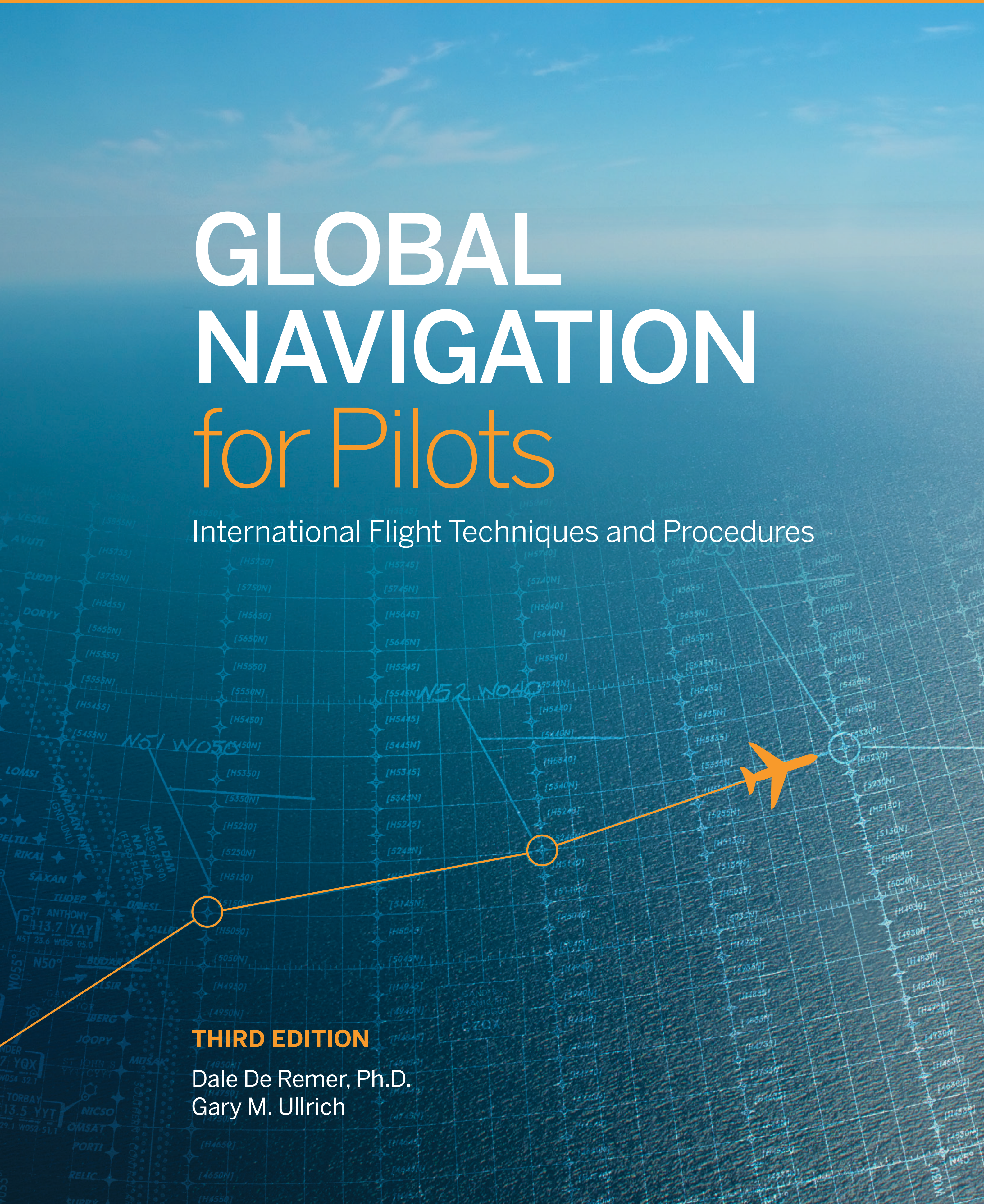

GLOBAL NAVIGATION for Pilots

International Flight Techniques and Procedures

THIRD EDITION

Dale De Remer, Ph.D.
Gary M. Ullrich

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Third Edition
by Dale De Remer, Ph.D. / Gary M. Ullrich

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Earth Reference Systems

LOCATION

"We are not lost…we're here…it's where we're going that's lost!"

Most pilots have experienced the undesirable feeling of not knowing exactly where they are and also the good feeling of re-establishing their position. Knowing and expressing where the aircraft is at any given time is done in reference to a point on the earth's surface. This point may be either real (an airport, a town, a navaid) or imaginary (intersection of a line of latitude and longitude, or VOR radial and DME distance). For most of us, our first reference point was the airport from which we departed, and for most of us, we concentrated so heavily on the mechanics of flying the airplane that we lost track of where the airport was. We had to rely on our instructor to help us find the airport. Remember?

In order to locate ourselves and to describe the location, reference systems are used to respond to the question: where are you? "I'm in room 206." "I'm at the corner of 5th and Main streets." "I'm in the garage." These are all examples of reference systems that are used daily. There are many reference systems that can be used by navigators, but only two are in general use by modern air navigators. These two systems are called FRD and latitude/longitude. In addition, there is a *concept* that is used by all navigators. First, let's take a look at that concept, which involves the LOP and the fix.

