h m	Moonset 15 h m	Moonset 16 h m	Moonset 17 h m	Moonset 18 h m
N 72	▭	▭	▭	23 38	23 25	23 12	22 54
N 70	▭	▭	▭	23 35	23 29	23 23	23 16
68	▭	▭	▭	23 34	23 33	23 32	23 32
66	▭	▭	▭	23 32	23 36	23 40	23 46
64	22 29	////	////	23 31	23 38	23 47	23 57
62	21 52	////	////	23 29	23 40	23 52	24 07
60	21 26	23 10	////	23 28	23 42	23 57	24 15
N 58	21 05	22 21	////	23 27	23 44	24 02	00 02
56	20 49	21 51	////	23 26	23 45	24 06	00 06
54	20 34	21 29	23 15	23 26	23 47	24 09	00 09
52	20 22	21 11	22 29	23 25	23 48	24 13	00 13
50	20 11	20 56	22 01	23 24	23 49	24 15	00 15
45	19 49	20 26	21 16	23 23	23 52	24 22	00 22
N 40	19 31	20 04	20 45	23 22	23 54	24 27	00 27
35	19 16	19 45	20 22	23 21	23 55	24 32	00 32
30	19 03	19 30	20 04	23 20	23 57	24 36	00 36
20	18 41	19 05	19 35	23 18	24 00	00 00	00 43
N 10	18 22	18 45	19 12	23 17	24 02	00 02	00 50
0	18 04	18 27	18 53	23 15	24 05	00 05	00 55
S 10	17 47	18 10	18 36	23 14	24 07	00 07	01 01
20	17 28	17 52	18 20	23 12	24 09	00 09	01 08
30	17 07	17 34	18 03	23 10	24 12	00 12	01 15
35	16 55	17 23	17 55	23 09	24 13	00 13	01 19
40	16 41	17 11	17 45	23 08	24 15	00 15	01 24
45	16 24	16 58	17 35	23 07	24 17	00 17	01 29
S 50	16 03	16 42	17 23	23 05	24 20	00 20	01 36
52	15 53	16 34	17 18	23 04	24 21	00 21	01 39
54	15 42	16 26	17 12	23 04	24 22	00 22	01 42
56	15 30	16 17	17 06	23 03	24 23	00 23	01 46
58	15 15	16 07	16 59	23 02	24 25	00 25	01 50
S 60	14 58	15 55	16 52	23 00	24 27	00 27	01 55

Day	SUN Eqn. of Time 00ʰ m s	SUN Eqn. of Time 12ʰ m s	SUN Mer. Pass. h m	MOON Mer. Pass. Upper h m	MOON Mer. Pass. Lower h m	MOON Age d	MOON Phase
15	00 17	00 24	12 00	17 04	04 39	06	◐
16	00 30	00 37	12 01	17 53	05 28	07	
17	00 43	00 49	12 01	18 43	06 18	08	

Figure 2007. Right hand daily page of the *Nautical Almanac* for June 16, 1994.

factor; it provides a correction to declination. Therefore, the trend in declination values, not the trend in *d* values, controls the sign of the *d* correction. Combine the tabulated declination and the *d* correction factor to determine the true declination. In this case, the moon's true declination is S 00° 13.8'

Having obtained the moon's GHA and declination, calculate LHA and determine the assumed latitude. Enter the *Sight Reduction Table* with the LHA, assumed latitude, and calculated declination. Calculate the intercept and azimuth in the same manner used for star and sun sights.

2008. Reducing A Planet Sight

There are four navigational planets: Venus, Mars, Jupiter, and Saturn. Reducing a planet sight is similar to reducing a sun or star sight, but there are a few important differences. This section will cover the procedure for determining h_o, the GHA and the declination for a planet sight.

On July 27, 1995, at 09-45-20 GMT, you take a sight of Mars. H_s is 33° 20.5'. The height of eye is 25 feet, and the index correction is +0.2'. Determine h_o, GHA, and declination. See Figure 2008.

Body	Mars
Index Correction	+0.2'
Dip Correction (25 feet)	-4.9'
Sum	-4.7'
h_s	33° 20.5'
h_a	33° 15.8'
Altitude Correction	-1.5'
Additional Correction	Not applicable
Horizontal Parallax	Not applicable
Additional Correction for Mars	+0.1'
Correction to h_a	-1.4'
h_o	33° 14.4'

The table above demonstrates the similarity between reducing planet sights and reducing sights of the sun and stars. Calculate and apply the index and dip corrections exactly as for any other sight. Take the resulting apparent altitude and enter the altitude correction table for the stars and planets on the inside front cover of the *Nautical Almanac*.

In this case, the altitude correction for 33° 15.8' results in a correction of -1.5'. The additional correction is not applicable because the sight was taken at standard temperature and pressure; the horizontal parallax correction is not applicable to a planet sight. All that remains is the correction specific to Mars or Venus. The altitude correction table in the *Nautical Almanac* also contains this correction. Its magnitude is a function of the body sighted (Mars or Venus), the time of year, and the body's apparent altitude. Entering this table with the data for this problem yields a correction of +0.1'. Applying these corrections to h_a results in an h_o of 33° 14.4'.

