

# CHAPTER 2

## GEODESY AND DATUMS IN NAVIGATION

### GEODESY, THE BASIS OF CARTOGRAPHY

#### 200. Definition

**Geodesy** is the application of mathematics to model the size and shape of the physical earth, enabling us to describe its magnetic and gravitational fields and a coordinate referencing system to precisely position and navigate globally using one 3-dimensional coordinate system.

Today's modern Global Navigation Satellite Systems (GNSS), such as GPS, have made it possible to establish a truly global geocentric reference system which can be quickly adapted for precise positioning and navigation over long distances.

Thus, the precision of today's navigation systems and the global nature of satellite and other long-range positioning methods demand a more complete understanding of geodesy by the navigator than has ever before been required.

#### 201. The Shape of the Earth

In geodetic applications, three primary reference surfaces for the Earth are used (See Table 201):

1. a **physical surface**,
2. an **ellipsoid of revolution**, which is a reference surface of purely mathematical nature, and
3. the **geoid** (an irregular surface, which has no complete mathematical expression).

A physical surface is tangible, it can be traversed and measurements can be made on it. The topography, ice caps, or sea surface area all physical surfaces.

An equipotential surface is one where the force of gravity is always equal and the direction of gravity is always perpendicular. The **geoid** is a particular equipotential surface that would coincide with the mean ocean surface of the Earth if the oceans and atmosphere were in equilibrium, at rest relative to the rotating Earth, and extended through the continents (such as with very narrow canals).

In common practice, an **ellipsoid height** is the distance a given point is above or below the ellipsoid surface, whereas a **geoid height** is the distance the geoid surface is above or below the ellipsoid surface. Determination of a "mean

sea level" is a difficult problem because of the many factors that affect sea level. Sea level varies considerably on several scales of time and distance and the extent of this variability is the result of seas that are in constant motion, affected by the solar and lunar tides, wind, atmospheric pressure, local gravitational differences, temperature, and salinity. In geodetic applications, the geoid is then used to serve as the vertical reference surface to approximate measure mean sea level (MSL) heights and a height measured from the geoid to a point is called an **orthometric height**. In areas where elevation data are not available from conventional geodetic leveling, an approximation of MSL heights using orthometric heights from the geoid can be obtained from the equation listed in Table 201. This equation

$H = h - N$
where
H = orthometric height (the height relative to the geoid)
h = ellipsoid (geodetic) height (the height relative to the ellipsoid)
N = geoid height (undulation)

Table 201. Relations between orthometric, ellipsoid and geoid heights.

illustrates the determination of the orthometric height (H) of a point as a subtraction of the geoid height (N) from the ellipsoid height (h).

#### 202. Defining the Ellipsoid

An **ellipsoid** is uniquely defined by specifying two parameters. Geodesists, by convention, use the **semi-major axis** and either **eccentricity** or **flattening**. The size is represented by the radius at the equator, the semi-major axis. The shape of the ellipsoid is given by the flattening, which indicates how closely an ellipsoid approaches a spherical shape. The flattening (f) is the ratio of the difference between the semi-major (a) and semi-minor (b) axes of the ellipsoid and the semi-major axis.

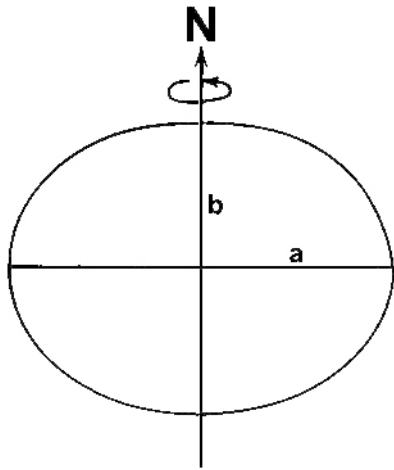


Figure 202. An ellipsoid of revolution, with semimajor axis (a), and semiminor axis (b).

$$f = \frac{a - b}{a}$$

The ellipsoidal Earth model has its minor axis parallel to the Earth's polar axis. Rotating the ellipse about the semi-minor axis gives the ellipsoid of revolution. See Figure 202.

**203. Ellipsoids and the Geoid as Reference Surfaces**

Since the surface of the geoid is irregular and the surface of an ellipsoid is regular, no ellipsoid can provide more than an approximation of part of the geoidal surface. Historically, ellipsoids that best fit the geoid regionally were employed. The widespread use of GNSS has facilitated the use of global, best fitting ellipsoids. The most common are the World Geodetic System 1984 (WGS 84) and the Geodetic Reference System of 1980 (GRS 80) ellipsoids. See Table 203 for WGS 84 defining parameters.