LOP AND FIX

A **line of position (LOP)** is a line containing all possible geographic positions of the observer at a given instant of time. If I told you that I was on Main street, you would know that I was somewhere on a line as defined by Main street. Other examples of lines of position: the aircraft's position is on the 335° radial of the VOR, or on the 335° bearing from the NDB, or on the center line of the LOC.

Additionally, the line of position doesn't have to be a straight line. It can be a curved line such as on the 7-mile DME arc (actually, DME provides a hemispherical LOP), or an irregular line such as over the west coastline. One LOP only partially defines a position. Two intersecting LOPs are required to define a position or establish a **fix**. Examples of a fix defined by two intersecting LOPs are: 5th and Main streets; the 335° radial of the VOR at 7 DME (remember, a **radial** is an imaginary line drawn from the VOR); over the coastline (an irregular LOP) 10 miles south of the Golden Gate Bridge (an arc LOP).

The term "fix" describes a geographic position which can be defined by intersecting LOPs, latitude/longitude (actually two LOPs), the location of a navaid, a well-known geographical feature, etc.

FRD

FRD is an acronym for Fix/Radial/Distance. It defines two LOPs, and thus a geographical position (fix). A distance and direction from a known geographical position defines the location of the aircraft. Examples are:

TVF / 094 / 14 ..... VOR / radial / distance

CKN / 176 / 24 ..... NDB or airport (co-located in this case) / radial (see *Note,* below) / distance

The above examples of FRDs would be acceptable as departure points, destinations, or enroute fixes when filing flight plans, provided the fix used in the FRD is defined in the NAS (National Airspace System computer).

Note: When studying VOR and NDB navigation, we learned that the term *radial* applied to VOR navigation and NDBs (ADF navigation stations) always used the term *bearing*, never radial. In the case of the FRD, however, *radial* refers to a magnetic direction from any fix. Perhaps it is time to pause and review the direction terms a pilot-navigator uses.

DIRECTION

Terms of Direction

Direction is the position of one point in space relative to another without reference to the distance between them. The time-honored nautical point system (22.5°/point) for specifying a direction (north, north-north- west, northwest, west-northwest, west, etc. or, in saltier terms: "steer two points west o' north") is not sufficiently accurate for modern navigation, but it provided the beginning of the compass rose direction system based on dividing the horizon into 360°. One of the two points in space, the reference point, is the direction to the true North Pole (000°) and the true South Pole (180°), giving a compass rose aligned to provide true direction (*see* Figure 2-1). If the compass rose is aligned with the magnetic north and south poles, magnetic direction values are provided. It is necessary for the navigator to always specify which system is in use.

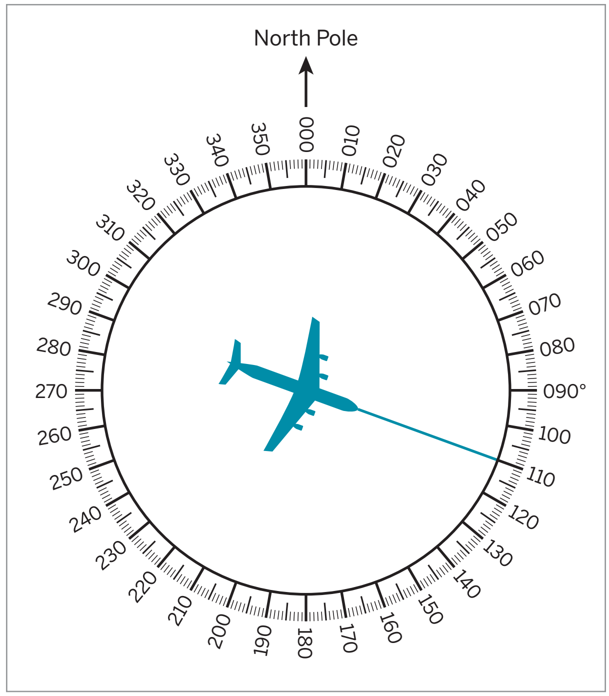

Figure 2-1. Compass rose, aligned to give true direction

Since determination of direction is one of the most important aspects of the navigator's work, the various terms of direction should be clearly understood.

Azimuth is the true direction to a point in space. Usually, the point in space is a celestial body (star, sun, moon or planet).

Bearing is the horizontal direction of one terrestrial point from another. As illustrated in Figure 2-2, the direction of the island from the aircraft is marked by the line of sight (a **visual bearing**). Bearings are usually expressed in terms of (1) true north (**true bearing**), (2) magnetic north (**magnetic bearing**), or (3) the direction clockwise from the nose of the aircraft (**relative bearing**). In Figure 2-2, the island is located on a visual relative bearing from the aircraft of 090° or a true bearing of 315° + 090° = 405° – 360° = 045°. (Remember from your study of ADF navigation that MH + RB = MB). Likewise, in the diagram, the radio station bears 295° relative from the aircraft. What is the radio station's true bearing from the aircraft?

