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1Lt Anthony Borra

Flying Training

AIR NAVIGATION

This manual provides information on all phases of air navigation for navigators and student navigators. Volume I is a consolidation of the superseded Volumes I and II. The present Volume III will be renumbered when it is revised. Volume I develops the art of navigation from the simplest concepts to the most advanced procedures and techniques; Volume III serves as an inflight handbook for navigator personnel. This text contains explanations on how to measure, map, and chart the earth; how to use basic instruments to obtain measurements of direction, altitude, temperature, and speed; and how to solve basic navigation problems by dead reckoning and map reading. Special techniques used to navigate by radio, radar, and Loran; by using celestial concepts and procedures; and in polar areas are covered. There is information on flight publications, weather services, mission planning, inflight procedures, and low level navigation. The final chapter covers automatic navigation systems.

[See summary of revised, deleted, or added material on page 27-14 below the signature element.]

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This manual supersedes AFM 51-40, Vol I, 15 Oct 59 as amended; AFM 51-40, Vol II, 15 Apr 60 as amended; and AFR 55-35, Navigation Forms and Tables, 25 Jun 57.

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CHAPTER 1

Introduction

DEFINING AIR NAVIGATION

The word *navigator* comes from two Latin words, *navis*, meaning ship, and *agere*, meaning to direct or move. Navigation is defined as the process of directing the movement of a craft from one place to another. The craft may be in its broadest sense any object requiring direction or capable of being directed. Unlike sea or naval navigation, air navigation involves movement above the surface of the earth within or beyond the atmosphere. Air navigation, then, can be defined as "the process of determining the geographical position and of maintaining the desired direction of an aircraft relative to the surface of the earth." Other terms, "avigation" and "aerial navigation" have fallen into disuse in favor of the term, "air navigation." Certain unique conditions are encountered in air navigation that have a special impact on the navigator.

- *Need for continued motion.* A ship or land vehicle can stop and resolve any uncertainty of motion or await more favorable conditions if necessary. Except to a limited extent, most aircraft must keep going.
- *Limited endurance.* Most aircraft can remain aloft for only a relatively short time, usually a matter of hours.
- *Greater speed.* Navigation of high speed aircraft requires detailed flight planning and navigation methods and procedures that can be accomplished quickly and accurately.
- *Effect of weather.* Visibility affects the availability of landmarks. The wind has a more direct effect upon the position of aircraft than upon that of ships or land vehicles. Changes of atmospheric pressure and temperature affect the height measurement of aircraft using barometric altimeters.

Some form of navigation has been used ever since man has ventured from his immediate surroundings with a definite destination in mind. Exactly how the earliest navigators found their way must remain to some extent a matter of conjecture but some of their methods are known. For example, the Phoenicians and Greeks were the first to navigate far from land and to sail at night. They made primitive charts and used a crude form of dead reckoning. They used observations of the sun and the North Star, or pole star, to determine direction. Early explorers were aided by the invention of the astrolabe (see figure 1-1), but it was not until the 1700's that an accurate chronometer (timepiece) and the sextant were invented making it possible for navigators to know exactly where they were, even when far from land.

Any purposeful movement in the universe ultimately involves an intention to proceed to a definite point. Navigation is the business of proceeding in such a manner as to arrive at that point. To do this safely is an art. Navigation is considered both an art and a science. Science is involved in the development of instruments and methods of navigation as well as in the computations involved. The skillful use of navigational instruments and the interpretation of available data may be considered an art. This combination has led some to refer to navigation as a "scientific art."

As instruments and other navigational aids have become more complicated, an increasing proportion of the development has been shifted from the practicing navigator to the navigational scientist who aids in drawing together the applications of principles from such sciences as astronomy, cartography, electronics, geodesy, mathematics, meteorology, oceanography, and physics. Such applica-

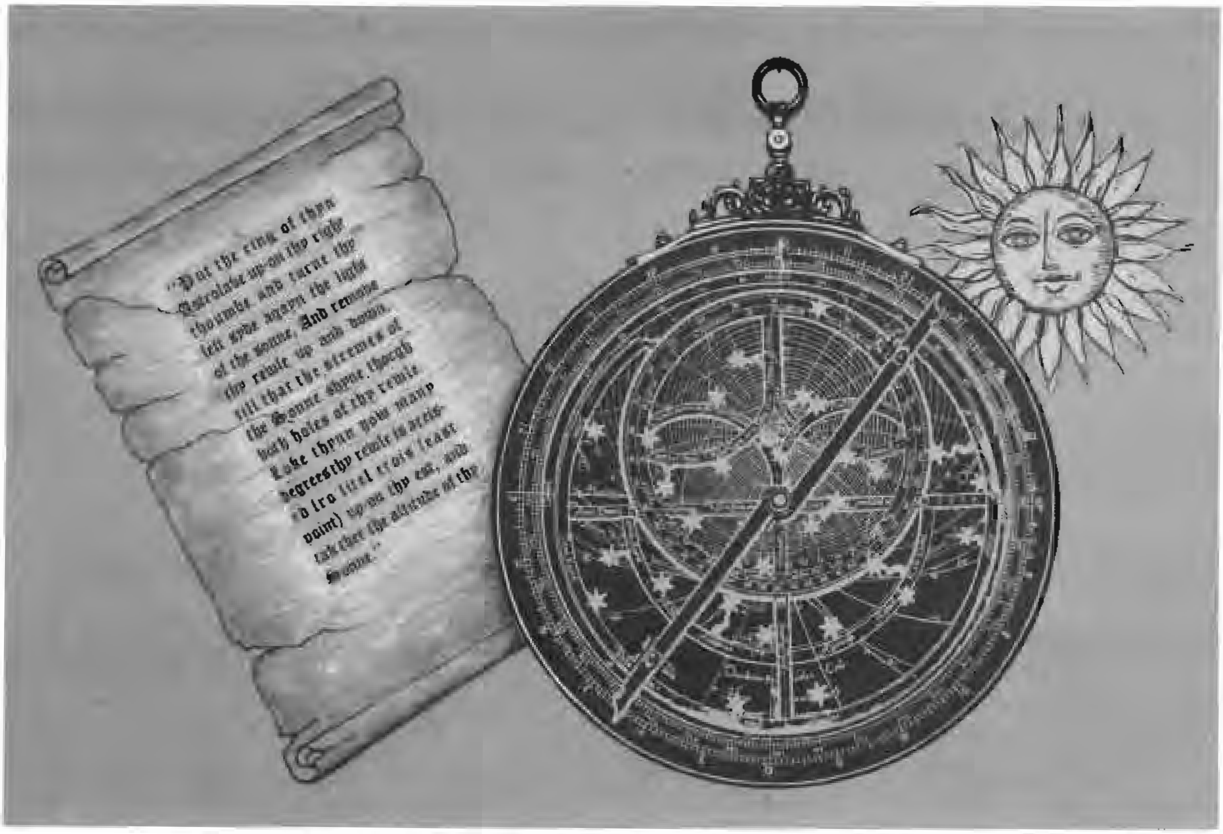


Figure 1-1. The Ancient Astrolabe

tions aid in explaining navigational phenomena and in developing improvements in speed, accuracy, or routine actions in practicing the "scientific art" of navigation.

The beginning navigator largely practices the science of navigation; that is, he gathers data and uses it to solve the navigation problem in a more or less mechanical manner. It is not until after many hours of flying that the navigator begins to realize that his total role involves an integration based on judgment. The navigator builds accuracy and reliability into his performance by judgment based upon experience. The military navigator is an indispensable part of many offensive and defensive missions. He must be able to plan a mission covering every eventuality; inflight, he must be able to evaluate the past and current progress of the aircraft and to derive a correct conclusion for the remainder of the mission. High speed navigation demands that he have the ability to anticipate changes in flight conditions—to think ahead of the aircraft—and to make the correct decision immediately on the basis of anticipated changes.

AIR NAVIGATION PROBLEM

The problem of air navigation is, primarily, to determine the direction necessary to accomplish the intended flight, to locate positions, and to measure distance and time as means to that end.

When navigation is performed without "aids," that is, without obtaining or deducing position information from special equipment specifically designed to provide only momentary knowledge of position, the basic method of navigation, "dead reckoning," is used.

Dead reckoning is the determination of position by advancing a previous position, using only direction and speed data. The navigator does this by applying, to the last well-determined position, a vector or a series of consecutive vectors representing the magnitude and direction of movement that has been made since the previous position. The new position obtained is for a specific time and is essentially a predicted or theoretical position. The navigator assumes that he can use direction and speed data previously determined with reasonable accuracy to obtain a future position.

The most important elements in the plotting of a dead-reckoning position are elapsed time, direction, distance, and speed. Knowing these and his starting point, a navigator can plot his approximate position, which in turn, can serve as a base for a subsequent course change.

When the function of air navigation is performed with "aids" to navigation, the navigator can provide a new and separate base or starting point from which to use dead reckoning procedures. When an aid to navigation provides the navigator with a position or fix, any cumulative errors in previous dead-reckoning elements are cancelled. In effect, the navigator can restart the mission, as far as the future is concerned, from each new fix or accurate position determined by the use of aids.

An adjective is often used with the word, "navigation," to indicate the type or primary method being used, such as *dead reckoning* navigation, *celestial* navigation, *radar* navigation, *pressure pattern* navigation, *doppler* navigation, *grid* navigation, *inertial* navigation, etc.

SOURCES OF NAVIGATION INFORMATION

In addition to this manual, several other sources provide complete or partial references to all methods and techniques of navigation. Some of these are:

- U.S. Dept of the Air Force. *Air Navigation,* AFM 51-40, Vol III. This manual is an inflight reference manual for navigator personnel. It contains preflight, operational, and inflight maintenance procedures for airborne navigational equipment in outline form. Reference tables, graphs, and brief reviews of specialized techniques are also included.
- U. S. Navy Hydrographic Office, *Air Navigation,* H.O. Pub. 216. This is a general reference book for air navigators.
- U. S. Navy Hydrographic Office, *American Practical Navigator,* Bowditch, H. O. Pub. No. 9. An epitome of navigation, this text provides a compendium of navigational material. Although designed primarily for the marine navigator, it has valuable application for the air navigator.
- United States Naval Institute, *Navigation and Piloting,* Dutton. This is a teaching text for the elements of marine navigation.
- Air Training Command, *Navigation for Pilots,* ATCM 51-7. This manual explains the basic principles and procedures of air navigation used by pilots and information on the navigation systems used by other crew members of multi-place aircraft.
- U. S. Air Force, *Navigator Refresher Course,* AFP 60-1-1, -2, and -3. This is a programmed text and ground mission primarily used for navigators requiring annual refresher training.
- USAF, Air Training Command, *The Navigator,* AFRP 50-3, published quarterly by ATC. This magazine contains a variety of articles from worldwide sources that relate to navigation and which advance new and different means for accomplishing techniques of navigation.

The following United States Observatory and U.S. Navy Hydrographic Office publications are also prescribed for Air Force use:

- Air Almanac
- American Ephemeris and Nautical Almanac
- H.O. Pub 9 (Part II), "Useful Tables for the American Practical Navigator"
- H.O. Pub 211, "Dead Reckoning Altitude and Azimuth Tables"
- H.O. Pub 249, "Sight Reduction Tables for Air Navigation"

The Department of Defense (DOD) Catalog of Aeronautical Charts and Flight Publications, published by Aeronautical Chart and Information Center, contains information on the basis of issue and procedures for requisitioning these publications. The use of the Air Almanac and H.O. 249 Tables is discussed in detail later in this manual.

SUMMARY

Some form of navigation has been accomplished since the ancient Greeks and Phoenicians began sailing far from land. The problems of air navigation and the navigator today are far different from those experienced by these ancient mariners. With the advent of newer and higher speed aircraft, the navigator must be able to quickly and accurately make decisions which directly affect the safety of the aircraft and the crew. Using proven techniques and modern aids, the navigator practices a scientific art.

CHAPTER 2

Earth and Its Coordinates

INTRODUCTION

Basic to the study of navigation is an understanding of certain terms which could be called the dimensions of navigation. These so-called dimensions of *position, direction, distance, and time* are basic references used by the air navigator. A clear understanding of these dimensions as they relate to navigation is necessary to provide the navigator with a means of expressing and accomplishing the practical aspects of air navigation. These terms are defined as follows:

- *Position* is a point defined by stated or implied coordinates. Though frequently qualified by such adjectives as "estimated," "dead reckoning," "no wind," and so forth, the word "position" always refers to some place that can be identified. It is obvious that a navigator must know his position before he can direct the aircraft to another position or in another direction.
- *Direction* is the position of one point in space relative to another without reference to the distance between them. Direction is not in itself an angle, but it is often measured in terms of its angular distance from a reference direction.
- *Distance* is the spatial separation between two points and is measured by the length of a line joining them. On a plane surface, this is a simple problem. However, consider distance on a sphere, where the separation between points may be expressed as a variety of curves. It is essential that the navigator decide exactly "how" the distance is to be measured. The length of the line, once the path or direction of the line has been determined, can be expressed in various units; e.g., miles, yards, and so forth.
- *Time* is defined in many ways, but those definitions used in navigation consist mainly of two: (1) the hour of the day and (2) an elapsed interval.

The methods of expressing position, direction, distance, and time are covered fully in appropriate chapters. It is desirable at this time to emphasize that these terms, and others similar to them, represent definite quantities or conditions which may be measured in several different ways. For example, the position of an aircraft may be expressed in coordinates such as at certain latitude and longitude. The position may also be expressed as being 10 miles south of a certain city. The study of navigation demands that the navigator learn how to measure quantities such as those just defined and how to apply the units by which they are expressed.