Tabulated GHA / *v*	256°10.6' / 1.1
GHA Increment	11° 20.0'
v correction	+0.8'
GHA	267°31.4'

The only difference between determining the sun's GHA and a planet's GHA lies in applying the *v* correction. Calculate this correction from the *v* or *d* correction section of the Increments and Correction table in the *Nautical Almanac*.

Find the *v* factor at the bottom of the planets' GHA columns on the daily pages of the *Nautical Almanac*. For Mars on July 27, 1995, the *v* factor is 1.1. If no algebraic sign precedes the *v* factor, add the resulting correction to the tabulated GHA. Subtract the resulting correction only when a negative sign precedes the *v* factor. Entering the *v* or *d* correction table corresponding to 45 minutes yields a correction of 0.8'. Remember, because no sign preceded the *v* factor on the daily pages, add this correction to the tabulated GHA. The final GHA is 267°31.4'.

Tabulated Declination / *d*	S 01° 06.1' / 0.6
d Correction	+0.5'
True Declination	S 01° 06.6'

Read the tabulated declination directly from the daily pages of the *Nautical Almanac*. The *d* correction factor is listed at the bottom of the planet column; in this case, the factor is 0.6. Note the trend in the declination values for the planet; if they are increasing during the day, the correction factor is positive. If the planet's declination is decreasing during the day, the correction factor is negative. Next, enter the *v* or *d* correction table corresponding to 45 minutes and extract the correction for a *d* factor of 0.6. The correction in this case is +0.5'.

From this point, reducing a planet sight is exactly the same as reducing a sun sight.

MERIDIAN PASSAGE

This section covers determining both latitude and longitude at the meridian passage of the sun, or Local Apparent Noon (LAN). Determining a vessel's latitude at LAN requires calculating the sun's zenith distance and declination and combining them according to the rules discussed below.

Latitude at LAN is a special case of the navigational triangle where the sun is on the observer's meridian and the triangle becomes a straight north/south line. No "solution" is necessary, except to combine the sun's zenith distance and its declination according to the rules discussed below.

Longitude at LAN is a function of the time elapsed since the sun passed the Greenwich meridian. The navigator must determine the time of LAN and calculate the GHA of the sun at that time. The following examples demonstrates these processes.