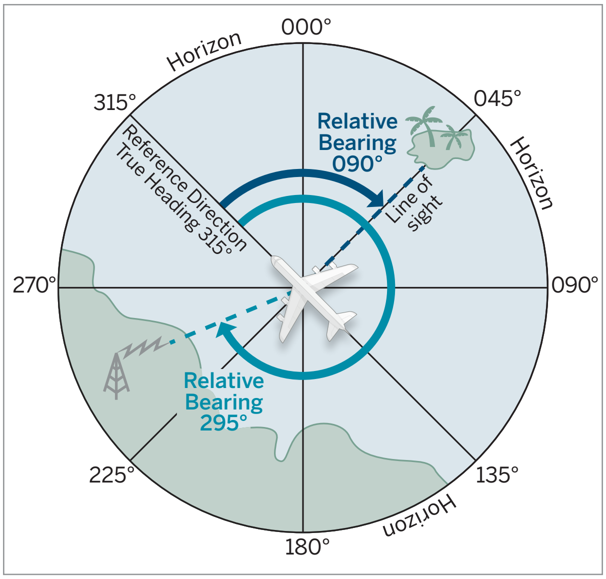

Figure 2-2. Relative bearings

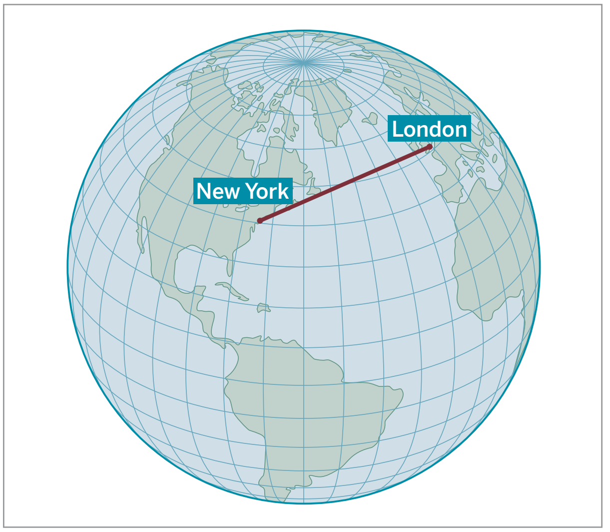

Figure 2-3. The great circle route crosses meridians at different angles.

Course is the intended horizontal direction of travel. Remember to specify true or magnetic.

Heading is the horizontal direction in which an aircraft is pointed—the orientation of the longitudinal axis of the aircraft, with respect to true or magnetic north.

Radial is the bearing from a VOR station to the aircraft. Expressed as magnetic direction except for a few VOR stations that are located at very high latitudes. A notable variation is the use of the term when defining an FRD.

Track is the actual horizontal direction of travel made by the aircraft.

Great Circle and Rhumb Line Direction

The *direction* of the **great circle route** (Figure 2-3) makes an angle of about 50° with the meridian of New York, about 90° with the meridian of Iceland, and a still greater angle with the meridian of London. In other words, the direction of the great circle with respect to true north is constantly changing as progress is made along the route, and is different at every point along the great circle. Flying such a route requires constant change of direction and therefore would be more difficult to fly than a rhumb line course defined below. The great circle route is more desirable because it is the shortest route between two points on a spheroid such as the earth.

The exception to the above would be a flight tracking true north or south, since meridians (lines of constant longitude) are great circles, and no change of true course is necessary to fly along a meridian. Obviously, the more east-west a great circle route lies, the more true heading change is necessary to maintain the great circle route.

A line that makes the same angle with each meridian (except a true north or true south line) is called a **rhumb line**. An aircraft holding a constant true heading (that has an easterly or westerly component) is flying a rhumb line. The rhumb line path results in a greater distance traveled. If continued, a rhumb line spirals toward one of the poles in a constant true direction, but theoretically never reaches the pole. The spiral formed is called a **loxodrome** or loxodromic curve, as shown in Figure 2-4.