EARTH'S SIZE AND SHAPE

For most navigational purposes, the earth is assumed to be a perfect sphere, although in reality it is not. 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 nautical miles. The difference in these diameters is 23.34 nautical miles, and this differenee may be used to express the ellipticity of the earth. It is sometimes expressed as a ratio between the difference and the equatorial diameter:

$$\text{Ellipticity} = \frac{22.34}{6{,}887.91} = \frac{1}{295}$$

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 2-1, Pn, E, Ps, and W represent the surface of the earth, and Pn-Ps represents the axis of rotation. The earth rotates from W to E. All points in the hemisphere Pn, W, Ps approach the reader, while those in the opposite hemisphere recede from him. The circumference W-E is called the equator, which is defined as that imaginary circle on the surface of the earth whose plane passes through the center of the earth and is perpendicular to the axis of rotation.

Great Circles and Small Circles

A great circle is defined as 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 passed through the center.

The arc of a great circle is the shortest distance between two points on a sphere, just as a straight line is the shortest distance between two points on a plane. On any sphere, an infinitely large number of great circles may be drawn through any point, though only one great circle may be drawn through any two points that are not diametrically opposite. Several great circles are shown in figure 2-2.

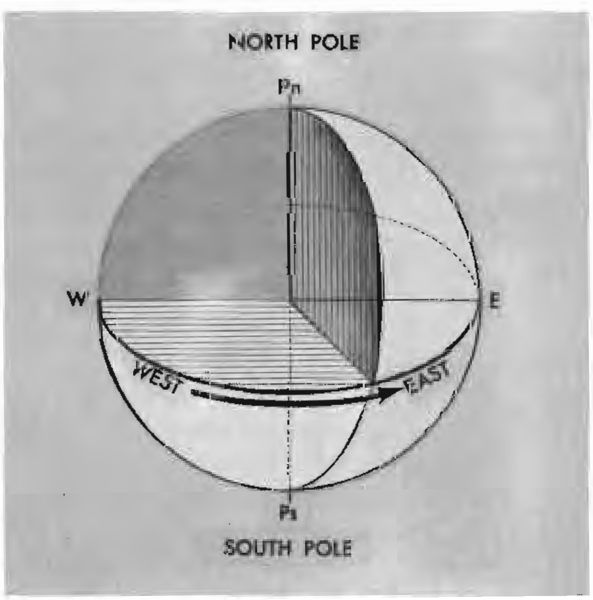


Figure 2-1. Schematic Representation of the Earth Showing Axis of Rotation and Equator

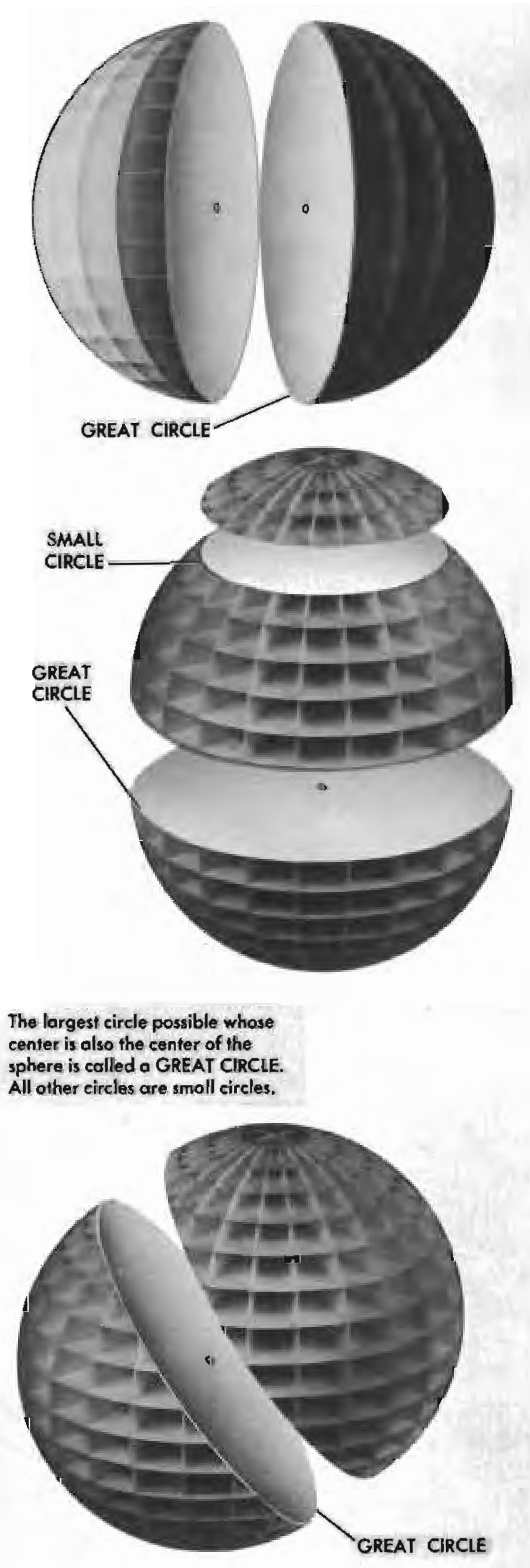


Figure 2-2. A Great Circle is the Largest Circle in a Sphere

Circles on the surface of the sphere other than great circles may be defined as small circles. A small circle is a circle on the surface of the earth whose center and/or radius are not that of the sphere. A special set of small circles, called latitude, is discussed later.

In summary, the intersection of a sphere and a plane is a circle—a great circle if the plane passes through the center of the sphere, and a small circle if it does not.

Latitude and Longitude

The nature of a sphere is such that any point on it is exactly like any other point. There is neither beginning nor ending as far as differentiation of points is concerned. In order that points may be located on the earth, some points or lines of reference are necessary so that other points may be located with regard to them. Thus the location of New York City with reference to Washington D. C., is stated as a number of miles in a certain direction from Washington. Any point on the earth can be located in this manner.

Such a system, however, does not lend itself readily to navigation, for it would be difficult to locate a point preeisely in mid-Pacific without any nearby known geographic features to use for reference. A system of coordinates has been developed to locate positions on the earth by means of imaginary reference lines. These lines are known as parallels of latitude and meridians of longitude.

LATITUDE. Once a day, the earth rotates on its north-south axis which is terminated by the two poles. The equator is constructed at the midpoint of this axis at right angles to it (see figure 2-3). A great circle drawn through the poles is called a meridian, and an infinite number of great circles may be constructed in this manner. Each meridian is divided into four quadrants by the equator and the poles. Since a circle is arbitrarily divided into 360 degrees, each of these quadrants therefore eontains 90 degrees.

Take a point on one of these meridians 30 degrees north of the equator. Through this point pass a plane perpendicular to the north-south axis of rotation. This plane will be parallel to the plane of the equator as shown in figure 2-3 and will intersect the earth in a small circle called a parallel or parallel of latitude. The particular parallel of latitude chosen is at 30° N, and every point on this parallel will be at 30°N. In the same way, other parallels can be constructed at any desired latitude, such as 10 degrees, 40 degrees, etc.

Bear in mind that the equator is drawn as the

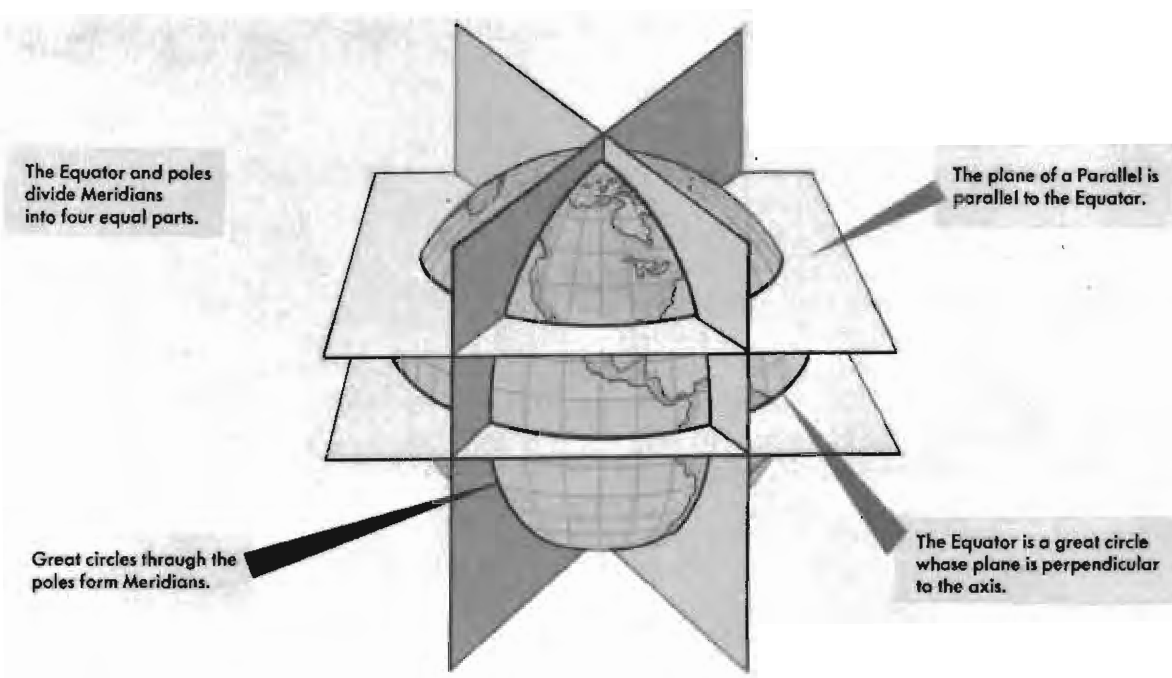


Figure 2-3. Planes of the Earth

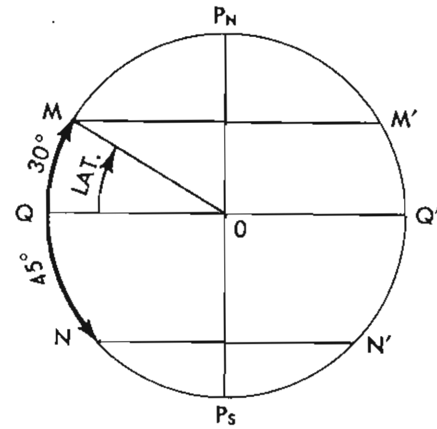


Figure 2-4. Latitude of M is Angle QOM or Arc QM

Figure 2-5. Longitude is Measured East and West of Greenwich Meridian

great circle midway between the poles, that the parallels of latitude are small circles constructed with reference to the equator, and that they are definitely located small circles parallel to the equator. The angular distance measured on a meridian north or south of the equator is known as latitude (see figure 2-4) and forms one component of the coordinate system.

LONGITUDE. The latitude of a point can be shown as 20° N or 20° S of the equator, but there is no way of knowing whether one point is east or west of another. This difficulty is resolved by use of the other component of the coordinate system, longitude, which is the measurement of this east-west distance.

There is not, as with latitude, a natural starting point for numbering, such as the equator. The solution has been to select an arbitrary starting point. A great many places have been used, but when the English speaking people began to make charts, they chose the meridian through their principal observatory in Greenwich, England, as the origin for counting longitude, and this point has now been adopted by most other countries of the world. This Greenwich meridian is sometimes called the prime or first meridian, though actually it is the zero meridian. Longitude is counted east and west from this meridian through 180 degrees, as shown in figure 2-5. Thus, the Greenwich meridian is the 0 degree longitude on one side of the earth, and after crossing the poles, it becomes the 180th meridian (180 degrees east or west of the 0-degree meridian).

SUMMARY. 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 place have been determined by observation, this point can be located on the globe in its proper position. (See figure 2-6.) In this way, a globe can be formed that resembles a small-scale copy of the spherical earth.

It may be well to point out here some of the measurements used in the coordinate system. Latitude is expressed in degrees up to 90, and

Figure 2-6. Latitude is Measured from the Equator; Longitude from the Prime Meridian

longitude is expressed in degrees up to 180. The total number of degrees in any one circle can not exceed 360. A degree (°) of arc may be subdivided into smaller units by dividing each degree into 60 minutes (′) of arc. Eaeh minute may be further subdivided into 60 seeonds (″) of arc. Measurement may also be made, if desired, in degrees, minutes, and tenths of minutes.

A position on the surface of the earth is expressed in terms of latitude and longitude. Latitude is expressed as being either north or south of the equator, and longitude as either east or west of the prime meridian.

Distance

Distance as previously defined is measured by the length of a line joining two points. In navigation the most common unit for measuring distances is the nautical mile. For most practical navigation purposes, all of the following units are used interchangeably as the equivalent of one nautical mile:

- 6,076.10 feet (nautical mile).
- One minute of arc of a great circle on a sphere having an area equal to that of the earth.
- 6,087.08 feet. One minute of arc on the earth's equator (geographic mile).
- One minute of arc on a meridian (one minute of latitude).
- Two thousand yards (for short distances).

Navigation is done in terms of nautical miles. However, it is sometimes necessary to interconvert statute and nautical miles. This conversion is easily made with the following ratio:

In a given distance:

$$\frac{\text{Number of statute miles}}{\text{Number of nautical miles}} = \frac{76}{66}$$

Closely related to the concept of distance is speed, which determines the rate of change of position. Speed is usually expressed in miles per hour, this being either statute miles per hour or nautical miles per hour. If the measure of distance is nautical miles, it is customary to speak of speed in terms of knots. Thus, a speed of 200 knots and a speed of 200 nautical miles per hour are the same thing. It is incorrect to say 200 knots per hour unless referring to acceleration.

Direction

Remember that direction is the position of one point in space relative to another without reference to the distance between them. The time-honored point system for specifying a direction as north, north-northwest, northwest, west-northwest, west, etc., is not adequate for modern navigation. It has been replaced for most purposes by a numerical system.

The numerical system, figure 2-7, divides the horizon into 360 degrees starting with north as 000 degrees, and continuing clockwise through east 090 degrees, south 180 degrees, west 270 degrees, and back to north.