1995 JULY 27, 28, 29 (THURS., FRI., SAT.)

UT (GMT) d h	ARIES G.H.A. ° ′	VENUS −3.9 G.H.A. ° ′	VENUS Dec. ° ′	MARS +1.3 G.H.A. ° ′	MARS Dec. ° ′	JUPITER −2.3 G.H.A. ° ′	JUPITER Dec. ° ′	SATURN +1.0 G.H.A. ° ′	SATURN Dec. ° ′
27 00	304 12.4	185 23.5	N21 31.7	121 00.7	S 1 00.4	60 23.8	S20 36.7	308 27.9	S 4 15.6
01	319 14.9	200 22.7	31.2	136 01.8	01.0	75 26.3	36.7	323 30.4	15.7
02	334 17.3	215 21.9	30.7	151 02.9	01.7	90 28.8	36.7	338 33.0	15.7
03	349 19.8	230 21.1	· · 30.2	166 04.0	· · 02.3	105 31.3	· · 36.7	353 35.5	· · 15.8
04	4 22.3	245 20.4	29.7	181 05.1	02.9	120 33.8	36.7	8 38.1	15.8
05	19 24.7	260 19.6	29.2	196 06.2	03.6	135 36.4	36.7	23 40.6	15.8
06	34 27.2	275 18.8	N21 28.7	211 07.3	S 1 04.2	150 38.9	S20 36.7	38 43.1	S 4 15.9
07	49 29.7	290 18.0	28.2	226 08.4	04.8	165 41.4	36.7	53 45.7	15.9
T 08	64 32.1	305 17.2	27.7	241 09.5	05.4	180 43.9	36.7	68 48.2	16.0
H 09	79 34.6	320 16.4	· · 27.1	256 10.6	· · 06.1	195 46.4	· · 36.7	83 50.7	· · 16.0
U 10	94 37.1	335 15.6	26.6	271 11.7	06.7	210 48.9	36.7	98 53.3	16.1
R 11	109 39.5	350 14.8	26.1	286 12.8	07.3	225 51.5	36.7	113 55.8	16.1
S 12	124 42.0	5 14.0	N21 25.6	301 13.9	S 1 08.0	240 54.0	S20 36.7	128 58.4	S 4 16.1
D 13	139 44.4	20 13.2	25.1	316 15.0	08.6	255 56.5	36.7	144 00.9	16.2
A 14	154 46.9	35 12.4	24.5	331 16.1	09.2	270 59.0	36.7	159 03.4	16.2
Y 15	169 49.4	50 11.6	· · 24.0	346 17.2	· · 09.8	286 01.5	· · 36.7	174 06.0	· · 16.3
16	184 51.8	65 10.8	23.5	1 18.3	10.5	301 04.0	36.7	189 08.5	16.3
17	199 54.3	80 10.0	23.0	16 19.4	11.1	316 06.6	36.7	204 11.1	16.4
18	214 56.8	95 09.2	N21 22.5	31 20.6	S 1 11.7	331 09.1	S20 36.7	219 13.6	S 4 16.4
19	229 59.2	110 08.4	21.9	46 21.7	12.4	346 11.6	36.7	234 16.1	16.4
20	245 01.7	125 07.7	21.4	61 22.8	13.0	1 14.1	36.7	249 18.7	16.5
21	260 04.2	140 06.9	· · 20.9	76 23.9	· · 13.6	16 16.6	· · 36.7	264 21.2	· · 16.5
22	275 06.6	155 06.1	20.3	91 25.0	14.2	31 19.1	36.7	279 23.8	16.6
23	290 09.1	170 05.3	19.8	106 26.1	14.9	46 21.6	36.7	294 26.3	16.6
28 00	305 11.6	185 04.5	N21 19.3	121 27.2	S 1 15.5	61 24.1	S20 36.7	309 28.8	S 4 16.7
01	320 14.0	200 03.7	18.8	136 28.3	16.1	76 26.7	36.7	324 31.4	16.7
02	335 16.5	215 02.9	18.2	151 29.4	16.8	91 29.2	36.7	339 33.9	16.8
03	350 18.9	230 02.1	· · 17.7	166 30.5	· · 17.4	106 31.7	· · 36.7	354 36.5	· · 16.8
04	5 21.4	245 01.3	17.1	181 31.6	18.0	121 34.2	36.7	9 39.0	16.8
05	20 23.9	260 00.6	16.6	196 32.7	18.6	136 36.7	36.7	24 41.5	16.9
06	35 26.3	274 59.8	N21 16.1	211 33.8	S 1 19.3	151 39.2	S20 36.7	39 44.1	S 4 16.9
07	50 28.8	289 59.0	15.5	226 34.9	19.9	166 41.7	36.7	54 46.6	17.0
08	65 31.3	304 58.2	15.0	241 36.0	20.5	181 44.2	36.7	69 49.2	17.0
F 09	80 33.7	319 57.4	· · 14.5	256 37.1	· · 21.2	196 46.7	· · 36.7	84 51.7	· · 17.1
R 10	95 36.2	334 56.6	13.9	271 38.2	21.8	211 49.2	36.7	99 54.3	17.1
I 11	110 38.7	349 55.8	13.4	286 39.3	22.4	226 51.8	36.7	114 56.8	17.2
D 12	125 41.1	4 55.1	N21 12.8	301 40.4	S 1 23.0	241 54.3	S20 36.7	129 59.3	S 4 17.2
A 13	140 43.6	19 54.3	12.3	316 41.5	23.7	256 56.8	36.7	145 01.9	17.2
Y 14	155 46.1	34 53.5	11.7	331 42.6	24.3	271 59.3	36.7	160 04.4	17.3
15	170 48.5	49 52.7	· · 11.2	346 43.6	· · 24.9	287 01.8	· · 36.7	175 07.0	· · 17.3
16	185 51.0	64 51.9	10.6	1 44.7	25.6	302 04.3	36.7	190 09.5	17.4
17	200 53.4	79 51.1	10.1	16 45.8	26.2	317 06.8	36.7	205 12.1	17.4
18	215 55.9	94 50.4	N21 09.5	31 46.9	S 1 26.8	332 09.3	S20 36.7	220 14.6	S 4 17.5
19	230 58.4	109 49.6	09.0	46 48.0	27.5	347 11.8	36.7	235 17.1	17.5
20	246 00.8	124 48.8	08.4	61 49.1	28.1	2 14.3	36.7	250 19.7	17.6
21	261 03.3	139 48.0	· · 07.9	76 50.2	· · 28.7	17 16.8	· · 36.7	265 22.2	· · 17.6
22	276 05.8	154 47.2	07.3	91 51.3	29.3	32 19.3	36.7	280 24.8	17.6
23	291 08.2	169 46.4	06.8	106 52.4	30.0	47 21.8	36.7	295 27.3	17.7
29 00	306 10.7	184 45.7	N21 06.2	121 53.5	S 1 30.6	62 24.3	S20 36.8	310 29.9	S 4 17.7
01	321 13.2	199 44.9	05.7	136 54.6	31.2	77 26.8	36.8	325 32.4	17.8
02	336 15.6	214 44.1	05.1	151 55.7	31.9	92 29.3	36.8	340 34.9	17.8
03	351 18.1	229 43.3	· · 04.5	166 56.8	· · 32.5	107 31.8	· · 36.8	355 37.5	· · 17.9
04	6 20.5	244 42.5	04.0	181 57.9	33.1	122 34.3	36.8	10 40.0	17.9
05	21 23.0	259 41.8	03.4	196 59.0	33.8	137 36.8	36.8	25 42.6	18.0
06	36 25.5	274 41.0	N21 02.9	212 00.1	S 1 34.4	152 39.3	S20 36.8	40 45.1	S 4 18.0
07	51 27.9	289 40.2	02.3	227 01.2	35.0	167 41.8	36.8	55 47.7	18.1
S 08	66 30.4	304 39.4	01.7	242 02.3	35.6	182 44.4	36.8	70 50.2	18.1
A 09	81 32.9	319 38.7	· · 01.2	257 03.4	· · 36.3	197 46.9	· · 36.8	85 52.8	· · 18.1
T 10	96 35.3	334 37.9	00.6	272 04.5	36.9	212 49.4	36.8	100 55.3	18.2
U 11	111 37.8	349 37.1	21 00.0	287 05.6	37.5	227 51.9	36.8	115 57.9	18.2
R 12	126 40.3	4 36.3	N20 59.4	302 06.7	S 1 38.2	242 54.4	S20 36.8	131 00.4	S 4 18.3
D 13	141 42.7	19 35.6	58.9	317 07.8	38.8	257 56.9	36.8	146 02.9	18.3
A 14	156 45.2	34 34.8	58.3	332 08.9	39.4	272 59.4	36.8	161 05.5	18.4
Y 15	171 47.7	49 34.0	· · 57.7	347 10.0	· · 40.1	288 01.8	· · 36.8	176 08.0	· · 18.4
16	186 50.1	64 33.2	57.2	2 11.0	40.7	303 04.3	36.8	191 10.6	18.5
17	201 52.6	79 32.5	56.6	17 12.1	41.3	318 06.8	36.8	206 13.1	18.5
18	216 55.0	94 31.7	N20 56.0	32 13.2	S 1 42.0	333 09.3	S20 36.8	221 15.7	S 4 18.6
19	231 57.5	109 30.9	55.4	47 14.3	42.6	348 11.8	36.8	236 18.2	18.6
20	247 00.0	124 30.1	54.9	62 15.4	43.2	3 14.3	36.8	251 20.8	18.6
21	262 02.4	139 29.4	· · 54.3	77 16.5	· · 43.8	18 16.8	· · 36.8	266 23.3	· · 18.7
22	277 04.9	154 28.6	53.7	92 17.6	44.5	33 19.3	36.8	281 25.9	18.7
23	292 07.4	169 27.8	53.1	107 18.7	45.1	48 21.8	36.8	296 28.4	18.8
Mer. Pass.	h m 3 38.6	v −0.8	d 0.5	v 1.1	d 0.6	v 2.5	d 0.0	v 2.5	d 0.0