Parameter	Symbol	Value	Units
Semi-major Axis (Equatorial Radius of the Earth)	a	6378137.0	m
Flattening factor of the Earth	1/f	298.257223563	
Geocentric Gravitational Constant	GM	3.986004418 10 <sup>+14</sup>	m <sup>3</sup> /s <sup>2</sup>
Nominal Mean Angular Velocity of the Earth	ω	7.292115 10 <sup>-05</sup>	rads / s

Table 203. WGS 84 defining parameters.

**204. Coordinates**

The **astronomic latitude** is the angle between a plumb line and the plane of the celestial equator. It is the latitude which results directly from observations of celestial bodies, uncorrected for deflection of the vertical component in the meridian (north-south) direction. Astronomic latitude applies only to positions on the Earth. It is reckoned from the astronomic equator (0°), north and south through 90°.

The **astronomic longitude** is the angle between the plane of the celestial meridian at a station and the plane of the celestial meridian at Greenwich. It is the longitude which results directly from observations of celestial bodies, uncorrected for deflection of the vertical component in the prime vertical (east-west) direction. These are the coordinates observed by the celestial navigator using a sextant and a very accurate clock based on the Earth's rotation.

Celestial observations by geodesists are made with optical instruments (theodolite, zenith camera, prismatic astrolabe) which all contain leveling devices. When properly adjusted, the vertical axis of the instrument coincides with the direction of gravity, which may not coincide with the plane of the meridian. Thus, geodetically derived astronomic positions are referenced to the geoid. The difference, from a navigational standpoint, is too small to be of concern.

The **geodetic latitude** is the angle which the normal to the ellipsoid at a station makes with the plane of the geodetic equator. In recording a geodetic position, it is essential that the geodetic datum on which it is based also be stated. A geodetic latitude differs from the corresponding astronomic latitude by the amount of the meridian component of the local deflection of the vertical. See Figure 204.

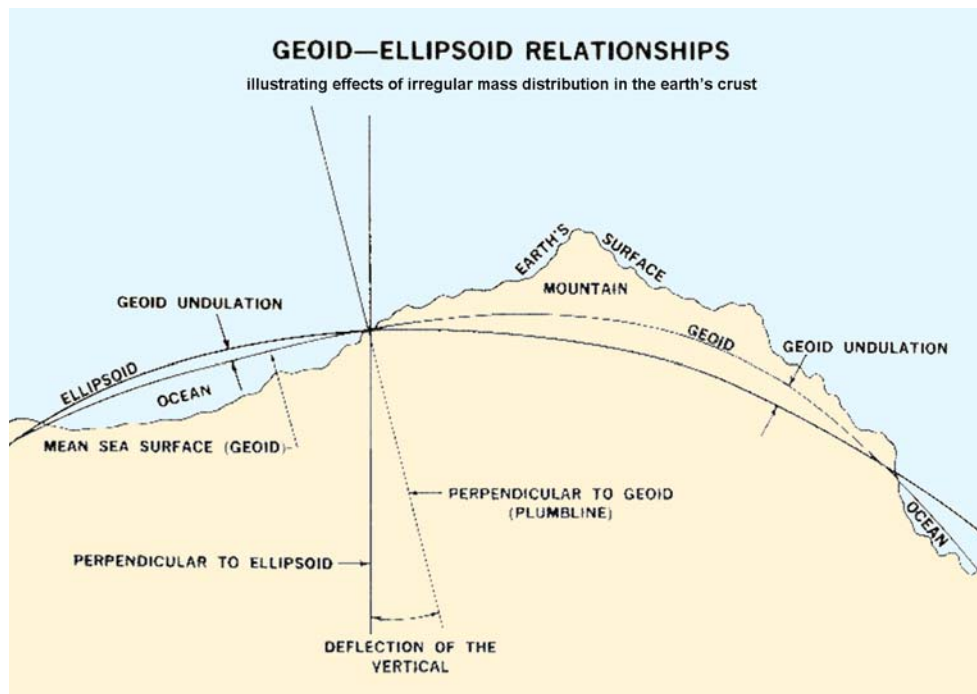


Figure 204. Geoid-ellipsoid relationships.