The circle, called a *compass rose,* represents the horizon divided into 360 degrees. The nearly vertical lines in the illustration are meridians drawn as straight lines with the meridian of position A passing through 000 degrees and 180 degrees of the compass rose. Position B lies at a true direction of 062 degrees from A, and position C is at a true direction of 295 degrees from A.

Since determination of direction is one of the most important parts of the navigator's work, the various terms involved should be clearly understood. Generally, in navigation unless otherwise stated, all directions are called *true* (T) directions.

- *Course* is the intended horizontal direction of travel.
- *Heading* is the horizontal direction in which an aircraft is pointed. Heading is the actual orientation of the longitudinal axis of the aircraft at any instant, while course is the direction intended to be made good.
- *Track* is the actual horizontal direction made by the aircraft over the earth.

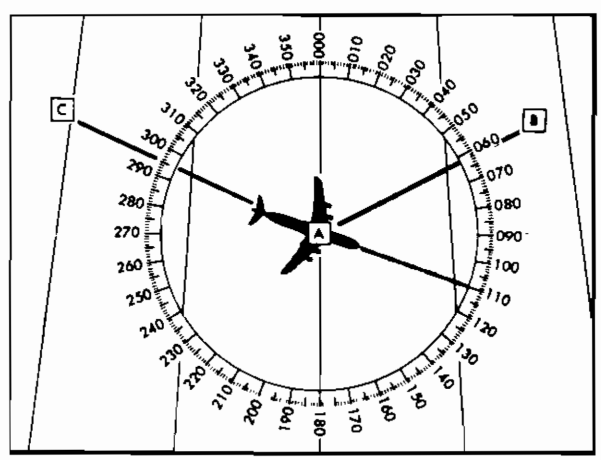


Figure 2-7. Numerical System is Used in Air Navigation

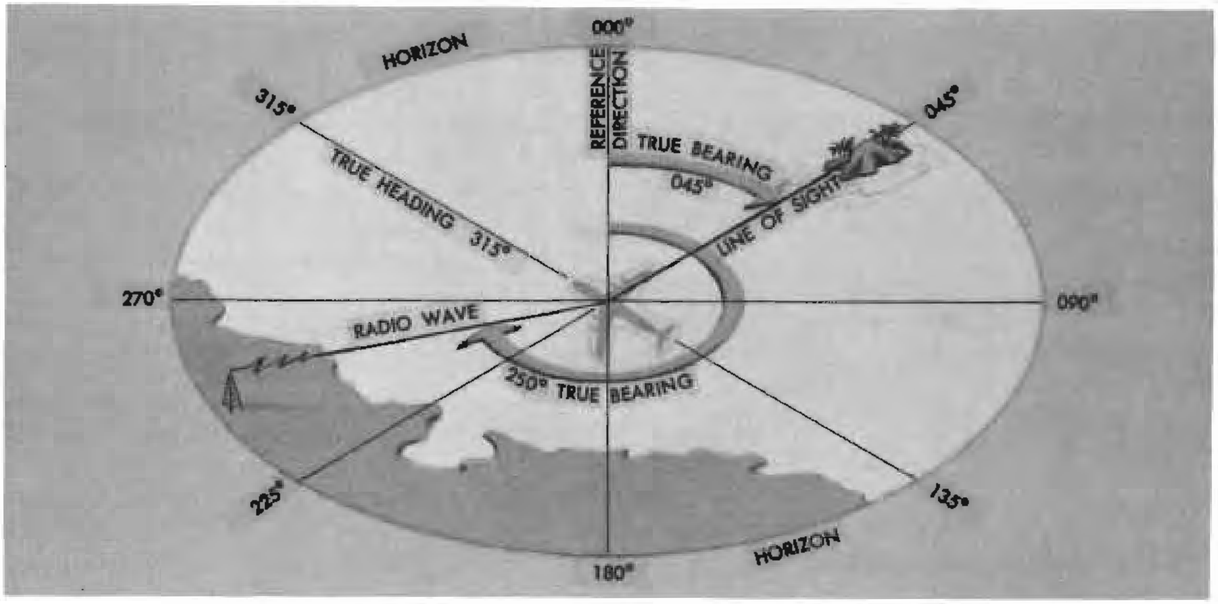


Figure 2-8. Measure True Bearing from True North

• *Bearing* is the horizontal direction of one terrestrial point from another. As illustrated in figure 2-8 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 one of two reference directions: (1) true north, or (2) the direction in which the aircraft is pointed. If true north is the reference direction, the bearing is called a *true bearing*. If the reference direction is the heading of the aircraft, the bearing is called a *relative bearing* as shown in figure 2-9. A complete explanation of these terms and their use in navigation is given in a later chapter of the manual.

Great Circle and Rhumb Line Direction

The direction of the great circle, shown in figure 2-10, makes an angle of about 50 degrees with

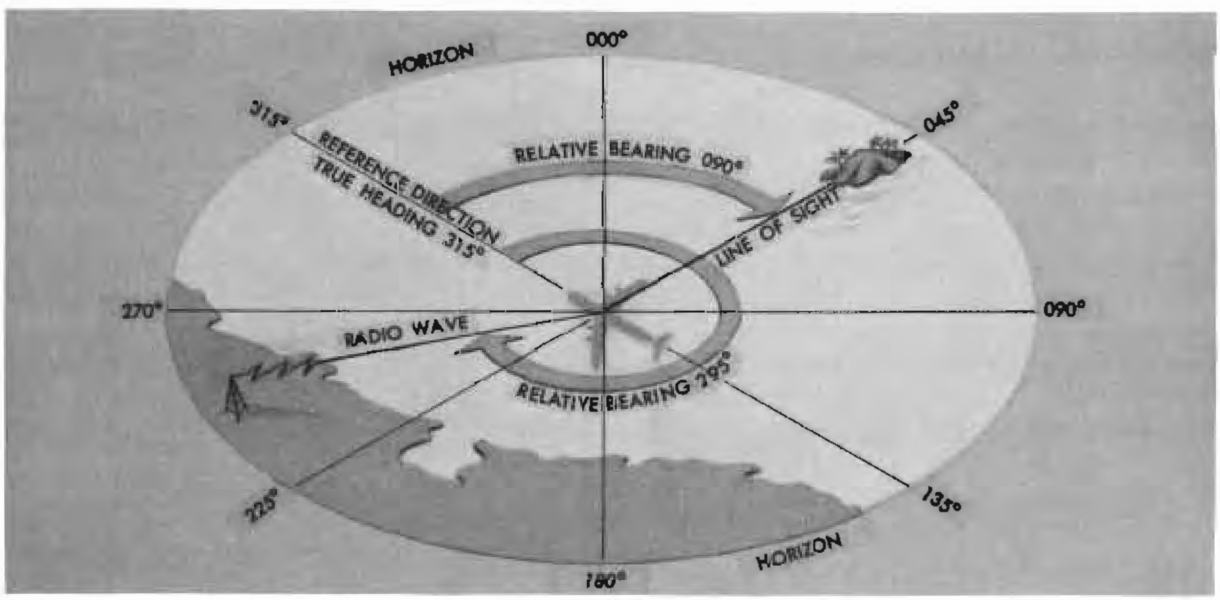


Figure 2-9. Measure Relative Bearing from Aircraft Heading

Figure 2-10. Great Circle and Rhumb Line

the meridian of New York, about 90 degrees with the meridian of Iceland, and a still greater angle with the meridian of London. In other words, the direction of the great circle 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 would be difficult to fly under ordinary conditions. Still, it is the most desirable route, since it is the shortest distance between any two points.

A line which makes the same angle with each meridian is called a rhumb line. An aircraft holding a constant true heading would be flying a rhumb line. Flying this sort of path results in a greater distance traveled, but it is easier to steer. If continued, a rhumb line spirals toward the poles in a constant true direction but never reaches them. The spiral formed is called a *loxodrome* or loxodromic curve as shown in figure 2-11.

Between two points on the earth, the great circle is shorter than the rhumb line, but the difference is negligible for short distances (except in high latitudes) or if the line approximates a meridian or the equator.

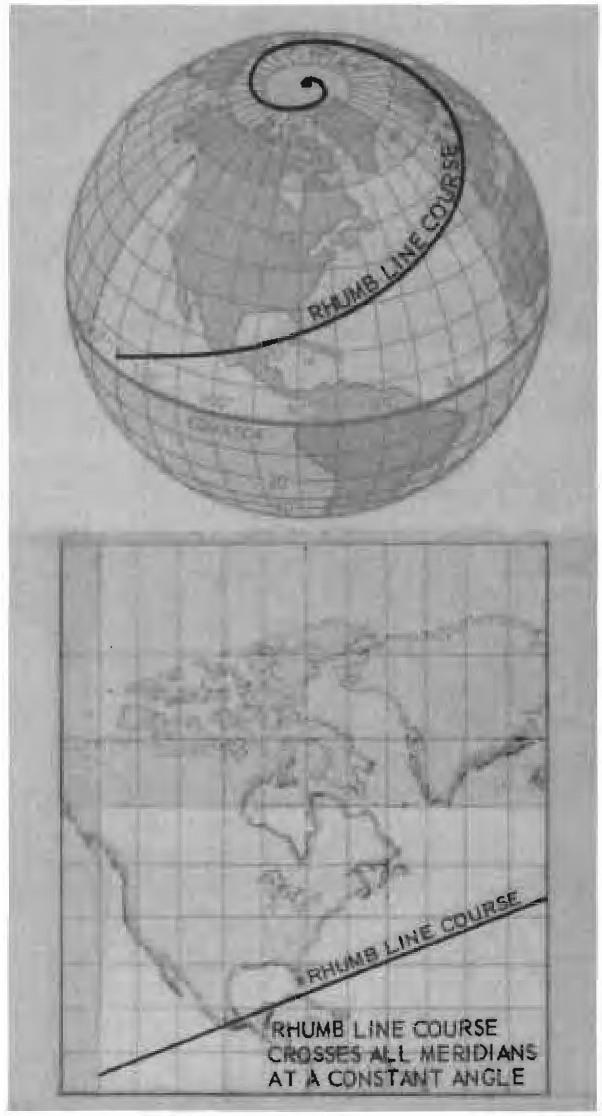


Figure 2-11. A Rhumb Line or Loxodrome

CHAPTER 3

Maps and Charts

INTRODUCTION

The history of map making is as old as history itself. The primitive peoples made rough maps on clay tablets as early as 2500 B. C. Since their maps were mere sketches of small areas, such as estates and villages, they required little geographic control. Moreover, the earth was considered flat, so the need for a projection did not arise. The idea of a spherical earth confronted the early cartographers with the basic projection problem of portraying the earth's spherical surface on a flat surface. Hipparchus (160-125 B. C.), the inventor of trigonometry, originated the basic azimuthal projections—the orthographic and the stereographic—which are in use to this day. From the time of Hipparchus to the present jet age, there has been continuing advancement in the devising of new map projections.

Basic Information

Before launching into the discussion of the projections used on the various types of aeronautical charts, the reader should become familiar with certain basic ideas and definitions relative to charts and projections in general.

- A map or chart is a small scale representation on a plane surface of the surface of the earth or some portion of it. Such a representation designed for navigational purposes is generally termed a "chart"; however, the terms "map" and "chart" are used interchangeably.
- A chart projection is a method for systematically representing the meridians and parallels of the earth on a plane surface.
- The chart projection forms the basic structure on which a chart is built and determines the fundamental characteristics of the finished chart. The positions and alignments of chart details such as roads, rivers, mountains, cities, airfields, etc., are controlled by their relationship to the projection. The relationship of position (distance and direction) of one feature to another on the chart is therefore determined by the characteristics of the projection, which must be understood in order to recognize the true relationships on the earth from the picture as presented on the chart.
- There are many difficulties which must be resolved when representing a portion of the surface of a sphere upon a plane. If you try to flatten a piece of orange skin, you will find that the outer edge must be stretched or torn before the central part will flatten into the plane with the outer part. Likewise, the surface of the earth cannot be perfectly represented on a flat surface without distortion. Distortion is misrepresentation of direction, shape, and relative size of the features of the earth's surface.

Note that you can flatten a small piece of orange peel with comparatively little tearing, stretching, or wrinkling, for it is nearly flat to begin with. Likewise, a small area of the earth, which is nearly flat, can be represented on a flat surface with little distortion. However, because the curvature of the earth is pronounced, distortion becomes a serious problem in the mapping of large areas.