STARS

Name	S.H.A. ° ′	Dec. ° ′
Acamar	315 28.7	S40 19.1
Achernar	335 36.7	S57 15.2
Acrux	173 24.6	S63 04.8
Adhara	255 23.4	S28 58.0
Aldebaran	291 05.0	N16 29.9
Alioth	166 32.7	N55 59.3
Alkaid	153 09.6	N49 20.4
Al Na'ir	28 00.2	S46 58.7
Alnilam	276 00.3	S 1 12.3
Alphard	218 09.6	S 8 38.4
Alphecca	126 22.3	N26 44.0
Alpheratz	357 57.2	N29 04.0
Altair	62 21.0	N 8 51.6
Ankaa	353 28.8	S42 19.5
Antares	112 42.5	S26 25.3
Arcturus	146 08.0	N19 12.5
Atria	107 56.1	S69 01.3
Avior	234 24.1	S59 29.8
Bellatrix	278 46.7	N 6 20.7
Betelgeuse	271 16.1	N 7 24.3
Canopus	264 02.6	S52 41.6
Capella	280 54.7	N45 59.4
Deneb	49 40.1	N45 16.0
Denebola	182 47.6	N14 35.9
Diphda	349 09.2	S18 00.4
Dubhe	194 08.7	N61 46.6
Elnath	278 29.9	N28 36.1
Eltanin	90 51.9	N51 29.7
Enif	34 00.0	N 9 51.5
Fomalhaut	15 38.5	S29 38.5
Gacrux	172 16.1	S57 05.6
Gienah	176 06.3	S17 31.1
Hadar	149 07.0	S60 21.3
Hamal	328 15.9	N23 26.4
Kaus Aust.	84 01.3	S34 23.1
Kochab	137 19.4	N74 10.8
Markab	13 51.5	N15 11.0
Menkar	314 29.2	N 4 04.4
Menkent	148 23.4	S36 21.0
Miaplacidus	221 43.3	S69 42.1
Mirfak	308 59.8	N49 50.5
Nunki	76 14.6	S26 18.0
Peacock	53 39.8	S56 44.8
Pollux	243 44.5	N28 02.1
Procyon	245 14.1	N 5 14.1
Rasalhague	96 18.7	N12 34.0
Regulus	207 58.1	N11 59.3
Rigel	281 25.2	S 8 12.4
Rigil Kent.	140 10.0	S60 49.2
Sabik	102 27.7	S15 43.1
Schedar	349 55.6	N56 30.6
Shaula	96 39.8	S37 06.0
Sirius	258 45.9	S16 42.6
Spica	158 45.5	S11 08.3
Suhail	223 02.7	S43 25.0
Vega	80 47.7	N38 47.1
Zuben'ubi	137 20.3	S16 01.4

	S.H.A. ° ′	Mer. Pass. h m
Venus	239 52.9	11 40
Mars	176 15.6	15 53
Jupiter	116 12.6	19 51
Saturn	4 17.3	3 22

Figure 2008. Left hand daily page of the *Nautical Almanac* for July 27, 1995.