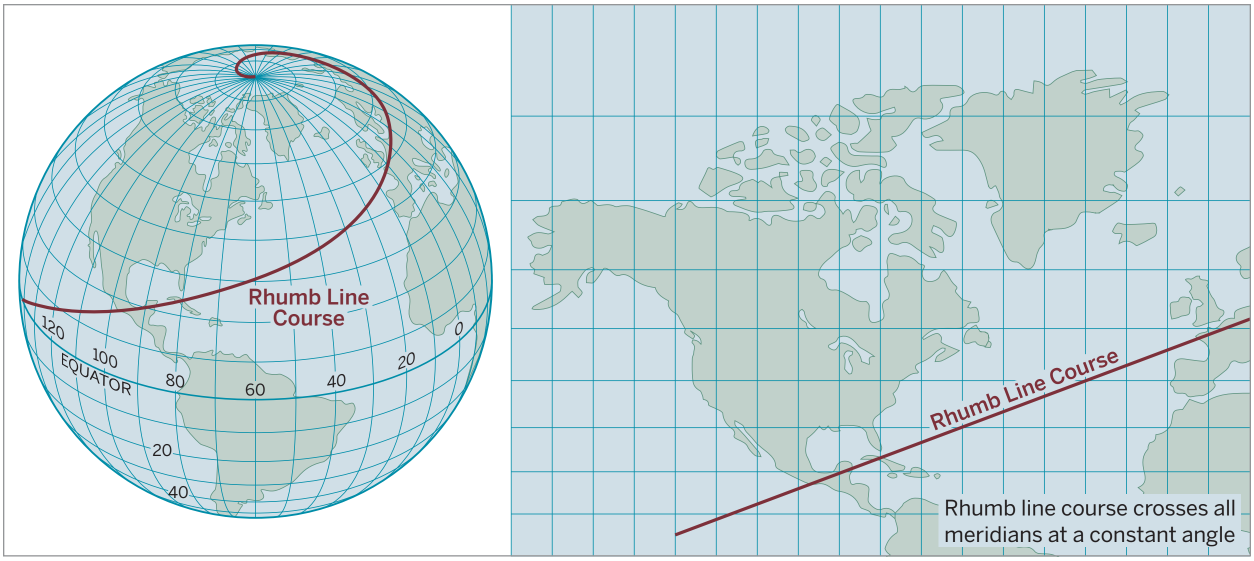

Figure 2-4. The rhumb line (or loxodrome) crosses all meridians at the same angle.

DISTANCE

Distance is the spatial separation between two points. It is measured by the length of a line joining the two points, expressed in units of length such as kilometers, statute miles, nautical miles, etc. Distance measured between two points on a plane surface is a relatively simple matter. However, distance between two points on a sphere such as the earth involves the length of arcs and the use of spherical trigonometry. In order to simplify calculations, air navigation sometimes utilizes the assumption that the earth is a plane surface. To do so requires that the navigator accept the error associated with this assumption. When navigating long distances, this error becomes too large to be acceptable. The fact that the earth is nearly a sphere must be acknowledged in order to achieve accuracy.

In air navigation, the most common unit of measuring distances is the **nautical mile**. For most practical navigational purposes, all of the following units are used interchangeably as being equivalent to one nautical mile:

- 6,076.1 feet (nautical mile)
- 6,087.08 feet—one minute of arc on the earth's equator (geographic mile)
- One minute of arc of a great circle on a sphere having the same area as that of the earth
- One minute of arc of latitude—that is, one minute of arc along a **meridian** (a line of longitude)

Conversion of statute miles to nautical miles can be accomplished by using the ratio of 76 statute miles to 66 nautical miles, or roughly 7 to 6, or 1.15:1.

Closely related to the concept of distance is **speed**, the rate of change of position, or distance/time. It is customary to use the terms **knots** for "nautical miles per hour," and MPH for statute miles per hour. For example, 150 nautical miles/hour is 150 knots, or 172.7 MPH. It is incorrect to use the term "150 knots/hour" unless referring to acceleration.

LATITUDE AND LONGITUDE

Since **latitude** and **longitude** and **great** and **small circles** are terms specific to spheres like the earth, a little background knowledge about the earth's size and shape is important.

Size and Shape of the Earth

For many navigational purposes, the earth is assumed to be a perfect sphere, although in reality it is not quite perfect. Inspection of the earth's crust reveals that there is a height variation of approximately 12 miles from the top of the tallest mountain to the bottom of the deepest point in the ocean.

Smaller variations in the surface (valleys, mountains, oceans, etc.) cause an irregular appearance.

Measured at the equator, the earth is approximately 6,887.91 nautical miles in diameter, while the polar diameter is approximately 6,864.57 NM. This difference expresses the **ellipticity** of the earth. Sometimes, this is expressed as a ratio of the difference between polar and equatorial diameters to the equatorial diameter:

Ellipticity = (6,887.91 – 6,864.57)/6,887.91 = 1:295

Since the equatorial diameter exceeds the polar diameter by only 1 part in 295, the earth is very nearly spherical. A symmetrical body having the same dimensions as the earth, but with a smooth surface, is called an **oblate spheroid**.

In Figure 2-5, the points Pn, E, Ps, and W represent points on the surface of the earth. Points Pn and Ps represent the axis of rotation. As viewed from space at the perspective of this figure, points on the visible surface move from left to right or west to east. If the earth were to be viewed looking down on the north pole, the earth would appear to be rotating counterclockwise at the rate of 15.04° per hour or 360.96° per 24-hour day.

The **equator** (the circumference W-E) is defined as an *imaginary circle on the surface of the earth, equidistant from the north and south poles, whose plane passes through the center of the earth and is perpendicular to the axis of rotation.*

Great and Small Circles

A **great circle** is a circle on the surface of a sphere whose center and radius are those of the sphere itself. It is the largest circle that can be drawn on the sphere. It is the intersection with the surface of the earth, of any plane which passes through the center of the earth.