The **geodetic longitude** is the angle between the plane of the geodetic meridian at a station and the plane of the geodetic meridian at Greenwich. A geodetic longitude differs from the corresponding astronomic longitude by the prime vertical component of the local deflection of the vertical divided by the cosine of the latitude. The geodetic coordinates are used for mapping.

The **geocentric latitude** is the angle at the center of the ellipsoid (used to represent the Earth) between the plane of the equator, and a straight line (or radius vector) to a point on the surface of the ellipsoid. This differs from geodetic latitude because the Earth is approximated more closely by a spheroid than a sphere and the meridians are ellipses, not perfect circles.

Both geocentric and geodetic latitudes refer to the reference ellipsoid and not the Earth. Since the parallels of latitude are considered to be circles, geodetic longitude is

geocentric, and a separate expression is not used.

Because of the oblate shape of the ellipsoid, the length of a degree of geodetic latitude is not everywhere the same, increasing from about 59.7 nautical miles at the equator to about 60.3 nautical miles at the poles.

A classic regional **horizontal geodetic datum** usually consists of the astronomic and geodetic latitude, and astronomic and geodetic longitude of an initial point (origin); an azimuth of a line (direction); the parameters (radius and flattening) of the ellipsoid selected for the computations; and the geoidal separation at the origin. A change in any of these quantities affects every point on the datum.

For this reason, while positions within a given datum are directly and accurately relatable, those from different datums must be transformed to a common datum for consistency.

## TYPES OF GEODETIC SURVEY

### 205. Satellite Positioning

The use of artificial satellite signals allows positioning without the necessity of line-of-sight. Positions (including heights) determined in this manner are *directly* referred to the ellipsoid. Static precise positioning is commonly employed to determine or extend geodetic control.

Absolute positioning uses a single stationary receiver to determine a position with respect to the center of the Earth. Relative static positioning determines a position with respect to another station and involves multiple receivers

operating simultaneously. Specialized processing is required for these highly accurate survey methods.

The position of a moving receiver often depends on a reference receiver at a known point that broadcasts corrections in some fashion. The corrections are derived from the difference between the known position of the base and the position determined by the current constellation.

The electro-optical survey methods discussed following this section on satellite positioning must be *reduced* to the ellipsoid for computations.

## 206. Triangulation

The most common type of geodetic survey is known as **triangulation**. Triangulation consists of the measurement of the angles of a series of triangles. The principle of triangulation is based on plane trigonometry. If the distance along one side of the triangle and the angles at each end are accurately measured, the other two sides and the remaining angle can be computed. In practice, all of the angles of every triangle are measured to provide precise measurements. Also, the latitude and longitude of one end of the measured side along with the length and direction (azimuth) of the side provide sufficient data to compute the latitude and longitude of the other end of the side.

The measured side of the base triangle is called a **baseline**. Measurements are made as carefully and accurately as possible with specially calibrated tapes or wires of Invar, an alloy with a very low coefficient of expansion. The tape or wires are checked periodically against standard measures of length.

To establish an arc of triangulation between two widely separated locations, the baseline may be measured and longitude and latitude determined for the initial points at each location. The lines are then connected by a series of adjoining triangles forming quadrilaterals extending from each end. All angles of the triangles are measured repeatedly to reduce errors. With the longitude, latitude, and azimuth of the initial points, similar data is computed for each vertex of the triangles, thereby establishing triangulation stations, or geodetic control stations. The coordinates of each of the stations are defined as geodetic coordinates.

Triangulation is extended over large areas by connecting and extending series of arcs to form a network or triangulation system. The network is adjusted so as to reduce observational errors to a minimum. A denser distribution of geodetic control is achieved by subdividing or filling in with other surveys.

There are four general classes or orders of triangulation. **First-order** (primary) triangulation is the most precise and exact type. The most accurate instruments and rigorous computation methods are used. It is costly and time-consuming, and is usually used to provide the basic framework of control data for an area, and the determination of the figure of the Earth. The most accurate first-order surveys furnish control points which can be interrelated with an accuracy ranging from 1 part in 25,000 over short distances to approximately 1 part in 100,000 for long distances.

**Second-order** triangulation furnishes points closer together than in the primary network. While second-order surveys may cover quite extensive areas, they are usually tied to a primary system where possible. The procedures are less exacting and the proportional error is 1 part in 10,000.

**Third-order** triangulation is run between points in a secondary survey. It is used to densify local control nets and

position the topographic and hydrographic detail of the area. Error can amount to 1 part in 5,000.