Distortion cannot be entirely avoided, but it can be controlled and systematized to some extent in the drawing of a chart. If a chart is drawn for a particular purpose, it can be drawn in such a way as to minimize the type of distortion which is most deterimental to the purpose. Surfaces that can be spread out in a plane without stretching or tearing such as a cone or cylinder are called developable surfaces, and those like the sphere or spheroid

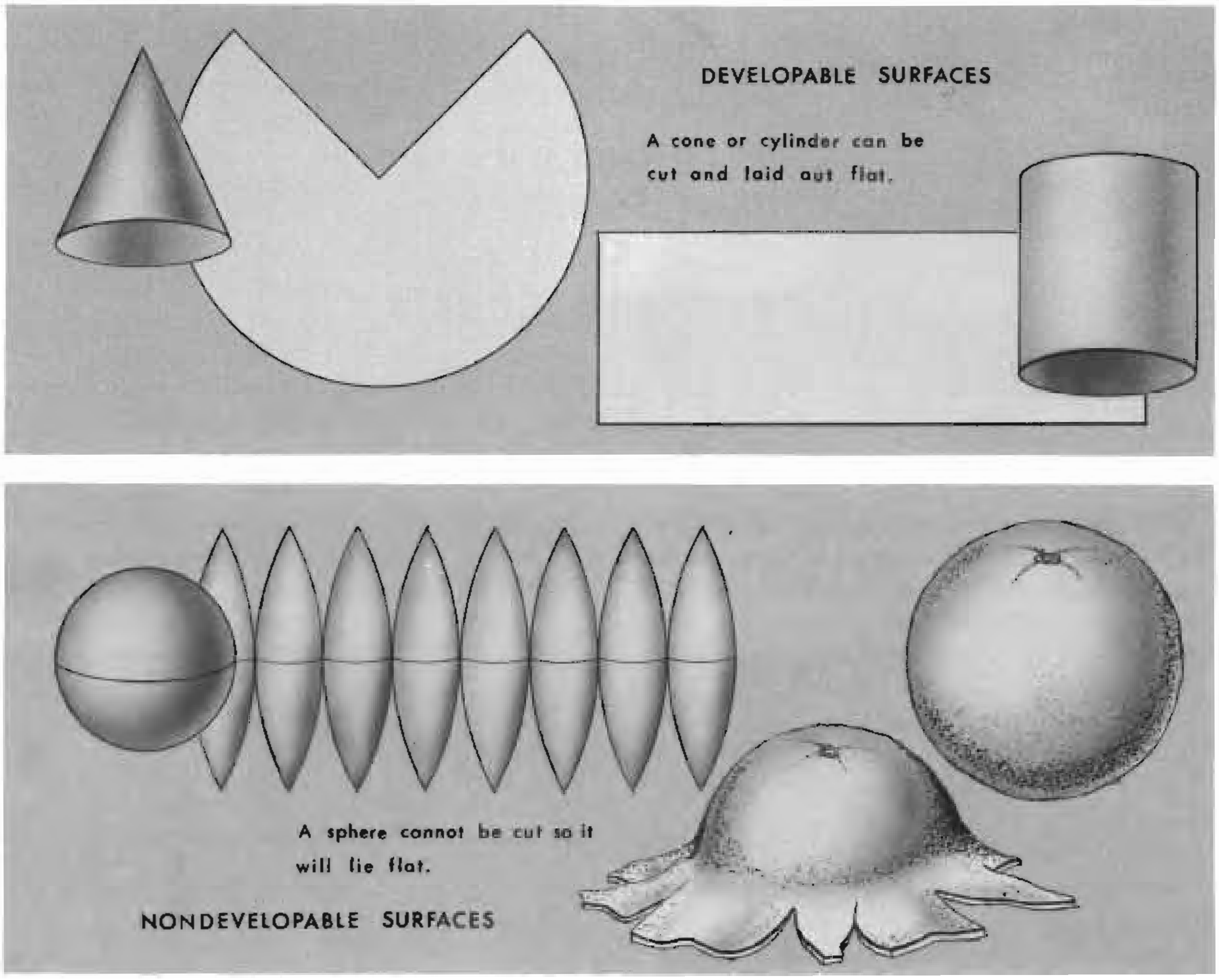


Figure 3-1. Developable and Nondevelopable Surfaces

that cannot be formed into a plane without distortion are called nondevelopable. (See figure 3-1.)

• The problem of creating a projection lies in developing a method for transferring the meridians and parallels to the chart in a manner that will preserve certain desired characteristics as nearly as possible. The methods of projection are either mathematical or perspective.

The *perspective or geometric projection* consists of projecting a coordinate system based on the earth-sphere from a given point directly onto a developable surface. The properties and appearance of the resultant map will depend upon two factors: the type of developable surface and the position of the point of projection.

• The *mathematical projection* is derived analytically to provide certain properties or characteristics which cannot be arrived at geometrically. Some of these properties or characteristics are discussed under the heading, Choice of Projection.

While it is easier to visualize the various projections in relation to a particular developable surface, in actual practice the projections used by the U.S. Air Force are not projected upon a surface but are constructed according to certain mathematical principles.

Choice of Projection

Before considering how charts are made, consider what characteristics are desirable in a chart. The ideal chart projection would portray the features of the earth in their true relationship to each other; that is, directions would be true and distance would be represented at a constant scale over the entire chart. This would result in equality of area and true shape throughout the chart.

Such a relationship can only be represented on a globe. It is impossible to preserve, on a flat chart, constant scale and true direction in all directions at all points, nor can both relative size and shape of the geographic features be accurately portrayed throughout the chart. The characteristics most commonly desired in a chart projection are:

- Conformality
- Constant scale
- Equal area
- Great circles as straight lines
- Rhumb lines as straight lines
- True azimuth
- Geographic position easily located

CONFORMALITY. Of the many projection characteristics, conformality is the most important for air navigation charts. The single property of conformality most nearly fulfills the exacting requirements levied by Air Force needs. The limitations imposed by selection of this characteristic, with the resulting loss of other desirable but inharmonious qualities, are offset by the advantages of conformality. For any projection to be conformal, three conditions must be satisfied. These three conditions are used to advantage in air navigation.

1. First, the scale at any point on the projection must be independent of azimuth. This does not imply, however, that the scale about two points at different latitudes will be equal. It means, simply, that the scale at any given point will, for a short distance, be equal in all directions.

2. Second, the outline of areas on the chart must conform in shape to the feature being portrayed. This condition applies only to small and relatively small areas; large land masses must necessarily reflect any distortion inherent in the projection.

3. Finally, since the meridians and parallels of earth intersect at right angles, the longitude and latitude lines on all conformal projections must exhibit this same perpendicularity. This characteristic facilitates the plotting of points by geographic coordinates.

CONSTANT SCALE. The property of constant scale throughout the entire chart is highly desirable but impossible to obtain, as it would require that the scale be the same at all points and in all directions throughout the chart. This would mean that the plane surface of the chart could be fitted to the globe at all points by simply bending without any stretching or contraction, an obvious impossibility.

EQUAL AREA. These charts are so designed as to maintain a constant ratio of area throughout, although original shapes may be distorted beyond recognition. Where longitudinal dimensions are increased by distortion on equal area projections, there is a corresponding decrease in latitude sufficient to maintain the area ratio. In other words, where the scale along a meridian is increased, the scale along the corresponding parallel is proportionally decreased. Equal area charts are of little value to the navigator, since an equal area chart cannot be conformal. They are, however, often used for statistical purposes.

STRAIGHT LINE. The nature of the straight line on a map is equally as important as conformality. The rhumb line and the great circle are the two curves that a navigator might wish to have represented on a map as straight lines. A rhumb line is a line that crosses all successive meridians at a constant angle. Therefore an aircraft that maintains a constant course will track a rhumb line. The rhumb line is convenient to fly; however, the only projection which shows all rhumb lines as straight lines is the Mercator. A great circle is the shortest distance between any two points on the globe. An aircraft flying a constant heading using a directional gyro compensated for earth's rotation will track a great circle course. In high latitudes, the great circle is certainly the best curve to follow, but in equatorial regions there will be little difference in following either the rhumb line or the great circle. In intermediate latitudes, a choice may be made, but on a long flight, the saving obtained by flying a great circle should be given consideration. The only projection which shows all great circles as straight lines is the gnomonic projection. However, this is not a conformal projection and cannot be used directly for obtaining direction or distance. No conformal chart will even represent all great circles as straight lines.

TRUE AZIMUTH. It would be extremely desirable to have a projection which showed directions or azimuths as true throughout the chart. This would be particularly important to the navigator, who must determine from the chart the heading he will fly. There is no chart projection that will represent true great circle direction along a straight line from all points to all other points. This would require a conformal chart on which all great circles are represented as straight lines and such a chart does not exist. The azimuthal chart, however, will show true direction for a great circle, but only from the center point or the point of tangency of the chart.

COORDINATES EASY TO LOCATE. The geographic latitudes and longitudes of places should be easily found or plotted on the map when the latitudes and longitudes are known.

CLASSIFICATION OF PROJECTIONS

Chart projections may, of course, be classified in many ways. There is no way, however, that projections may be classified to be mutually exclusive. In this manual, the various projections are divided into three classes according to the type of developable surface to which the projections are related. Projections on these surfaces are termed azimuthal, cylindrical, and conical.

Azimuthal Projections

An azimuthal or zenithal projection is one in which points on the earth are transferred directly to a plane tangent to the earth. According to the positioning of the plane and the point of projection, various geometric projections may be derived. If the origin of the projecting rays (point of projection) is the center of the sphere, a gnomonic projection results. If it is located on the surface of the earth opposite the point of the tangent plane, the projection is a stereographic, and if it is at infinity, an orthographic projection results. Figure 3-2 shows these various points of projection.

GNOMONIC PROJECTION. All gnomonic projections are direct perspective projections. The graticule is projected from a source at the center of the sphere onto a plane surface tangent at any given point. Since the plane of every great circle cuts through the center of the sphere, the point of projection is in the plane of every great circle. The arc of any great circle, being in the plane of the great circle, will intersect another plane surface in a straight line. This property then becomes the most important and useful characteristic of the gnomonic projection. Each and every great circle is represented by a straight line on the projection.

Obviously a complete hemisphere cannot be projected onto this plane, since, for points 90° distant from the center of the map, the projecting lines are parallel to the plane of projection.

Because the gnomonic is nonconformal, shapes or land masses are distorted, and measured angles are not true. At only one point, the center of the projection, are the azimuths of lines true. At this point, the projection is said to be azimuthal.

Gnomonic projections are classified according to the point of tangency of the plane of projection. A gnomonic projection is polar gnomonic when

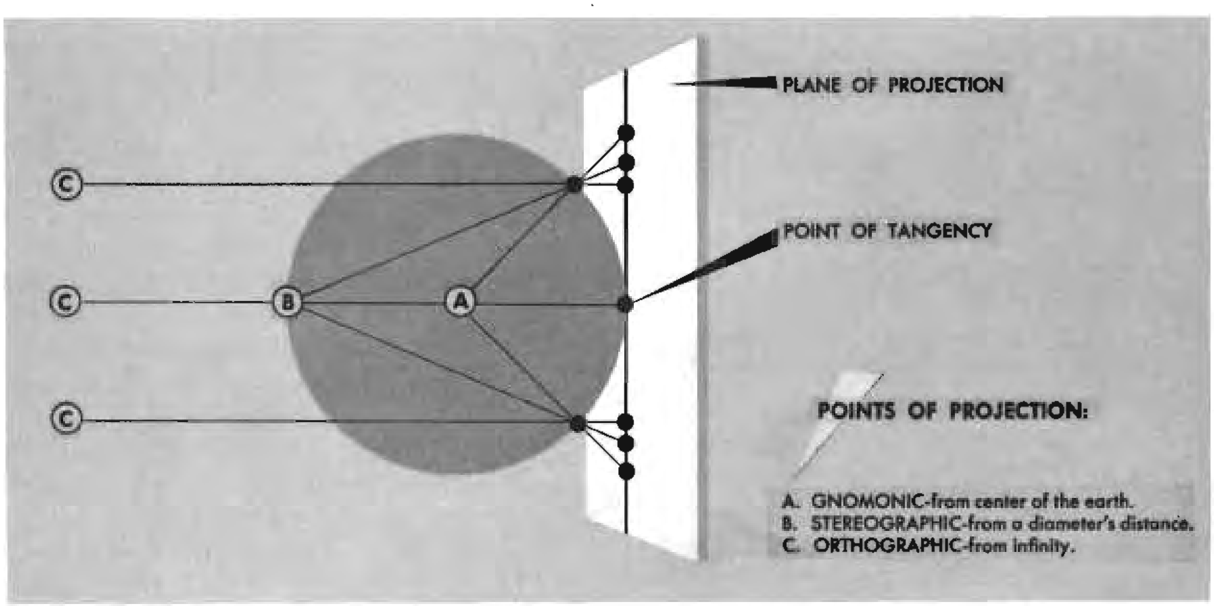


Figure 3-2. Azimuthal Projections

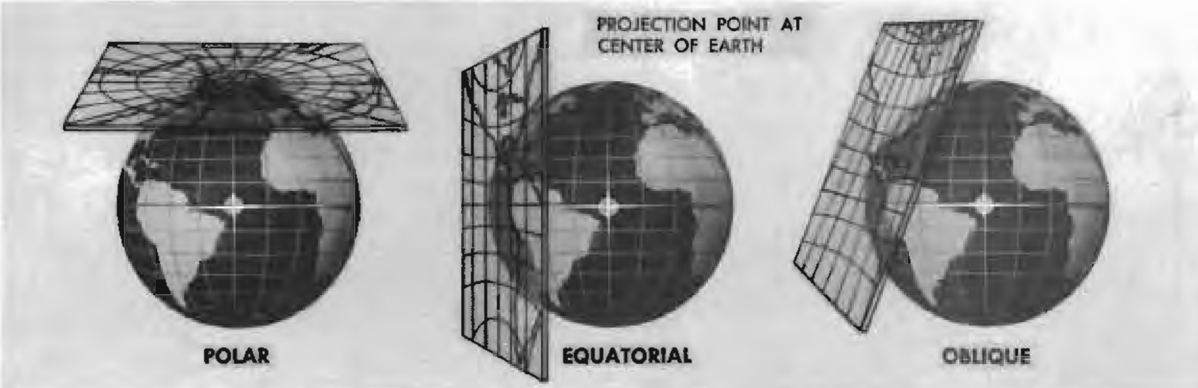


Figure 3-3. Gnomonic Projections

the point of tangency is one of the poles, equatorial gnomonic when the point of tangency is at the equator and any selected meridian, and oblique gnomonic when the point of tangency is at any point other than one of the poles or the equator. Figure 3-3 shows the plane of projection tangent to the earth at the pole, at the equator, and at a point of tangency other than one of the poles or the equator.

Polar Gnomonic. The meridians on a polar gnomonic, as on any polar projection, are radiating straight lines from the pole at true angles since the gnomonic is azimuthal at the center of the projection.

The parallels, as small circles on the sphere, are projected in concentric circles. An increasing area distortion occurs as the boundaries of the projection are approached. The equator cannot be projected, since the plane of the projection and the plane of equator are parallel. Although meridians and parallels intersect at right angles, the scale expansion along the parallels differs from rate of expansion along the meridians, therefore the polar gnomonic is not conformal.