Understanding the concept of the great circle is important to any navigator because the arc of a great circle is the shortest distance and most direct route between any two points on the surface of a sphere, just as a straight line is on a plane surface.

Circles on the surface of a sphere other than great circles are called **small circles**. Great and small circles are shown in Figure 2-6.

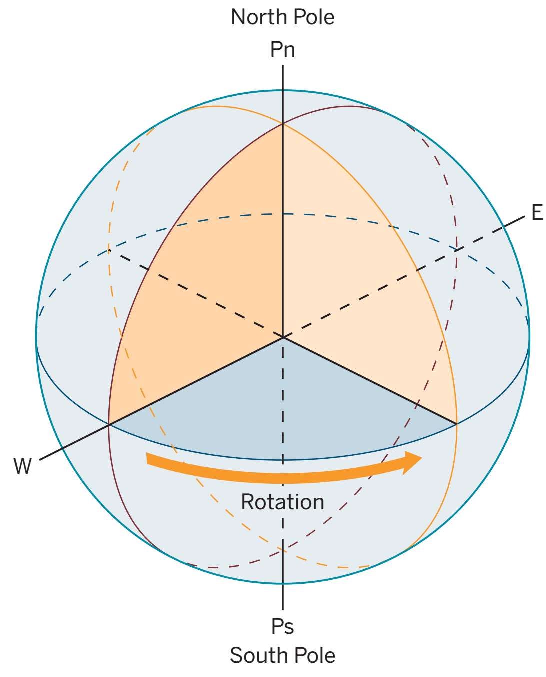

Figure 2-5. A representation of the earth showing rotation, spin axes, and equator.

Latitude and Longitude as a Reference System

This is the geographical reference system most commonly used for spherical surfaces. Air and marine navigators, particularly those working with long distances, utilize this system to a great extent. All long distance navigation systems such as GPS and INS use the latitude/longitude system.

Once a day, the earth rotates on its north-south axis which is terminated by the north and south geographic poles. The imaginary line of the **equator** is constructed along the surface of our sphere, midway between the poles, creating a great circle. It is the only great circle on our planet that is oriented true east-west.

If one were able to journey to the exact center of the earth and there set up a surveyor's transit to measure the angle between a sight to the north or south pole and a sight to any point on the equator, the angle (Pn-C-Q or Ps-C-Q of Figure 2-7) would be found to be 90°. Arbitrarily, let us call the equator, which is the only possible great circle lying directly