2009. Latitude At Meridian Passage

At 1056 ZT, May 16, 1995, a vessel's DR position is L 40° 04.3'N and λ 157° 18.5' W. The ship is on course 200°T at a speed of ten knots. (1) Calculate the first and second estimates of Local Apparent Noon. (2) The navigator actually observes LAN at 12-23-30 zone time. The sextant altitude at LAN is 69° 16.0'. The index correction is +2.1' and the height of eye is 45 feet. Determine the vessel's latitude.

Date	16 May 1995
DR Latitude (1156 ZT)	39° 55.0' N
DR Longitude (1156 ZT)	157° 23.0' W
Central Meridian	150° W
d Longitude (arc)	7° 23' W
d Longitude (time)	+29 min. 32 sec
Meridian Passage (LMT)	1156
ZT (first estimate)	12-25-32
DR Longitude (12-25-32)	157° 25.2'
d Longitude (arc)	7° 25.2'
d Longitude (time)	+29 min. 41 sec
Meridian Passage	1156
ZT (second estimate)	12-25-41
ZT (actual transit)	12-23-30 local
Zone Description	+10
GMT	22-23-30
Date (GMT)	16 May 1995
Tabulated Declination / *d*	N 19° 09.0' / +0.6
d correction	+0.2'
True Declination	N 19° 09.2'
Index Correction	+2.1'
Dip (48 ft)	-6.7'
Sum	-4.6'
h_s (at LAN)	69° 16.0'
h_a	69° 11.4'
Altitude Correction	+15.6'
89° 60'	89° 60.0'
h_o	69° 27.0'
Zenith Distance	N 20° 33.0'
True Declination	N 19° 09.2'
Latitude	39° 42.2'

First, determine the time of meridian passage from the daily pages of the *Nautical Almanac*. In this case, the meridian passage for May 16, 1995, is 1156. That is, the sun crosses the central meridian of the time zone at 1156 ZT and the observer's local meridian at 1156 local time. Next, determine the vessel's DR longitude for the time of meridian passage. In this case, the vessel's 1156 DR longitude is 157° 23.0' W. Determine the time zone in which this DR longitude falls and record the longitude of that time zone's central meridian. In this case, the central meridian is 150° W. Enter the Conversion of Arc to Time table in the *Nautical Almanac* with the difference between the DR longitude and the central meridian longitude. The conversion for 7° of arc is 28^m of time, and the conversion for 23' of arc is 1^m32^s of time. Sum these two times. If the DR position is west of the central meridian (as it is in this case), add this time to the time of tabulated meridian passage. If the longitude difference is to the east of the central meridian, subtract this time from the tabulated meridian passage. In this case, the DR position is west of the central meridian. Therefore, add 29 minutes and 32 seconds to 1156, the tabulated time of meridian passage. The estimated time of LAN is 12-25-32 ZT.

This first estimate for LAN does not take into account the vessel's movement. To calculate the *second estimate* of LAN, first determine the DR longitude for the time of first estimate of LAN (12-25-32 ZT). In this case, that longitude would be 157° 25.2' W. Then, calculate the difference between the longitude of the 12-25-32 DR position and the central meridian longitude. This would be 7° 25.2'. Again, enter the arc to time conversion table and calculate the time difference corresponding to this longitude difference. The correction for 7° of arc is 28' of time, and the correction for 25.2' of arc is 1'41" of time. Finally, apply this time correction to the original tabulated time of meridian passage (1156 ZT). The resulting time, 12-25-41 ZT, is the *second estimate* of LAN.

Solving for latitude requires that the navigator calculate two quantities: the sun's declination and the sun's zenith distance. First, calculate the sun's true declination at LAN. The problem states that LAN is 12-28-30. (Determining the exact time of LAN is covered in section 2010.) Enter the time of observed LAN and add the correct zone description to determine GMT. Determine the sun's declination in the same manner as in the sight reduction problem in section 2006. In this case, the tabulated declination was N 19° 19.1', and the d correction +0.2'. The true declination, therefore, is N 19° 19.3'.

Next, calculate zenith distance. Recall from Navigational Astronomy that zenith distance is simply 90° - observed altitude. Therefore, correct h_s to obtain h_a; then correct h_a to obtain h_o. Then, subtract h_o from 90° to determine the zenith distance. Name the zenith distance North or South depending on the relative position of the observer and the sun's declination. If the observer is to the north of the sun's declination, name the zenith distance north. Conversely, if the observer is to the south of the sun's declination, name the zenith distance south. In this case, the DR latitude is N 39° 55.0' and the sun's declination is N 19° 19.3'. The observer is to the north of the sun's declination; therefore, name the zenith distance north. Next, compare the names of the zenith distance and the declination. If their names are the same (i.e., both are north or both are south), add the two values together to obtain the latitude. This was the case in this problem. Both the sun's declination and zenith distance were north; therefore, the observer's latitude is the sum of the two.

If the name of the body's zenith distance is contrary to the name of the sun's declination, then subtract the smaller of the two quantities from the larger, carrying for the name of the difference the name of the larger of the two quantities. The result is the observer's latitude. The following examples illustrate this process.