The chart is used to determine great circle courses which are then transferred to a navigation plotting chart.

CHARACTERISTICS:

MERIDIANS: Straight lines radiating from the pole

PARALLELS: Concentric circles, distance apart increasing away from the pole

ANGLES: Angles between meridians and parallels: 90°

CONFORMALITY: Nonconformal

GREAT CIRCLES: Straight lines

RHUMB LINES: Spiral toward the pole

Figure 3-4 gives the appearance of the polar gnomonic.

Equatorial Gnomonic. The meridians on the equatorial gnomonic appear as parallel straight lines unequally spaced along and perpendicular to the equator.

The equator is also a straight line, while all other parallels are represented as hyperbolas. The equator will be an axis of symmetry for each hyperbola. The projection is also symmetrical about the central meridian (meridian of the point of tangency).

This chart is also used to determine the great

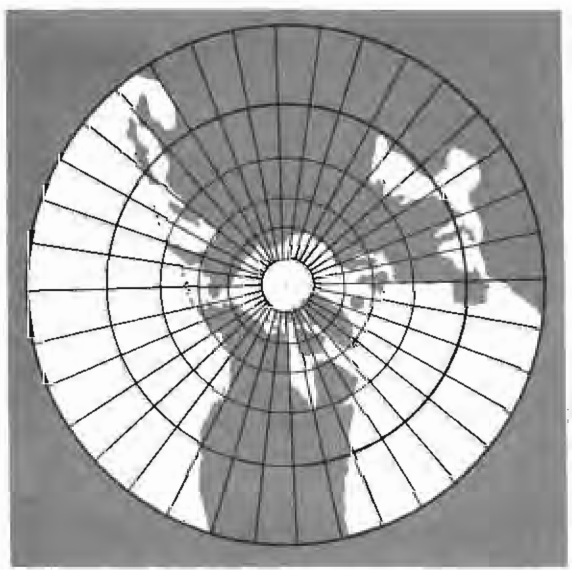


Figure 3-4. Polar Gnomonic Projection

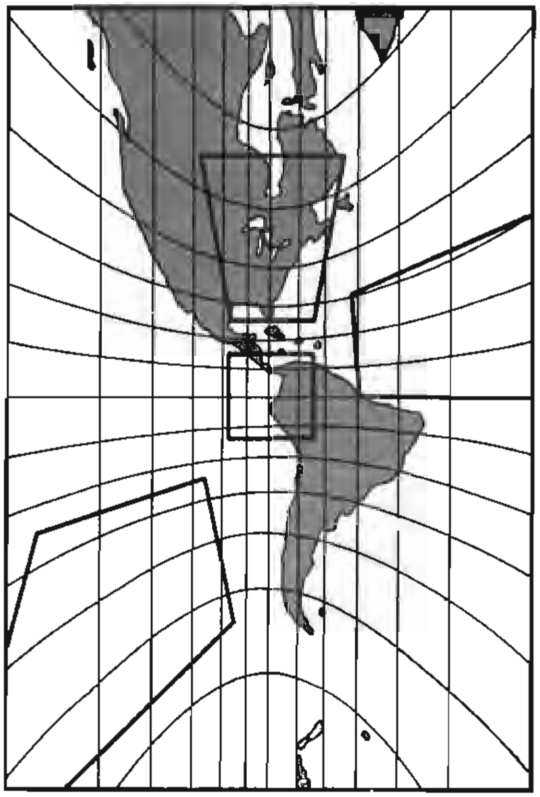


Figure 3-5. Equatorial Gnomonic Projection

circle course which can be transferred to an navigational plotting chart.

CHARACTERISTICS:

MERIDIANS: Parallel straight lines unequal distance apart

PARALLELS: Hyperbolas, concave toward the poles

ANGLES: Angles between meridians and parallels: Variable

CONFORMALITY: Nonconformal

GREAT CIRCLES: Straight lines

RHUMB LINES: Curved

Figure 3-5 gives the configuration of the equatorial gnomonic.

Oblique Gnomonic. The meridians on an oblique gnomonic projection converge in straight lines at a point representing the pole. Since the projection is nonconformal, the angles of convergence are not true.

The parallels are represented as unequally spaced, nonparallel curves convex to the equator. The oblique gnomonic has only one axis of symmetry, the central meridian passing through the center of the projection.

This chart is used by Direction Finding stations in laying off their radio bearings; it is primarily used for accurate tracking of aircraft by electronic devices.

CHARACTERISTICS:

MERIDIANS: Converging straight lines towards the pole

PARALLELS: Curved and concaved towards the pole

ANGLES: Between meridians and parallels: Variable

CONFORMALITY: Nonconformal

GREAT CIRCLES: Straight lines

RHUMB LINES: Curved

The oblique gnomonic projection is shown on figure 3-6.

STEREOGRAPHIC PROJECTION. The stereographic projection is a perspective conformal projection of the sphere. A projection based on a spheroidal surface is also a stereographic projection, having like characteristics except that it is

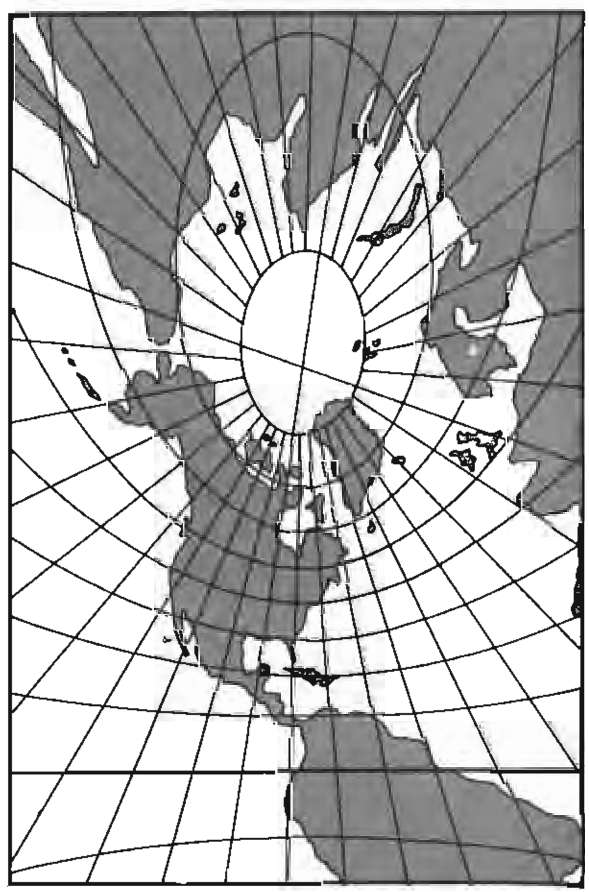


Figure 3-6. Oblique Gnomonic Projection

nonperspective. It is the only azimuthal projection which has no angular distortion and in which every circle within the area of the chart is projected as a circle. The stereographic projection is one in which the point of projection is placed on the surface at the end of the earth's diameter opposite the point of tangency.

The term horizon stereographic is applied to any stereographic projection where the center of the projection is positioned at any point other than the geographic poles or the equator. If the center is coincident with one of the poles of the reference surface, then the projection is called polar stereographic. If the center lies on the equator, then the primitive circle is a meridian, which gives the name meridian stereographic or equatorial stereographic. The illustration in figure 3-7 shows the three stereographic projections.

Horizon and Meridian Stereographic. Since the horizon stereographic and the meridian stereographic are not used in navigation, they are not discussed in this manual.

Polar Stereographic. The polar stereographic is the only stereographic projection where all the meridians are represented as straight lines. This is because all meridians pass through the projecting point. The meridians are not only represented as straight lines, but also as radiating from a point which is the center of the projection representing either the North or South Pole. The angles between meridians are true and are equal to the difference of their respective longitude values. The parallels are a series of concentric circles, their radial distances varying with the distance from the pole of the projection. Since the distance between parallels increases at the same rate as the circumference of the parallels, the scale will be the same along both the meridians and parallels at any one place.

The appearance of a great circle path on a projection is of special interest. In general, on a polar stereographic, the great circle path is an arc of a circle concave toward the pole. This is true for all great circles except meridians. The curvature of the great circle depends upon its distance from the center of projection. The closer a great circle path is to the center of the projection, the less is the curvature; i.e., the closer it is to the center of the projection, the more the curve approaches a straight line.

The great circle path represented on a stereographic projection is often stated as being approximately straight. This is true if the charted area of a stereographic projection is a small portion of a hemisphere or if the area considered is near the center of a projection. Thus the statement of a great circle path being approximately straight on a stereographic projection must be made with reservation.

CHARACTERISTICS:

MERIDIANS: Straight lines radiating from pole

PARALLELS: Concentric circles, distance apart increasing away from the pole

ANGLES: Between meridians and parallels: 90°

GREAT CIRCLE: Approximately straight near the poles, curved when not near the poles and concaved toward the pole

RHUMB LINE: Spirals toward the pole intersecting the meridians at a constant angle.

Although the rhumb line is of very little use on

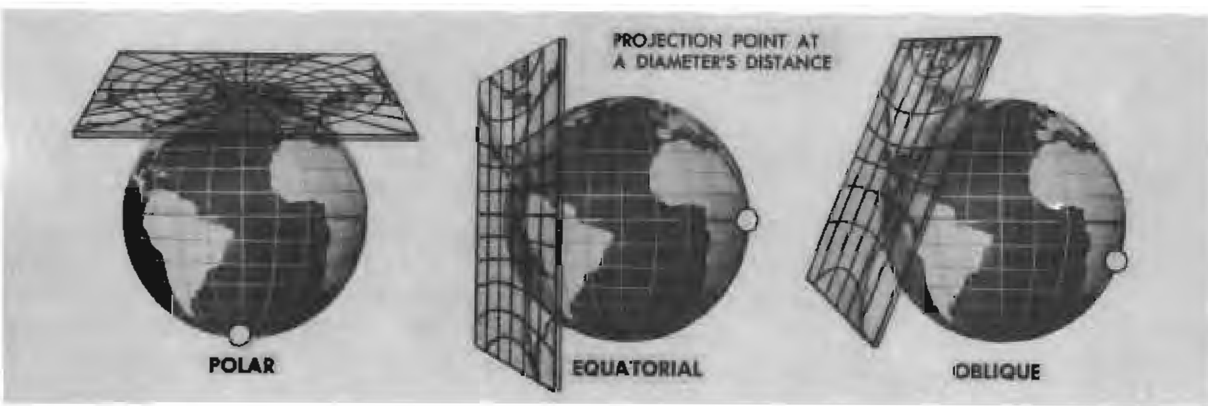


Figure 3-7. Stereographic Projections

a polar stereographic, it does present interesting sidelights and adds information to the characteristics of the projection. The rhumb line is shown as spiraling toward the pole, intersecting the meridians at a constant angle. The spiral approaches the pole more and more closely, never quite touching it. This constant angle on interesection is the same angle of intersection for the corresponding rhumb line on the surface of the earth. This is a further indication of the conformality of the projection.

The polar stereographic projection is illustrated in figure 3-8.

ORTHOGRAPHIC PROJECTION. An orthographic projection results when a light source at infinity projects the graticule of the reduced earth onto a plane tangent to the earth at some point perpendicular to the projecting rays. If the plane is tangent to the earth at the equator, the parallels appear as straight lines and the meridians as elliptical curves, except the meridian through the point of tangency, which is a straight line.

The illustration in figure 3-9 shows an equatorial orthographic projection. Its principal use in navigation is in the field of navigational astronomy, where it is useful for illustrating celestial coordinates, since the view of the moon, the sun, and other celestial bodies from the earth is essentially orthographic.

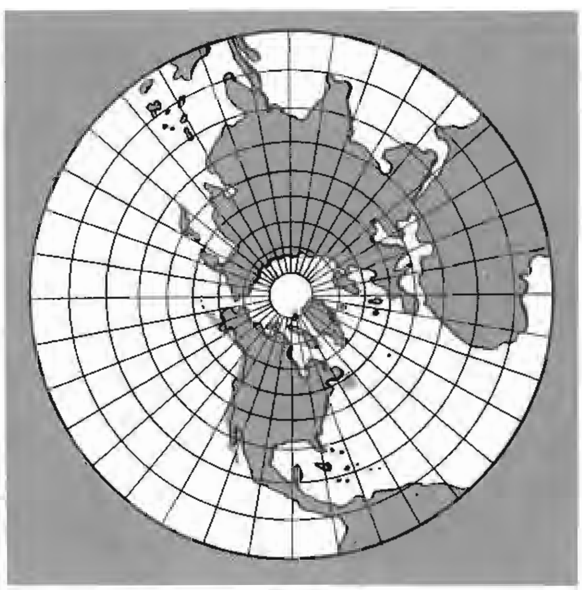


Figure 3-8. Polar Stereographic Projection

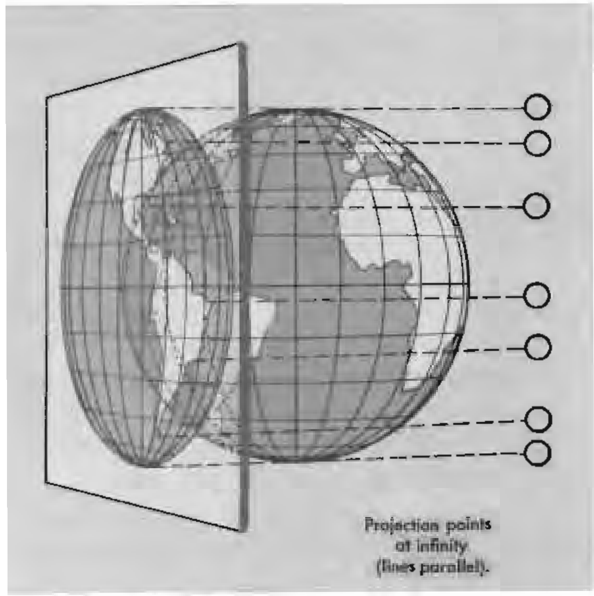


Figure 3-9. Equatorial Orthographic Projection

AZIMUTHAL EQUIDISTANT PROJECTION. This projection is neither perspective, equal area, nor conformal. It is called azimuthal equidistant because straight lines radiating from the center represent great circles as true azimuths and distances along these lines are true to scale.