The sole accuracy requirement for **fourth-order** triangulation is that the positions be located without any appreciable error on maps compiled on the basis of the control. Fourth-order control is done primarily as mapping control.

## 207. Trilateration, Traverse, And Vertical Surveying

**Trilateration** involves measuring the sides of a chain of triangles or other polygons. From them, the distance and direction from A to B can be computed. Figure 207 shows this process.

**Traverse** involves measuring distances and the angles between them without triangles for the purpose of computing the distance and direction from A to B. See Figure 207.

**Vertical surveying** is the process of determining elevations above mean sea-level. In geodetic surveys executed primarily for mapping, geodetic positions are referred to an ellipsoid, and the elevations of the positions are referred to the geoid. However, for satellite geodesy the geoidal heights must be considered to establish the correct height above the geoid.

Precise geodetic **leveling** is used to establish a basic network of vertical control points. From these, the height of other positions in the survey can be determined by supplementary methods. The mean sea-level surface used as a reference (vertical datum) is determined by averaging the hourly water heights for a specified period of time at specified tide gauges.

There are three leveling techniques: **differential**, **trigonometric**, and **barometric**. Differential leveling is the most accurate of the three methods. With the instrument locked in position, readings are made on two calibrated staffs held in an upright position ahead of and behind the instrument. The difference between readings is the difference in elevation between the points.

Trigonometric leveling involves measuring a vertical angle from a known distance with a theodolite and computing the elevation of the point. With this method, vertical measurement can be made at the same time horizontal angles are measured for triangulation. It is, therefore, a somewhat more economical method but less accurate than differential leveling. It is often the only mechanical method of establishing accurate elevation control in mountainous areas.

In barometric leveling, differences in height are determined by measuring the differences in atmospheric pressure at various elevations. Air pressure is measured by mercurial or aneroid barometer, or a boiling point thermometer. Although the accuracy of this method is not as great as either of the other two, it obtains relative heights very rapidly at points which are fairly far apart. It is used in reconnaissance and exploratory surveys where more accurate measurements will be made later or where a high degree of accuracy is not required.

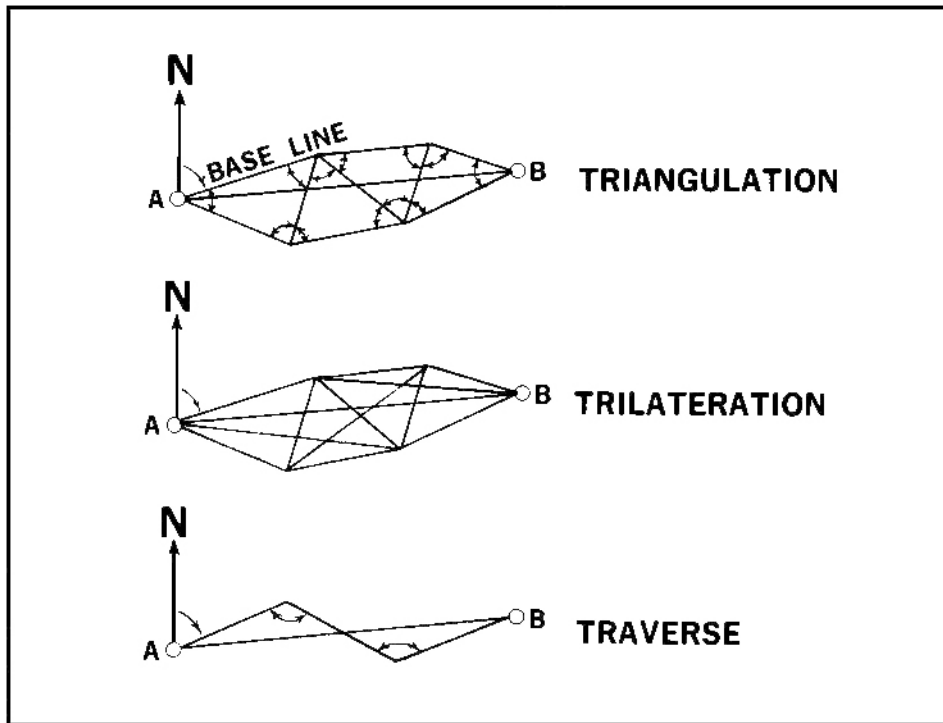


Figure 207. Triangulation, trilateration, and traverse.