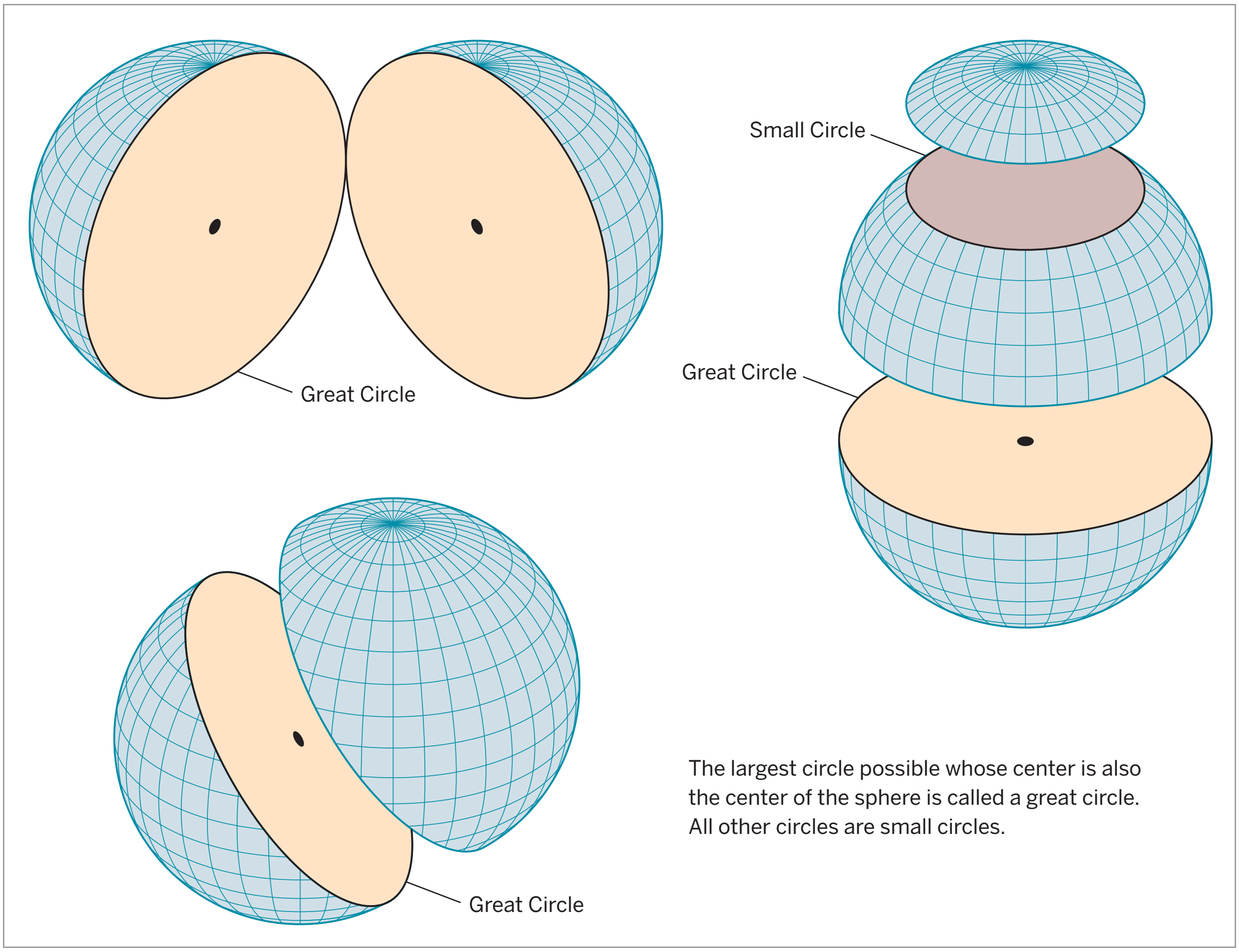

Figure 2-6. Great and small circles

east-west, the reference for east-west lying lines of position, and assign it a value of zero degrees.

Now, after sighting from the center of the earth (C) to the equator (Q), imagine changing the angle of the sight 30° toward the north pole and having the surveyor's helper pound stakes wherever the line of the sight intersected the earth's surface. The stakes would mark the 30° north parallel (M-M'). It is labeled such because it is located in the northern hemisphere and is separated from the equator (the reference point) by 30° of arc (Q-M).

It is apparent from Figure 2-7 that the lines of **latitude** are labeled based on the degrees of angle or arc, north or south of the equator, and that these lines are circles (when viewed from a perspective above the north or south poles). Except for the equator, they are small circles because they do not fit the definition of a great circle. They are all parallel to each other when viewed from the perspective of Figure 2-7, hence they are called **parallels**.

It should now be apparent that line N-N' (in Figure 2-7) describes the 45° south parallel. All points on this line are at latitude 45° south. The north pole is at latitude 90° north and the south pole is 90° south. Thus, any point on the surface of the earth may be assigned a value of latitude, which is a line of position (LOP) running E-W, parallel to the equator. The point requires another LOP (longitude) to properly define its location (fix) on the surface of the sphere.

Half of a great circle, which is a line drawn on the earth's surface from pole to pole, is called a **meridian**.

If a meridian is drawn from the north pole, through a point on the grounds of the royal observatory near

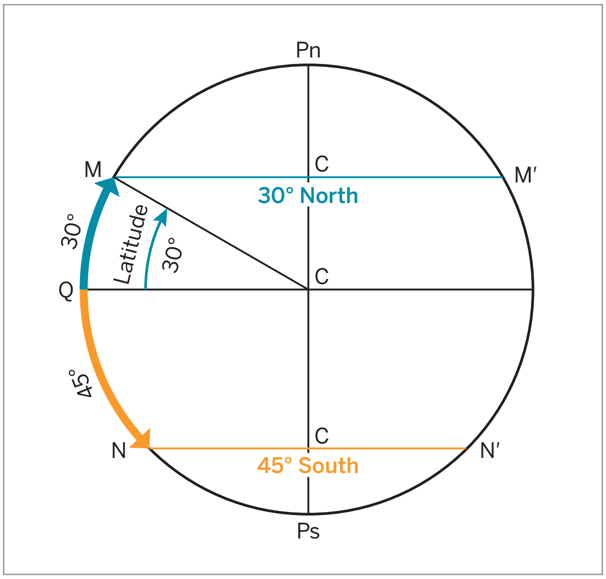

Figure 2-7. Latitude of M is angle QCM or arc QM.

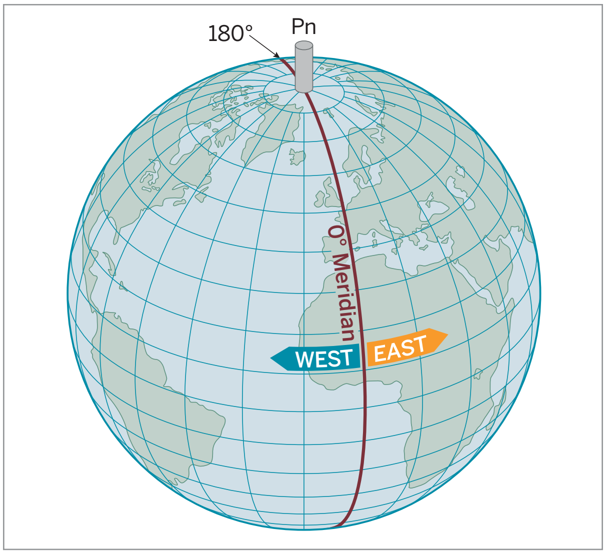

Figure 2-8. Longitude is measured east and west of the Greenwich Meridian.