The entire surface of the sphere is mapped in a circle, the diameter being equal to the circumference of the earth at reduced scale. With respect to the entire earth, the perimeter of the circle represents the points diametrically opposite the center of the projection. The appearance of the curves representing the parallels and meridians depends upon the point selected as the center of the projection and may be described in terms of three general classifications.

1. If the center is one of the poles, the meridians are represented as straight lines radiating from it, with convergence equal to unity, and the parallels are represented as equally spaced concentric circles.

2. If the center is on the equator, the meridian of the center point and its anti-meridian form a diameter of the circle (shown as a vertical line) and the equator is also a diameter perpendicular to it. One-fourth of the earth's surface is mapped in each of the quadrants of the circle determined by these two lines.

3. If the center is any other point, only the central meridian (and its anti-meridian) form a

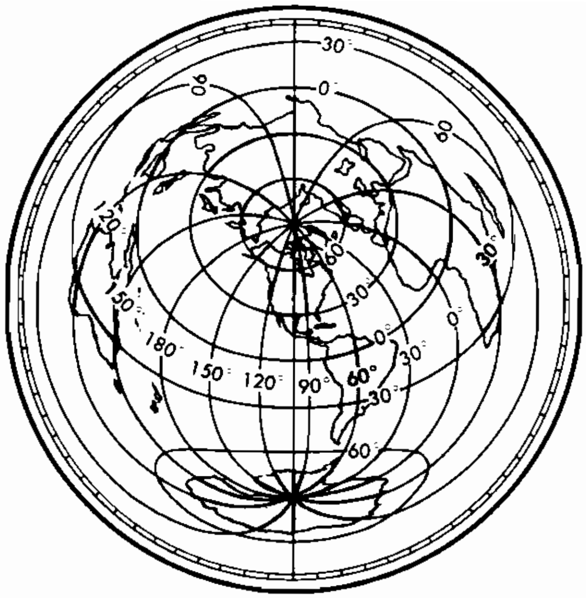


Figure 3-10. Azimuthal Equidistant Projection with Point of Tangency Lat. 40° N, Long. 100° W

straight line diameter. All other lines are curved. For an example of this projection, see figure 3-10.

The property of true distance and azimuth from the central point makes the projection useful in aeronautics and radio engineering. For example, if an important airport is selected for the point of tangency, the great circle distance and course from that point to any other position on the earth are quickly and accurately determined. Similarly, for communications work at a fixed point (point of tangency), the path of an incoming signal whose direction of arrival has been determined is at once apparent, as is the direction in which to train a directional antenna for desired results.

Cylindrical Projections

The only cylindrical projection used for navigation is the Mercator, named after its originator, Gerhard Mercator (Kramer), who first derived this type of chart in the year 1569. Before the time of this projection, mariners used a variety of charts, none of which satisfied the need for a conformal chart that depicted a rhumb line as a straight line. The Mercator is the only projection ever constructed that is conformal and at the same time displays the rhumb line as a straight line. The Mercator is probably the best known of all projections. It is used for navigation, for nearly all atlases (a word coined by Mercator), and for many wall maps.

Although copies of the original Mercator still exist, the exact method that was used in its construction is not known as Mercator himself did not indicate the method. For the sake of historical accuracy, it might be stated that his results were derived by approximate formula. The projection was further refined some years later when calculus was invented (about 1715), and better values were determined for the size of the earth.

Imagine a cylinder tangent to the equator, with the source of projection at the center of the earth. It would appear much like the illustration in figure 3-11, with the meridians being straight lines and the parallels being unequally spaced circles around the cylinder. It is obvious from the illustration that those parts of the terrestrial surface close to

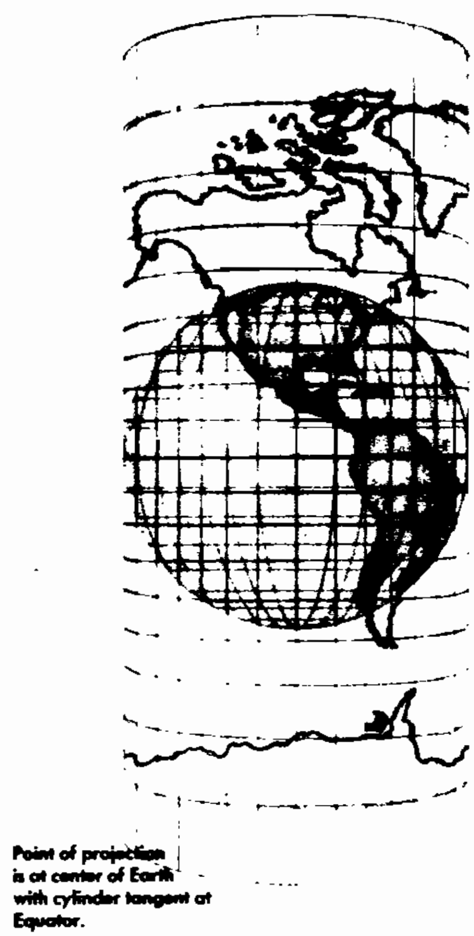


Figure 3-11. Cylindrical Projection

the poles could not be projected unless the cylinder were tremendously long, and that the poles could not be projected at all.

On the earth, the parallels of latitude are perpendicular to the meridians, forming circles of progressively smaller diameters as the latitude increases. On the cylinder, the parallels of latitude are shown perpendicular to the projected meridians, but since the diameter of a cylinder is the same at any point along the longitudinal axis, the projected parallels are all the same length. If the cylinder is cut along a vertical line—a meridian—and spread flat, the meridians appear as equalspaced, vertical lines, and the parallels as horizontal lines.

The cylinder may be tangent at some great circle other than the equator, forming other types of cylindrical projections. If the cylinder is tangent at some meridian, it is a transverse cylindrical projection, and if it is tangent at any other point than the equator or a meridian, it is called an oblique cylindrical projection. The patterns of latitude and longitude appear quite different on these projections, since the line of tangency and the equator no longer coincide.

MERCATOR PROJECTION. The Mercator projection is a conformal, nonperspective projection; it is constructed by means of a mathematical transformation and cannot be obtained directly by graphical means. The distinguishing feature of the Mercator projection among cylindrical projections is that at any latitude the ratio of expansion of both meridians and parallels is the same, thus preserving the relationship existing on the earth. This expansion is equal to the secant of the latitude, with a small correction for the ellipticity of the earth. Since expansion is the same in all directions and since all directions and all angles are correctly represented, the projection is conformal. Rhumb lines appear as straight lines, and their directions can be measured directly on the chart. Distance can also be measured directly, but not by a single distance scale on the entire chart, unless the spread of latitude is small. Great circles appear as curved lines, concave to the equator, or convex to the nearest pole. The shapes of small areas are very nearly correct, but are of increased size unless they are near the equator as shown in figure 3-12.

CHARACTERISTICS: The Mercator has the following characteristics:

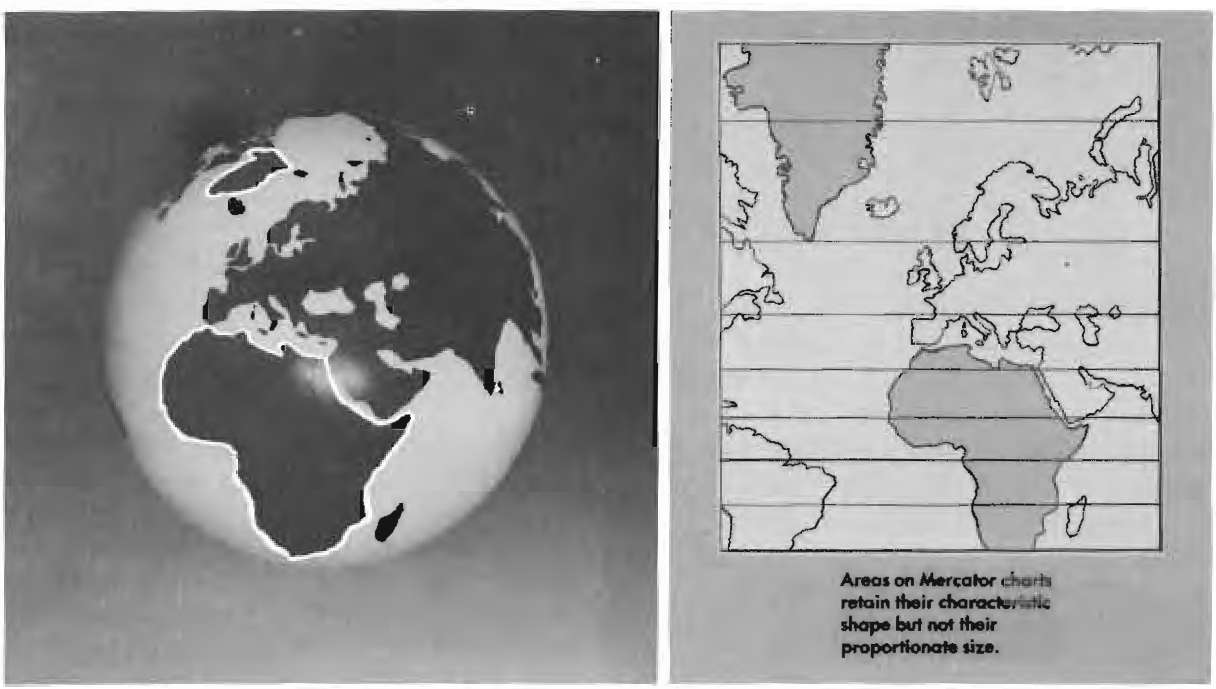


Figure 3-12. Mercator is Conformal But Not Equal-Area

MERIDIANS: Straight, parallel lines, intersecting the parallels.

PARALLELS: Straight, parallel lines, at right angles.

SCALE: Correct only at the equator; elsewhere it expands as the secant of the latitude. Thus, the scale of a chart can apply only to a given latitude, and a variable scale is required to measure distances.

POLES: Because the secant of 90 degrees is infinity, the poles cannot be shown on the equatorial Mercator.

RHUMB LINE: Straight line.

GREAT CIRCLE: Curved line convex to the nearest pole.

CONFORMALITY: Projection is conformal and accordingly cannot be equal area. Areas are greatly exaggerated in high latitudes.

The Mercator projection has the following disadvantages:

- Difficulty of measuring large distances accurately.
- Conversion angle must be applied to great circle bearing before plotting.
- The chart is useless in polar regions above 80° N or S since the poles cannot be shown.

TRANSVERSE MERCATOR. The transverse or inverse Mercator is a conformal map designed for areas not covered by the equatorial Mercator. With the transverse Mercator, the property of straight meridians and parallels is lost, and the rhumb line is no longer represented by a straight line. The parallels and meridians become complex curves, and with geographic reference, the transverse Mercator is difficult to use as a plotting chart. The transverse Mercator, though often considered analogous to a projection onto a cylinder, is in reality a nonperspective projection that is constructed mathematically. This analogy (illustrated in figure 3-13) however, does permit the reader to visualize that the transverse Mercator will show scale eorrectly along the central meridian which forms the great circle of tangency. In effect, the cylinder has been turned 90 degrees from its position for the ordinary Mercator, and some meridian, called the central meridian, becomes the tangential great circle. One series of USAF charts using this type of projection places the cylinder tangent to the 90°E-90°W longitude.

These projections use a fictitious graticule similar to, but offset from, the familiar network of meridians and parallels. The tangent great circle is the fictitious equator. Ninety degrees from it are two fictitious poles. A group of great circles through these poles and perpendicular to the tangent constitutes the fictitious meridians, while a series of lines parallel to the plane of the tangent great circle forms the fictitious parallels.

On these projections, the fictitious graticule appears as the geographical one ordinarily appears on the equatorial Mercator. That is, the fictitious meridians and parallels are straight lines perpendicular to each other. The actual meridians and parallels appear as curved lines, except the line of tangency. Geographical coordinates are usually expressed in terms of the conventional graticule. A straight line on the transverse Mercator projection makes the same angle with all fictitious meridians, but not with the terrestrial meridians. It is therefore, a fictitious rhumb line.

The appearance of a transverse Mercator using the 90°E-90°W meridian as a reference or fictitious equator is shown in figure 3-13. The dotted lines are the lines of the fictitious projection. The N-S meridian through the center is the fictitious equator, and all other original meridians are now curves concave to the N-S meridian with the original parallels now being curves concave to the nearer pole.

CHARACTERISTICS:

MERIDIANS: The meridian of tangency and the two meridians 90 degrees removed from it are straight lines; all other meridians are curves concave to the tangent meridian.