## MODERN GEODETIC SYSTEMS

### 208. Development of the World Geodetic System

By the late 1950's the increasing range and sophistication of weapons systems had rendered local or national datums inadequate for military purposes; these new weapons required datums at least continental, if not global, in scope. In response to these requirements, the U.S. Department of Defense generated a geocentric (earth-centered) reference system to which different geodetic networks could be referred, and established compatibility between the coordinate systems. Efforts of the Army, Navy, and Air Force were combined, leading to the development of the DoD **World Geodetic System of 1960 (WGS 60)**.

In January 1966, a World Geodetic System Committee was charged with the responsibility for developing an improved WGS needed to satisfy mapping, charting, and geodetic requirements. Additional surface gravity observations, results from the extension of triangulation and trilateration networks, and large amounts of Doppler and optical satellite data had become available since the development of WGS 60. Using the additional data and improved techniques, the Committee produced **WGS 66** which served DoD needs following its implementation in 1967.

The same World Geodetic System Committee began work in 1970 to develop a replacement for WGS 66. Since the

development of WGS 66, large quantities of additional data had become available from both Doppler and optical satellites, surface gravity surveys, triangulation and trilateration surveys, high precision traverses, and astronomic surveys.

In addition, improved capabilities had been developed in both computers and computer software. Continued research in computational procedures and error analyses had produced better methods and an improved facility for handling and combining data. After an extensive effort extending over a period of approximately three years, the Committee completed the development of the Department of Defense **World Geodetic System 1972 (WGS 72)**.

Further refinement of WGS 72 resulted in the new **World Geodetic System of 1984 (WGS 84)**, now referred to as simply WGS. For surface navigation, WGS 60, 66, 72 and the new WGS 84 are essentially the same, so that positions computed on any WGS coordinates can be plotted directly on the others without correction.

The WGS system is not based on a single point, but many points, fixed with extreme precision by satellite fixes and statistical methods. The result is an ellipsoid which fits the real surface of the Earth, or geoid, far more accurately than any other. The WGS system is applicable worldwide. All regional datums can be referenced to WGS once a survey tie has been made.

### 209. The North American Datum of 1983

The Office of Coast Survey of the National Ocean Service (NOS), NOAA, is responsible for charting United States waters. From 1927 to 1987, U.S. charts were based on North American Datum 1927 (NAD 27), using the Clarke 1866 ellipsoid. In 1989, the U.S. officially switched to **NAD 83** (navigationally equivalent to WGS) for all mapping and charting purposes, and all new NOAA chart production is based on this new standard.

The grid of interconnected surveys which criss-crosses the United States consists of some 250,000 control points, each consisting of the latitude and longitude of the point, plus additional data such as elevation. Converting the NAD 27 coordinates to NAD 83 involved recomputing the position of each point based on the new NAD 83 datum. In addition to the 250,000 U.S. control points, several thousand more were added to tie in surveys from Canada, Mexico, and Central America.

Conversion of new edition charts to the new datums, either WGS 84 or NAD 83, involves converting reference points on each chart from the old datum to the new, and adjusting the latitude and longitude grid (known as the graticule) so that it reflects the newly plotted positions. This adjustment of the graticule is the only difference between charts which differ only in datum. All charted features remain in exactly the same relative positions.

The Global Positioning System (GPS) has transformed the science of surveying, enabling the establishment of precise ties to WGS in areas previously found to be too remote to survey to modern standards. As a result, new charts are increasingly precise as to position of features. The more recent a chart's date of publishing, the more likely it is that it will be accurate as to positions. Navigators should always refer to the title block of a chart to determine the date of the chart, the date of the surveys and sources used to compile it, and the datum on which it is based.

## DATUMS AND NAVIGATION

### 210. Datum Shift

One of the most serious impacts of different datums on navigation occurs when a navigation system provides a fix based on a datum *different* from that used for the nautical chart. The resulting plotted position may be different from the actual location on that chart. This difference is known as a **datum shift**.

Modern electronic navigation systems have software installed that can output positions in a variety of datums, eliminating the necessity for applying corrections. All electronic charts produced by NGA are compiled on WGS and are not subject to datum shift problems as long as the GPS receiver is outputting WGS position data to the display system. The same is true for NOAA charts of the U.S., which are compiled on NAD 83 datum, very closely related to WGS. GPS receivers default to WGS, so that no action is necessary to use any U.S.-produced electronic charts.