Greenwich, England, to the south pole (remember, the plane within this semicircular line must pass through the center of the earth), the **Prime Meridian** is the result, which is given the value of 0° of longitude. The other half of this great circle, occurring halfway around a 360° circle, has a value of 180° of longitude and is the meridian called the **International Date Line**. (*See* Figures 2-8 and 2-9).

Longitude is the angular distance along the arc from the Prime Meridian or Greenwich Meridian to the location of the point. This defines a second LOP which runs N-S through the point. All lines of longitude (meridians) are great circles.

Values of latitude range from 0° to 90° north and 0° to 90° south. Values of longitude range from 0° to 180° east and west. When expressing latitude and longitude, latitude values are always given first. A degree may be broken down into its smaller parts: minutes and seconds. There are 60 seconds per minute and 60 minutes per degree. One minute of latitude (measured N-S along any meridian) is equal to one nautical mile. One minute of longitude (measured E-W along lines of latitude) is equal to one nautical mile *only at the equator.*

It is apparent that meridians get closer together as they approach the poles, so the distance between minutes of longitude decreases as latitude increases. Nautical miles per minute of longitude = 1 × cosine of

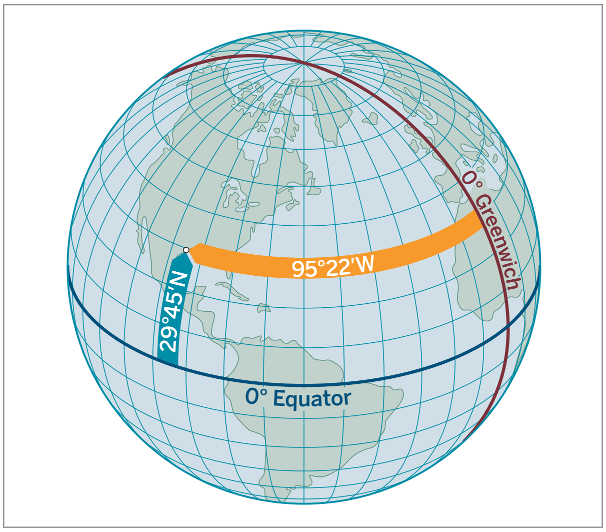

Figure 2-9. Latitude is measured north and south from the equator. Longitude is measured east and west from the Prime Meridian.

the latitude. For example: at 50° north, one minute of longitude = 1 × cos 50° = .643 NM.

Formatting Lat/Lon Coordinates

Various formats for reporting lat./lon. are in use today, including degrees, minutes and seconds (ddd:mm:ss); degrees, minutes and decimal fractions of minutes (ddd:mm.m) or (ddd:mm.mm).

Converting from one to the other is not difficult, recalling that 60s = 1 NM, so 6s = .1 NM. For example, 35°12'18" converts to 35°12.3' and to 35.205'.

In addition, the computers in our navigation equipment today are not standardized with respect to lat./lon. input format. For example, the input format for the example in the paragraph above could be 3512.3, 35.12.3, 3512.30, 35.12.30, or 35123 or 351230, if the value was for latitude. Longitude values are slightly more complex as there is one more digit. Some computers require the input to be preceded by a zero if the value of longitude is less than 100°, and some computers do not require this. For example, the longitude 94°30 minutes west is input into the DUAT system as 9430 when filing a flight plan. It is input into the FAA (flight service station) computer as 09430. The values north and west (lat./lon.) are not required as they are assumed for U.S. flight plans because all areas within the U.S. are north latitudes and west longitudes.

I used to use a LORAN in which the same value was entered as 094.30.00 (west was assumed by the computer but could be changed during input). My more modern GPS allows the user to select the format from the three versions available. Be careful! You don't want to enter most countries if you are not expected.

The need for standardization is obvious, but it simply doesn't exist; therefore, there is a tremendous need to *exercise extreme caution when values are input into any navigation or flight planning system.*

Will standardization occur? A pessimist would say that we need only take a look at the CDI instruments manufactured by King and Narco to see standardization is not likely (flying an older airplane today with one of these radios in it?)—they were the "big two" general aviation avionics manufacturers during the past thirty years. One manufacturer's unit reads the value at the top and the reciprocal at the bottom, while the other's is reversed.

A Change in the Geodetic Referencing System

On October 15, 1992, the horizontal geodetic referencing system used in all charts and chart products published by the National Oceanic and Atmospheric Administration (NOAA)/National Ocean Service (NOS) changed from the North American Datum of 1927 (NAD 27) to the North American Datum of 1983 (NAD 83). Pilots should be familiar with this congressionally-mandated change because it affects the latitude and longitude coordinates of almost all points identified in the National Airspace System. The coordinates have changed by zero to 16 seconds (of latitude and longitude).