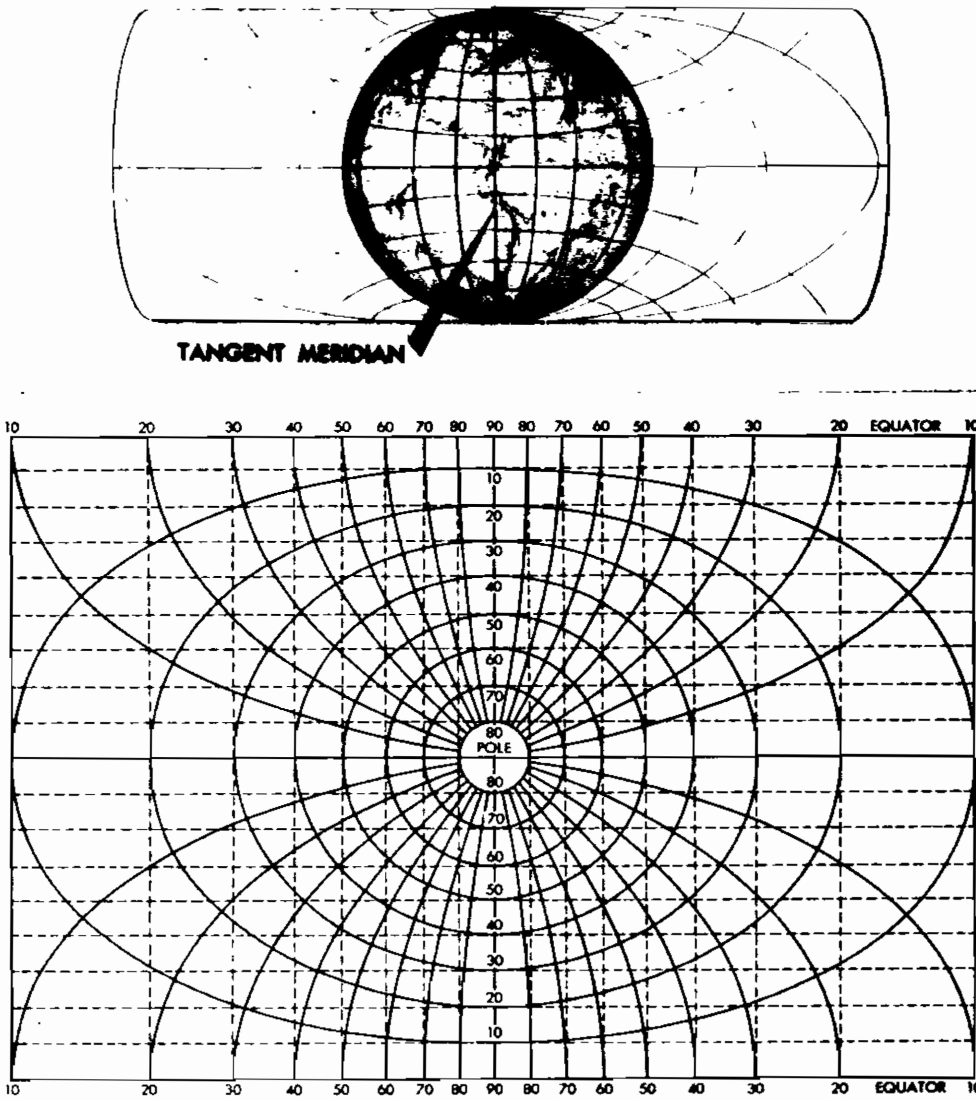
PARALLELS: The equator is represented by a straight line; all other parallels are curves concave to the nearer pole. Meridians and parallels intersect at right angles.

SCALE: Scale is correct only along the tangent meridian; elsewhere, it is expanded. But at any point, scale expansion is the same in all directions.

GREAT CIRCLES: All lines perpendicular to the tangent meridian are great circles. Lines running parallel to the tangent meridian are small circles. Points 90 degrees from the tangent meridian cannot be projected.

CONFORMALITY: The projection is conformal, and accordingly cannot be equal-area.

OBLIQUE MERCATOR. The cylindrical projection in which the cylinder is tangent at a great



Transverse Mercator with Superimposed Conventional Mercator Graticule.

Figure 3-13. Transverse Cylindrical Projection—Cylinder Tangent at the Poles

circle other than the equator or a meridian is called an oblique Mercator (figure 3-14).

You can see that as a sphere fits into a cylinder, it makes no difference how it is turned. The fit, or line of tangency, can be any great circle. Thus, the Oblique Mercator projection is unique in that it is prepared and used for special purposes. This projection is used principally to depict an area in the near vicinity of an oblique great circle, as, for instance, along the great circle route between two important centers a relatively great distance apart (see figure 3-15).

Consider a flight between Seattle and Tokyo. The shortest distance is naturally the great circle distance and is, therefore, the route to fly. Plotting the great circle on a Mercator, you find that it takes the form of a high arching curve as shown. Since the scale on a Mercator changes with latitude, there will be a considerable scale change

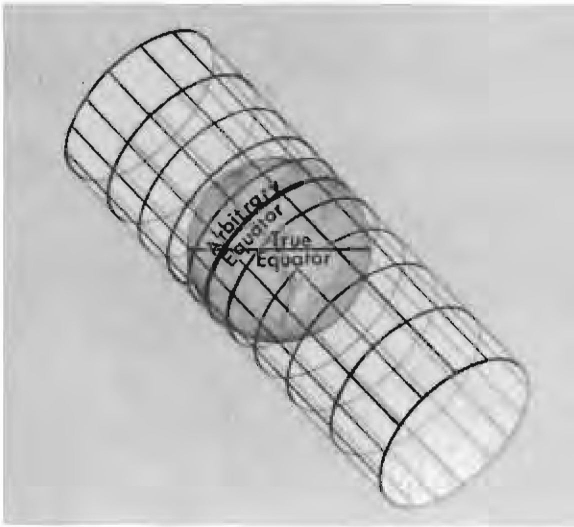


Figure 3-14. Oblique Mercator Projection

when you consider the latitude band that this great circle route covers.

If you were only concerned with the great circle route and a small band of latitude (say 5°) on either side, the answer to your problem would be the Oblique Mercator. With the cylinder made tangential along the great circle joining Seattle and Tokyo, the resultant graticule would enjoy most of the good properties found near the equator on a conventional Mercator.

Advantages. The Oblique Mercator projection has several desirable properties. The projection is conformal. The x axis is a great circle course at true scale. The projection can be constructed using any desired great circle as the x axis. The scale is equal to the secant of the angular distance from the x axis. Therefore, near the x axis the scale change is slight. This makes the projection almost ideal for strip charts of great-circle flights.

Limitations. The projection also has many disadvantages. Rhumb lines are curved lines, therefore, the chart is of little use to the navigator. Scale expansion and area distortion in the region of the oblique pole are the same as that of the standard Mercator in the region of the pole. Radio bearings cannot be plotted directly on the chart. All meridians and parallels are curved lines. A separate projection must be computed and constructed for each required great circle course.

Conic Projections

There are two classes of conic projections. The first is a simple conic projection constructed by placing the apex of the cone over some part of the earth (usually the pole) with the cone tangent to a parallel called the standard parallel and project-

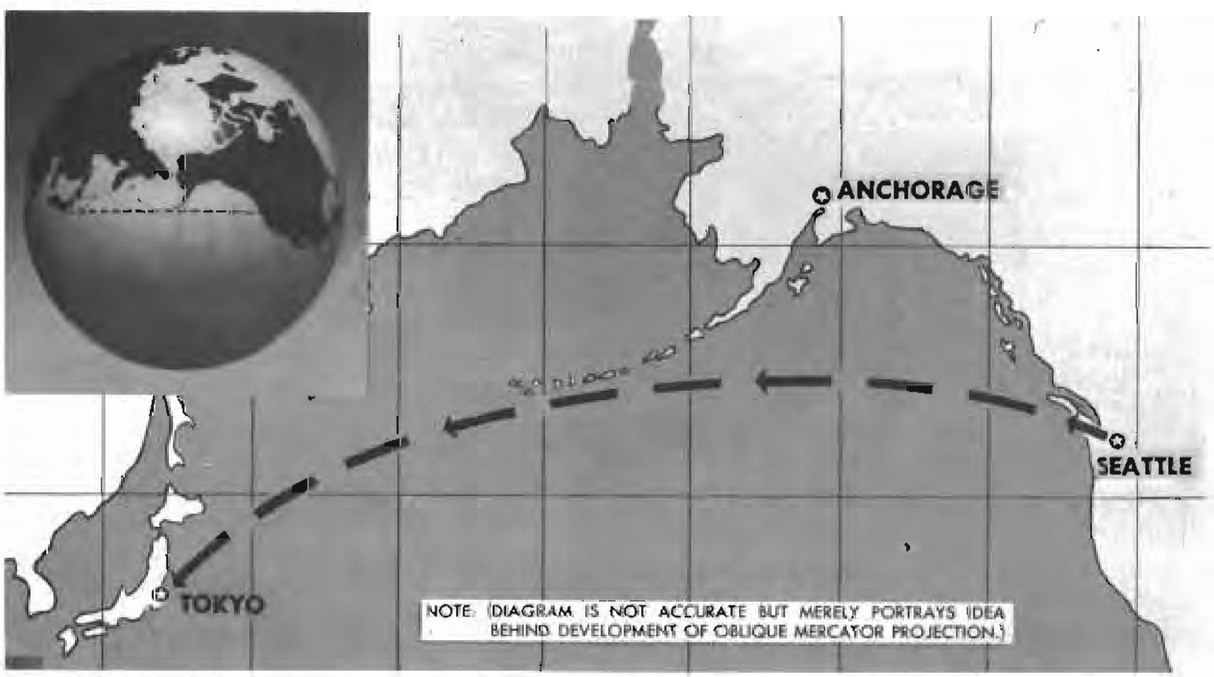


Figure 3-15. Great Circle Route from Seattle to Tokyo on Mercator Projection

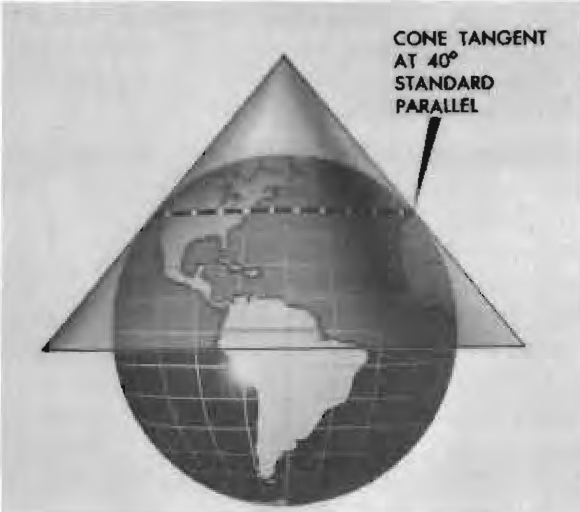


Figure 3-16. Simple Conic Projection

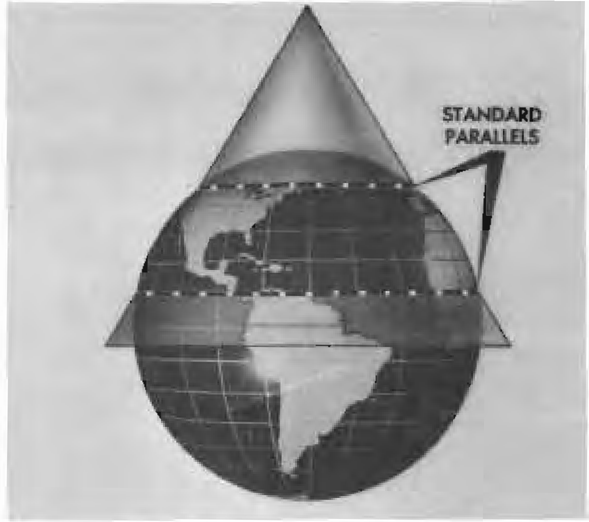


Figure 3-18. Conic Projection Using Secant Cone

ing the graticule of the reduced earth onto the cone as shown in figure 3-16. The chart is obtained by cutting the cone along some meridian and unrolling it to form a flat surface. Notice in figure 3-17, the characteristic gap that appears when the cone is unrolled. The second is a secant cone, cutting through the earth and actually contacting the surface at two standard parallels as shown in figure 3-18.

LAMBERT CONFORMAL (Secant Cone).

Characteristics. The Lambert Conformal conic projection is of the conical type in which the meridians are straight lines which meet at a common point beyond the limits of the chart and parallels are concentric circles, the center of which is the point of intersection of the meridians. Meridians and parallels intersect at right angles. Angles formed by any two lines or curves on the earth's surface are correctly represented.

The projection may be developed by either the graphic or mathematical method. It employs a secant cone intersecting the spheroid at two parallels of latitude, called the standard parallels, of the area to be represented. The standard parallels are represented at exact scale. Between these parallels the scale factor is less than unity and beyond them greater than unity. For equal distribution of scale error (within and beyond the standard parallels) the standard parallels are selected at one-sixth and five-sixths of the total length of the segment of the central meridian represented. The development of the Lambert Conformal conic projection is shown by figure 3-19.

The great elliptic is a curve closely approximating a straight line.

The geodesic is a curved line always concave toward the mid-parallel, except in the case of a meridian where, by definition, it is a straight line.

The loxodrome, with the exception of meridians, is a curved line concave toward the pole.