To automate datum conversions, a number of datum transformation software programs have been written that will convert from any known datum to any other, in any location. MSPGEO-TRANS is such a program. The amount of datum shift between two different datums is not linear. That is, the amount of shift is a function of the position of the observer, which must be specified for the shift to be computed. Varying differences of latitude and longitude between two different datums will be noted as one's location changes.

There are still a few NGA-produced paper charts, and a number of charts from other countries, based on datums other than WGS. If the datum of these charts is noted in the title block of the chart, most GPS receivers can be set to output position data in that datum, eliminating the datum shift problem. If the datum is not listed, extreme caution is nec-

essary. An offset can sometimes be established if the ship's actual position can be determined with sufficient accuracy, and this offset applied to GPS positions in the local area. But remember that since a datum shift is not linear, this offset is only applicable locally.

Another effect on navigation occurs when shifting between charts that have been compiled using different datums. If a position is replotted on a chart of another datum using latitude and longitude, the newly plotted position will not match with respect to other charted features. The datum shift may be avoided by transferring positions using bearings and ranges to common points. If datum shift conversion notes for the applicable datums are given on the charts, positions defined by latitude and longitude may be replotted after applying the noted correction.

The positions given for chart corrections in the *Notice to Mariners* reflect the proper datum for each specific chart and edition number. Due to conversion of charts based on old datums to more modern ones, and the use of many different datums throughout the world, chart corrections intended for one edition of a chart may not necessarily be safely plotted on any other.

As noted, datum shifts are not constant throughout a given region, but vary according to how the differing datums fit together. For example, the NAD 27 to NAD 83 conversion resulted in changes in latitude of 40 meters in Miami, 11 meters in New York, and 20 meters in Seattle. Longitude changes for this conversion amounted to 22 meters in Miami, 35 meters in New York, and 93 meters in Seattle.

Most charts produced by NGA and NOAA show a "datum note." This note is usually found in the title block or in the upper left margin of the chart. According to the

year of the chart edition, the scale, and policy at the time of production, the note may say “World Geodetic System 1972 (WGS-72)”, “World Geodetic System 1984 (WGS-84)”, or “World Geodetic System (WGS).” A datum note for a chart for which satellite positions can be plotted without correction will read: “Positions obtained from satellite navigation systems referred to (Reference Datum) can be plotted directly on this chart.”

NGA reproductions of foreign charts will usually be in the datum or reference system of the producing country. In these cases a conversion factor is given in the following format: “Positions obtained from satellite navigation systems referred to the (Reference Datum) must be moved X.XX minutes (Northward/Southward) and X.XX minutes (Eastward/ Westward) to agree with this chart.”

Some charts cannot be tied in to WGS because of lack of recent surveys. Currently issued charts of some areas are based on surveys or use data obtained in the Age of Sail. The lack of surveyed control points means that they cannot be properly referenced to modern geodetic systems. In this case there may be a note that says: “Adjustments to WGS cannot be determined for this chart.”

A few charts may have no datum note at all, but may carry a note which says: “From various sources to (year).” In these cases there is no way for the navigator to determine the mathematical difference between the local datum and WGS positions. However, if a radar or visual fix can be accurately determined, and an offset established as noted above. This offset can then be programmed into the GPS receiver.

To minimize problems caused by differing datums:

- Plot chart corrections only on the specific charts and editions for which they are intended. Each chart correction is specific to only one edition of a chart. When the same

correction is made on two charts based on different datums, the positions for the same feature may differ slightly. This difference is equal to the datum shift between the two datums for that area.

- Try to determine the source and datum of positions of temporary features, such as drill rigs. In general they are given in the datum used in the area in question. Since these are precisely positioned using satellites, WGS is the normal datum. A datum correction, if needed, might be found on a chart of the area.
- Remember that if the datum of a plotted feature is not known, position inaccuracies may result. It is wise to allow a margin of error if there is any doubt about the datum.
- Know how the datum of the positioning system you are using relates to your chart. GPS and other modern positioning systems use WGS datum. If your chart is on any other datum, you must program the system to use the chart’s datum, or apply a datum correction when plotting GPS positions on the chart.

For more information regarding geodetic datums visit the link provided in Figure 210.



*Figure 210.*

[http://www.colorado.edu/geography/gcraft/notes/datum/datum\\_f.html](http://www.colorado.edu/geography/gcraft/notes/datum/datum_f.html)