Zenith Distance	N 25°	Zenith Distance	S 50°
True Declination	S 15°	True Declination	N10°
Latitude	N 10°	Latitude	S 40°

2010. Longitude At Meridian Passage

Determining a vessel's longitude at LAN is straightforward. In the western hemisphere, the sun's GHA at LAN equals the vessel's longitude. In the eastern hemisphere, subtract the sun's GHA from 360° to determine longitude. The difficult part lies in determining the precise moment of meridian passage.

Determining the time of meridian passage presents a problem because the sun appears to hang for a finite time at its local maximum altitude. Therefore, noting the time of maximum sextant altitude is not sufficient for determining the precise time of LAN. Two methods are available to obtain LAN with a precision sufficient for determining longitude: (1) the graphical method and (2) the calculation method. The graphical method is discussed first below.

See Figure 2010. Approximately 30 minutes before the estimated time of LAN, measure and record sextant altitudes and their corresponding times. Continue taking sights for about 30 minutes after the sun has descended from the maximum recorded altitude. Increase the sighting frequency near the predicted meridian passage. One sight every 20-30 seconds should yield good results near meridian passage; less frequent sights are required before and after.

Plot the resulting data on a graph of sextant altitude versus time. Fair a curve through the plotted data. Next, draw a series of horizontal lines across the curve formed by the data points. These lines will intersect the faired curve at two different points. The x coordinates of the points where these lines intersect the faired curve represent the two different times when the sun's altitude was equal (one time when the sun was ascending; the other time when the sun was descending). Draw three such lines, and ensure the lines have sufficient vertical separation. For each line, average the two times where it intersects the faired curve. Finally, average the three resulting times to obtain a final value for the time of LAN. From the *Nautical Almanac*, determine the sun's GHA at that time; this is your longitude in the western hemisphere. In the eastern hemisphere, subtract the sun's GHA from 360° to determine longitude.

The second method of determining LAN is similar to the first. Estimate the time of LAN as discussed above, Measure and record the sun's altitude as the sun approaches its maximum altitude. As the sun begins to descend, set the sextant to correspond to the altitude recorded just before the sun's reaching its maximum altitude. Note the time when the sun is again at that altitude. Average the two times. Repeat this procedure with two other altitudes recorded before LAN, each time presetting the sextant to those altitudes and recording the corresponding times that the sun, now on its descent, passes through those altitudes. Average these corresponding times. Take a final average among the three averaged times; the result will be the time of meridian passage. Determine the vessel's longitude by determining the sun's GHA at the exact time of LAN.