In the United States, latitude and longitude are based on a network of geodetic control points established and maintained by the National Geodetic Survey (Department of Commerce). Control point coordinates are determined mathematically based on a reference point. The NAD 27 used a reference point in Kansas for the lower 48 states (conterminous U.S.), Canada, and Alaska. Technological advances of Global Positioning Systems (GPS) and other systems now allow satellite systems to pinpoint much more accurately geographic locations by referencing the center of the earth. NAD 83 is based on the center of the earth and geodetically ties Puerto Rico and Hawaii to North America.

The greatest coordinate shifts are in Alaska and Hawaii where latitude has been moved by as much as 1,200 feet and longitude by up to 950 feet. In the conterminous U.S., the maximum changes were approximately 165 feet in latitude and 345 feet in longitude. Magnetic variation will be altered so minutely the aviation community need not be concerned.

Not so very long ago, my GPS mapping system showed our boat, chugging happily along, ashore on San Marcos Island in the Sea of Cortez when actually there was water all around us and visually, we were near the island. That changed to far better accuracy when the mapping source was changed from NAD 27 to NAD 83. With some GPS units, the NAD in use is user-selectable.

The shift is not significant enough to change the latitude and longitude grid on Sectional Charts or WACs, but it could change the grid on the TACs, Helicopter Charts, and Sectional Insets, and most certainly will affect Airport Diagram Charts. All coordinates in the Digital Aeronautical Chart Supplement, Airport/ Facility Directory, Pacific and Alaska Chart Supplements, on enroute navigation charts and all digital products are carefully imprinted with a date, and some have the statement indicating they are based on the NAD 83 database. Also, check the user guide for the navigation systems you are using to be sure they are using the NAD 83 mapping database and which lat./lon. format is being used. Most are user changeable, as are the map systems available on the internet such as Google Earth.

SUMMARY

All of the information in this chapter is considered basic and necessary to the knowledge base of the pilot/navigator, so the reader should not consider this summary section as the "bottom line, all that's needed to know" part of the chapter. In fact, the reader should use the study questions at the end of this chapter in an effort to solidify the principles above into a position of familiarity.

If a globe has the circles of latitude and longitude drawn upon it according to the principles described, and the latitude and longitude of a certain point have been determined by observation, this point can be located on the globe in its proper position. In this way, a globe can be formed that resembles a small-scale copy of the spherical earth (*see* Figure 2-9). Thus, a small-scale reproduction of the surface above which the pilot navigates is produced, to allow the pilot to gain the perspective needed to understand the navigational concepts and be able to predict what the surface that is about to be flown over should look like.

This brings us to the subject of maps and charts, which need to be understood in order to be able to fully utilize this major navigator's aid at a high level of sophistication. However, before going on to the study of maps and charts in Chapter 3, go through the study questions in order to fully understand the concepts presented in this chapter.

Study Questions

1. Find a globe of the earth. Note how the lines of latitude and longitude are placed. Find and list the latitude and longitude of ten major cities in the world, including one near the equator, one each nearest the south and north poles.
2. Set up a table with four columns labeled: city; lat./lon. from globe; airport lat./lon. from IFIM (International Flight Information Manual), ICAO airport identifier. From the globe, find the latitude and longitude of the following cities. Then, using the IFIM, list the airport lat./lon. and four-letter identifier for the city. Compare the two lat./lon. values. Are they close? Write a short conclusion about what you have learned from these efforts.
   a. Lisbon
   b. Tokyo
   c. Yellowknife (Canada)
   d. Moscow
   e. Cairo
   f. Georgetown (How many can you find?)
3. Show how you solved the following: how far is
   a. 46°34'12"N/096°12.0W from 48°10'00"N/096°12.0'W?
   b. 12°16'18"N/94°30'W from 10°08'12"S/ 094°30'W?
   c. 00°00'/80°20'W from 00°00'/160°20'E? (Determine values for both short and long path.)
   d. 46°30'N/93°00'W from 46°30'N/94°56'E?

   Now, error-proof your answer by using another method to solve the problem (it's okay to use a digital device here).
4. Define:
   a. LOP
   b. fix
   c. radial
   d. FRD
   e. nautical compass point
   f. bearing
   g. azimuth
   h. course
   i. track
   j. heading
   k. knot
   l. oblate spheroid

m. equator

n. great circle

o. latitude

p. longitude

5. This will require some outside-the-book research—include your sources: How many points do each of these compass roses have and how many degrees are between each point? Name the points.

   a. Mariner's

   b. Traditional

   c. Meteorological

   d. Primary points compass

6. What is the difference between a bearing and a rhumb line? What is a rumbo in the Spanish language?

7. If there is an error in your NAV system of each of the following values, what is the error expressed in nautical miles?

   a. 1 degree (N-S)

   b. 1 minute (N-S)

   c. 1 second (N-S)

8. The equator is the only east-west great circle. The rest of the east-west lines of equal latitude are called: ______________________ and/or ________________________.

9. Convert these angles to both of the other formats:

   a. 123.2837°
   ____________________ (DDD.MM.SS); _________________(DDD.mmm)

   b. 142°01'14"
   __________________(_________); _________________(_________)

   c. 003°12.13'
   __________________ (_________); _________________(_________)

10. Are the numbers in Question 7 values of latitude or longitude? Why?