Uses. The chief use of the Lambert Conformal conic projection is in mapping areas of small latitudinal width but great longitudinal extent. No projection can be both conformal and equal area,

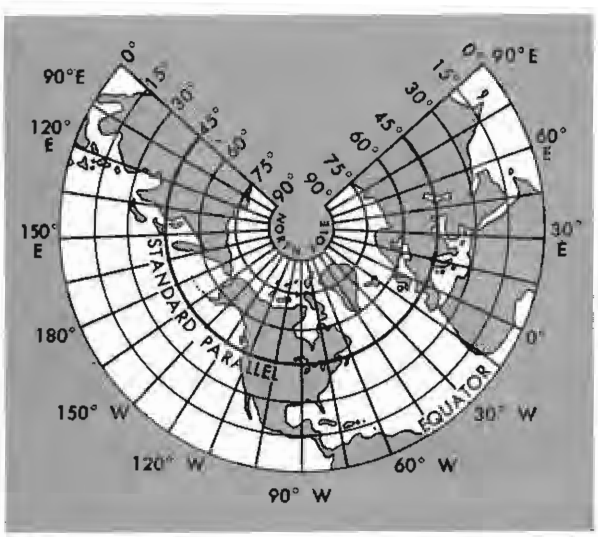


Figure 3-17. Simple Conic Projection of Northern Hemisphere

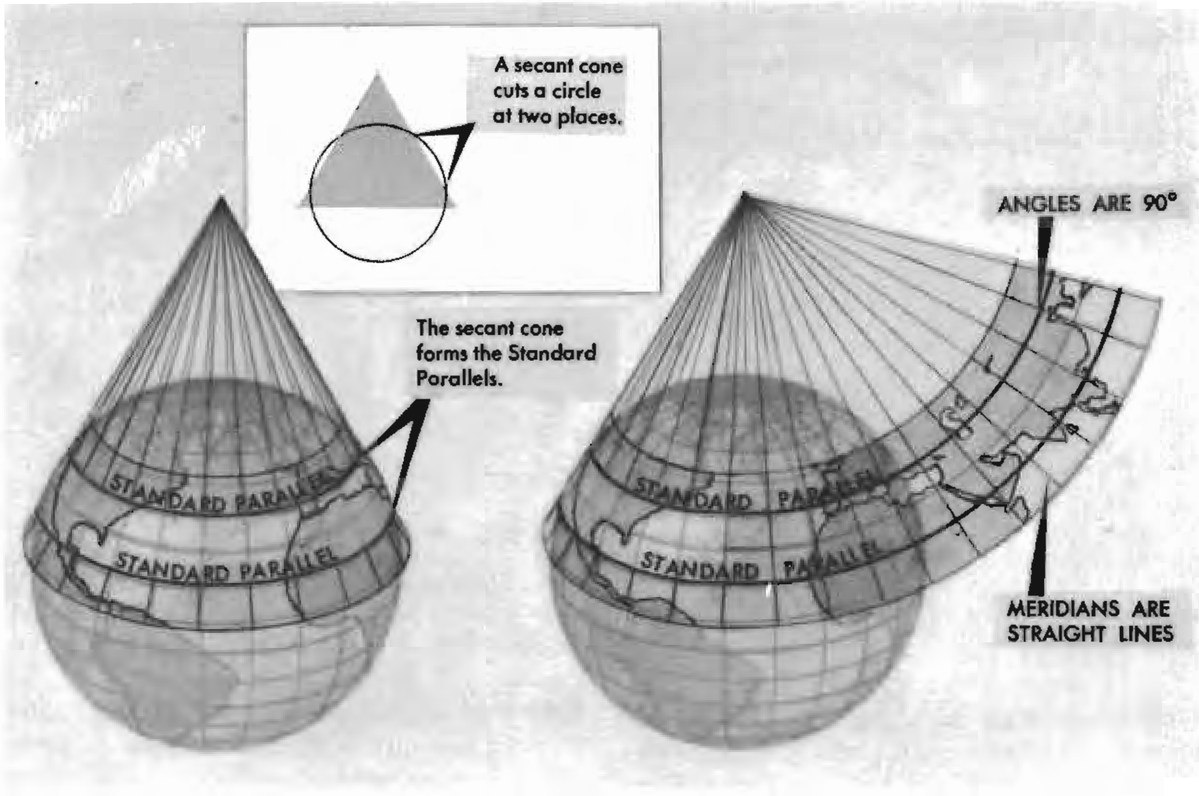


Figure 3.19. Lambert Conformal Conic Projection

but by limiting latitudinal width, scale error is decreased to the extent that the projection gives very nearly an equal area representation in addition to the inherent quality of conformality. This makes the projection very useful for aeronautical charts.

Advantages. Some of the chief advantages of the Lambert Conformal conic projection are:

- Conformality
- Great circles are approximated by straight lines (actually concave toward the mid-parallel).
- For areas of small latitudinal width, scale is nearly constant. For example, the U.S. may be mapped with standard parallels 33°N and 45°N with a scale error of only 2½% for southern Florida. The maximum scale error between 30° 30'N and 47°30'N is only one-half of 1%.
- Positions are easily plotted and read in terms of latitude and longitude.
- Construction is relatively simple.
- Its two standard parallels give it two "lines of strength" (lines along which elements are represented true to shape and scale).
- Distances may be measured quite accurately. For example the distance from Pittsburgh to Constantinople is 5,277 statute miles; distance as measured by the graphic scale on a Lambert projection (standard parallels 36°N and 54°N) without application of the scale factor is 5,258 statute miles, an error of less than four-tenths of 1%.

Limitations. Some of the chief limitations of the Lambert Conformal Conic projection are:

- Rhumb lines are curved lines which cannot be plotted accurately.
- Great circles are curved lines concave toward the mid-parallel.
- Maximum scale increases as latitudinal width increases.
- Parallels are curved lines (arcs of concentric circles).
- Continuity of conformality ceases at the junction of two bands, even though each is conformal. If both have the same scale along their standard parallels, the common parallel (junction) will have a different radius for each band, therefore they will not join perfectly.

CONSTANT OF THE CONE. Most conic charts have the constant of the cone (convergence factor)

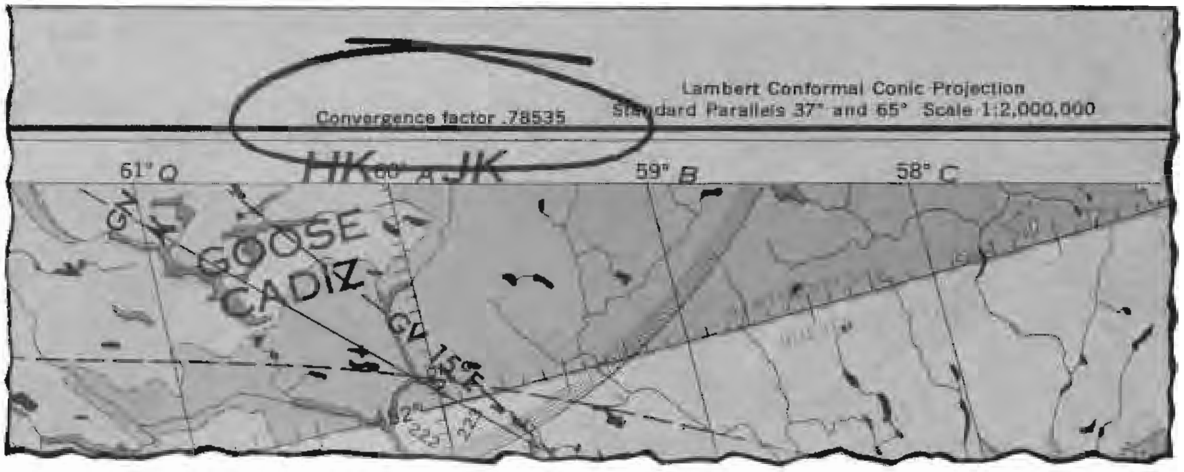


Figure 3-20. Convergence Factor on JN Chart

computed and listed on the chart as shown in figure 3-20.

CONVERGENCE ANGLE. The convergence angle is the actual angle on a chart formed by the intersection of the Greenwich meridian and some other meridian; the pole serves as the vertex of the angle. Convergence angles, like longitudes, are measured east and west from the Greenwich meridian.

CONVERGENCE FACTOR. A chart's convergence factor is a decimal number which expresses the ratio between meridional convergence as it actually exists on the earth and as it is portrayed on the chart. When the convergence angle equals the number of the selected meridian, the chart convergence factor is 1.0. When the convergence angle is less than the number of the selected meridian, the chart convergence factor is proportionately less than 1.0.

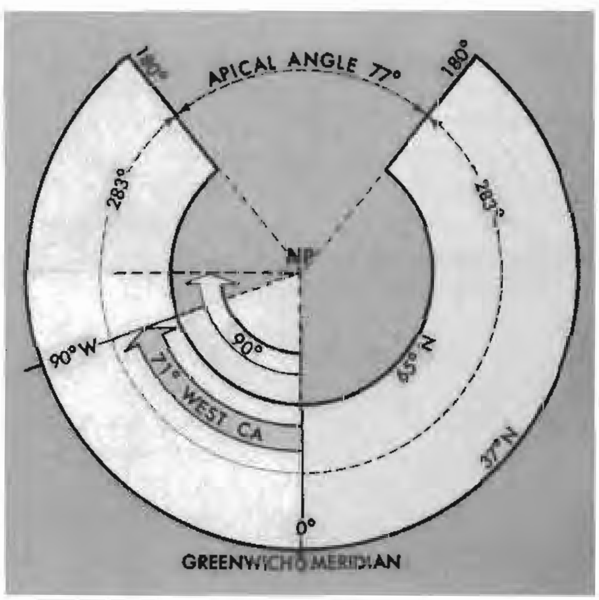


Figure 3-21. A Lambert Conformal, Convergence Factor 0.785

The subpolar projection illustrated in figure 3-21 portrays the standard parallels, 37°N and 65°N. It presents 360 degrees of the earth's surface on 283 degrees of paper. Therefore, the chart has a convergence factor (CF) of 0.785 (283 degrees divided by 360 degrees equals 0.785). Meridian 90°W forms a west convergence angle (CA) of 71° with the Greenwich meridian. Expressed as a formula:

$CF \times \text{longitude} = CA$

$0.785 \times 90°W = 71°$ west CA

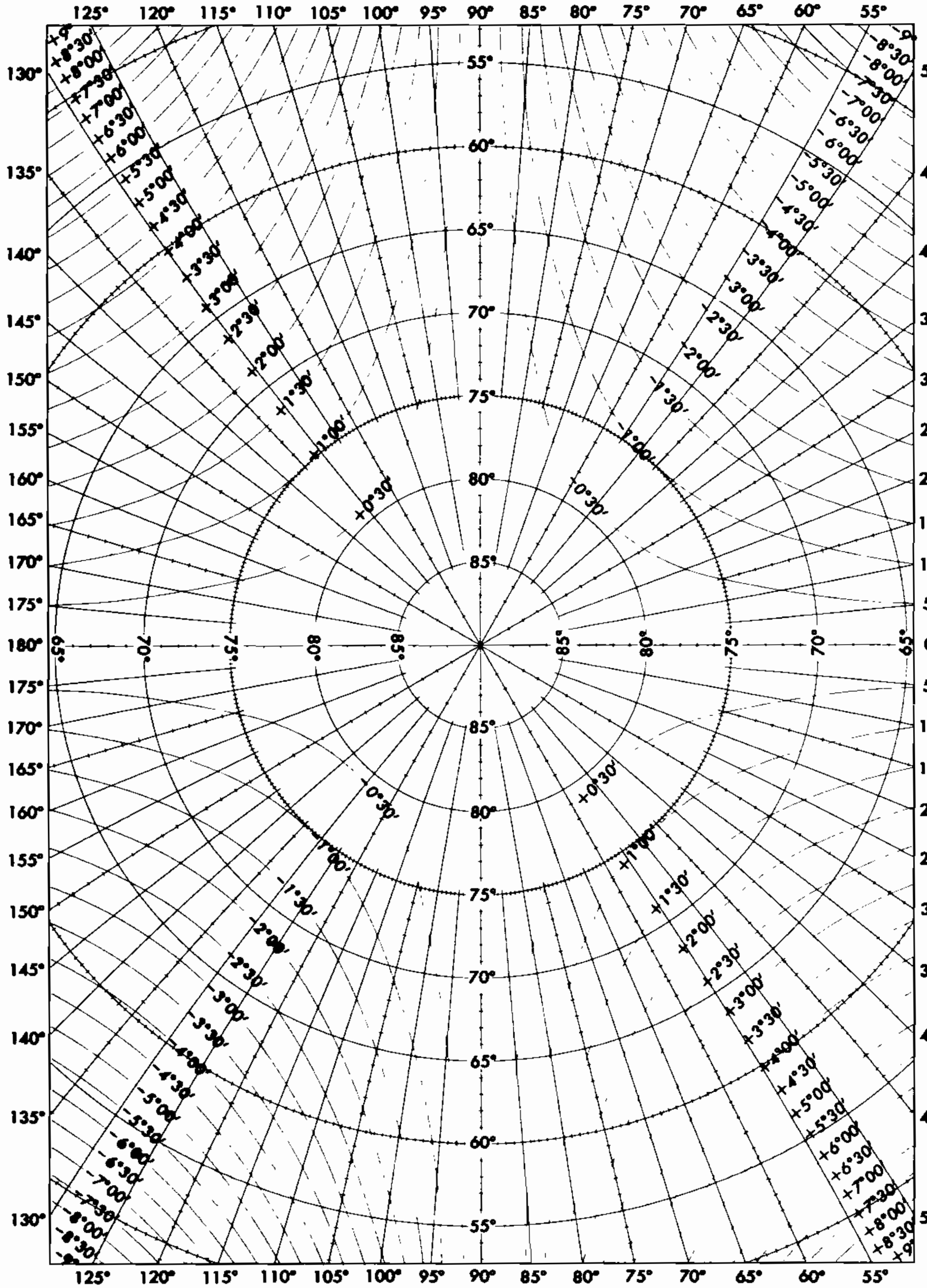
A chart's convergence factor is easily approximated on subpolar charts by:

1. Drawing a straight line which covers 10 lines of longitude.

2. Measuring the true course at each end of the line, noting the difference between them, and dividing the difference by 10.

3. The quotient represents the chart's convergence factor.

On the Transverse Mercator projections the convergence factor varies with latitude and longitude. To obtain the correct convergence factor follow the instructions in figure 3-22.



To obtain the convergence angle required for determination of heading information:

A. Place pencil point on geographic location for which heading information is to be determined.

B. Note correction factor lines indicating ½ degree interval of correction annotated in green.

C. Interpret correction factor to closest ¼ degree.

D. Add correction factor algebraically to longitude of point. The result is the convergence angle for that specific point.

E. Grid Heading equals True Heading plus or minus Convergence Angle: GH = TH ± Convergence Angle.

Figure 3-22. Transverse Mercator Convergence Graph