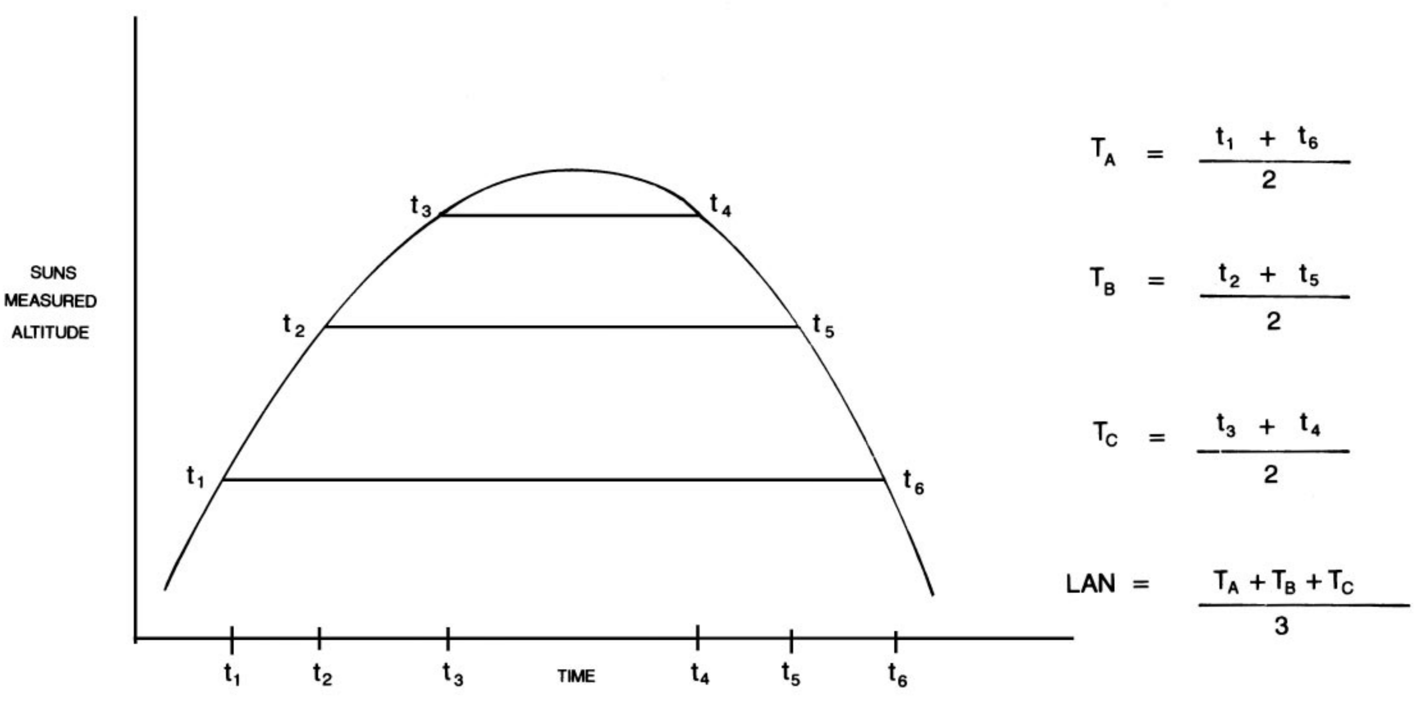

Figure 2010. Time of LAN.

LATITUDE BY POLARIS

2011. Latitude By Polaris

Since Polaris is always within about 1° of the North Pole, the altitude of Polaris, with a few minor corrections, equals the latitude of the observer. This relationship makes Polaris an extremely important navigational star in the northern hemisphere.

The corrections are necessary because Polaris orbits in a small circle around the pole. When Polaris is at the exact same altitude as the pole, the correction is zero. At two points in its orbit it is in a direct line with the observer and the pole, either nearer than or beyond the pole. At these points the corrections are maximum. The following example illustrates converting a Polaris sight to latitude.

At 23-18-56 GMT, on April 21, 1994, at DR λ=37° 14.0' W, L = 50° 23.8' N, the observed altitude of Polaris (h_o) is 49° 31.6'. Find the vessel's latitude.

To solve this problem, use the equation:

$$\text{Latitude} = h_o - 1° + A_0 + A_1 + A_2$$

where h_o is the sextant altitude (h_s) corrected as in any other star sight; 1° is a constant; and A_0, A_1, and A_2 are correction factors from the Polaris tables found in the *Nautical Almanac*. These three correction factors are always positive. One needs the following information to enter the tables: LHA of Aries, DR latitude, and the month of the year. Therefore:

Tabulated GHA ♈ (2300 hrs.)	194° 32.7'
Increment (18-56)	4° 44.8'
GHA ♈	199° 17.5'
DR Longitude (-W +E)	37° 14.0'
LHA ♈	162° 03.5'
A_0 (162° 03.5')	+1° 25.4'
A_1 (L = 50°N)	+0.6'
A_2 (April)	+0.9'
Sum	1° 26.9'
Constant	-1° 00.0'
Observed Altitude	49° 31.6'
Total Correction	+26.9'
Latitude	N 49° 58.5'

Enter the Polaris table with the calculated LHA of Aries (162° 03.5'). See Figure 2011. The first correction, A_0, is a function solely of the LHA of Aries. Enter the table column indicating the proper range of LHA of Aries; in this case, enter the 160°-169° column. The numbers on the left hand side of the A_0 correction table represent the whole degrees of LHA ♈ ; interpolate to determine the proper A_0 correction. In this case, LHA ♈ was 162° 03.5'. The A_0 correction for LHA = 162° is 1° 25.4' and the A_0 correction for LHA = 163° is 1° 26.1'. The A_0 correction for 162° 03.5' is 1° 25.4'.

To calculate the A_1 correction, enter the A_1 correction table with the DR latitude, being careful to stay in the 160°-169° LHA column. There is no need to interpolate here; simply choose the latitude that is closest to the vessel's DR latitude. In this case, L is 50°N. The A_1 correction corresponding to an LHA range of 160°-169° and a latitude of 50°N is + 0.6'.

Finally, to calculate the A_2 correction factor, stay in the 160°-169° LHA ♈ column and enter the A_2 correction table. Follow the column down to the month of the year; in this case, it is April. The correction for April is + 0.9'.

Sum the corrections, remembering that all three are always positive. Subtract 1° from the sum to determine the total correction; then apply the resulting value to the observed altitude of Polaris. This is the vessel's latitude.

POLARIS (POLE STAR) TABLES, 1994
FOR DETERMINING LATITUDE FROM SEXTANT ALTITUDE AND FOR AZIMUTH

LHA ARIES	120° – 129°	130° – 139°	140° – 149°	150° – 159°	160° – 169°	170° – 179°	180° – 189°	190° – 199°	200° – 209°	210° – 219°	220° – 229°	230° – 239°
	a_0	a_0	a_0	a_0	a_0	a_0	a_0	a_0	a_0	a_0	a_0	a_0
°	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′
0	0 53·9	1 01·8	1 09·7	1 17·2	1 24·1	1 30·3	1 35·5	1 39·6	1 42·5	1 44·1	1 44·3	1 43·2
1	54·7	02·6	10·4	17·9	24·8	30·9	36·0	40·0	42·7	44·2	44·3	43·0
2	55·5	03·4	11·2	18·6	25·4	31·4	36·4	40·3	42·9	44·3	44·2	42·8
3	56·3	04·2	12·0	19·3	26·1	32·0	36·9	40·6	43·1	44·3	44·1	42·6
4	57·1	05·0	12·7	20·0	26·7	32·5	37·3	40·9	43·3	44·4	44·0	42·4
5	0 57·8	1 05·8	1 13·5	1 20·7	1 27·3	1 33·0	1 37·7	1 41·2	1 43·5	1 44·4	1 43·9	1 42·1
6	58·6	06·6	14·2	21·4	27·9	33·5	38·1	41·5	43·6	44·4	43·8	41·9
7	0 59·4	07·3	15·0	22·1	28·5	34·1	38·5	41·8	43·8	44·4	43·7	41·6
8	1 00·2	08·1	15·7	22·8	29·1	34·6	38·9	42·0	43·9	44·4	43·5	41·3
9	01·0	08·9	16·4	23·5	29·7	35·0	39·3	42·3	44·0	44·4	43·4	41·0
10	1 01·8	1 09·7	1 17·2	1 24·1	1 30·3	1 35·5	1 39·6	1 42·5	1 44·1	1 44·3	1 43·2	1 40·7
Lat.	a_1	a_1	a_1	a_1	a_1	a_1	a_1	a_1	a_1	a_1	a_1	a_1
°	′	′	′	′	′	′	′	′	′	′	′	′
0	0·2	0·2	0·3	0·3	0·4	0·4	0·5	0·6	0·6	0·6	0·6	0·6
10	·3	·3	·3	·4	·4	·5	·5	·6	·6	·6	·6	·6
20	·3	·4	·4	·4	·4	·5	·5	·6	·6	·6	·6	·6
30	·4	·4	·4	·5	·5	·5	·5	·6	·6	·6	·6	·6
40	0·5	0·5	0·5	0·5	0·5	0·6	0·6	0·6	0·6	0·6	0·6	0·6
45	·5	·5	·5	·6	·6	·6	·6	·6	·6	·6	·6	·6
50	·6	·6	·6	·6	·6	·6	·6	·6	·6	·6	·6	·6
55	·7	·7	·7	·7	·6	·6	·6	·6	·6	·6	·6	·6
60	·8	·8	·7	·7	·7	·7	·6	·6	·6	·6	·6	·6
62	0·8	0·8	0·8	0·8	0·7	0·7	0·7	0·6	0·6	0·6	0·6	0·6
64	·9	·9	·8	·8	·8	·7	·7	·6	·6	·6	·6	·6
66	0·9	0·9	·9	·8	·8	·7	·7	·6	·6	·6	·6	·6
68	1·0	1·0	0·9	0·9	0·8	0·8	0·7	0·7	0·6	0·6	0·6	0·6
Month	a_2	a_2	a_2	a_2	a_2	a_2	a_2	a_2	a_2	a_2	a_2	a_2
	′	′	′	′	′	′	′	′	′	′	′	′
Jan.	0·6	0·6	0·6	0·5	0·5	0·5	0·4	0·4	0·4	0·4	0·4	0·4
Feb.	·8	·8	·7	·7	·6	·6	·5	·5	·4	·4	·4	·3
Mar.	0·9	0·9	0·9	·8	·8	·7	·6	·6	·5	·5	·4	·4
Apr.	1·0	1·0	1·0	0·9	0·9	0·8	0·8	0·7	0·7	0·6	0·5	0·5
May	0·9	1·0	1·0	1·0	1·0	0·9	·9	·9	·8	·8	·7	·6
June	·8	0·9	0·9	0·9	0·9	1·0	·9	·9	·9	·9	·8	·8
July	0·7	0·7	0·8	0·8	0·8	0·9	0·9	0·9	0·9	0·9	0·9	0·9
Aug.	·5	·5	·6	·6	·7	·7	·8	·8	·8	·9	·9	·9
Sept.	·3	·4	·4	·5	·5	·6	·6	·7	·7	·7	·8	·8
Oct.	0·3	0·3	0·3	0·3	0·3	0·4	0·4	0·5	0·5	0·6	0·6	0·7
Nov.	·2	·2	·2	·2	·2	·2	·2	·3	·3	·4	·5	·5
Dec.	0·3	0·2	0·2	0·2	0·1	0·1	0·1	0·2	0·2	0·2	0·3	0·4
Lat.	AZIMUTH											
°	°	°	°	°	°	°	°	°	°	°	°	°
0	359·2	359·2	359·3	359·3	359·4	359·5	359·6	359·7	359·8	0·0	0·1	0·2
20	359·2	359·2	359·2	359·3	359·4	359·5	359·6	359·7	359·8	0·0	0·1	0·3
40	359·0	359·0	359·1	359·1	359·2	359·3	359·5	359·6	359·8	0·0	0·1	0·3
50	358·8	358·8	358·9	359·0	359·1	359·2	359·4	359·6	359·8	0·0	0·2	0·4
55	358·7	358·7	358·7	358·8	359·0	359·1	359·3	359·5	359·7	0·0	0·2	0·4
60	358·5	358·5	358·6	358·7	358·8	359·0	359·2	359·5	359·7	0·0	0·2	0·5
65	358·2	358·2	358·3	358·4	358·6	358·8	359·1	359·4	359·6	359·9	0·3	0·6

Figure 2011. Excerpt from the Polaris Tables.