Chapter 5
Geodetic Reference Datums and Local Coordinate Systems

5-1. Purpose and Background

This chapter provides guidance on geodetic reference datums, coordinate systems, and local horizontal and vertical reference systems that are used to georeference Corps military construction and civil works projects. Use of State Plane Coordinate Systems (SPCS) is covered in detail since these systems are most commonly used to reference topographic surveys of local projects. Transformations between datums and coordinate systems are discussed. Site calibration techniques needed for RTK topographic surveys are covered in Chapter 9.

a. Topographic surveys can be performed on any coordinate system. Most localized total station topographic surveys are initiated on (or referenced to) an arbitrary coordinate grid system, e.g., X=5,000 ft, Y=5,000 ft, Z=100 ft, and often elevation or scale reductions are ignored. Planimetric and topographic data points collected on this arbitrary grid in a data collector are then later translated, rotated, scaled, and/or "best fit" to some established geographical reference system--e.g., the local State Plane Coordinate System (SPCS).

b. The process of converting the observed topographic points on the arbitrary grid system to an established geographical reference system (e.g., SPCS) is termed a “datum transformation.” In order to perform this transformation, a few points (preferably three or more) in the topographic database must be referenced to the external reference system. These “control” points on a topographic survey have been previously established relative to an installation or project’s primary control network. They normally were established using more accurate “geodetic control” survey procedures, such as differential leveling, static or kinematic DGPS observations, or total station traverse.

c. Most USACE topographic surveys require “control surveys” to bring in a geodetic reference network to the local project site where detailed topographic surveys are performed. It is important that the correct geodetic reference network is used, and that it is consistent with the overall installation or project reference system. It may also important that these reference systems conform to regional or nationwide reference systems, such as the National Spatial Reference System (NSRS), North American Datum of 1983 (NAD 83), or the North American Vertical Datum of 1988 (NAVD 88). These various reference datums and systems are discussed in this chapter.

d. Not all topographic surveys require a rigid reference to some local or regional geographic coordinate system, and thus do not need time consuming and expensive preliminary control surveys. Some project feature or on going construction applications may only require a simple local reference--for example, a single monument with assumed or scaled coordinates and an arbitrary reference azimuth may suffice.

e. Other topographic surveys outside Army installations or Corps civil project areas may require rigid references to established property boundaries (corner pins, section corners, road intersections/centerlines, etc.). These ties to legal boundaries and corners will thus establish the reference system by which all topographic survey features are detailed. Regional geodetic or SPCS networks may or may not be required on such surveys, depending on local practice or statute.

f. For additional details on geodetic datums and coordinate systems, refer to EM 1110-1-1003 (*NAVSTAR GPS Surveying*) or consult one of the technical references listed in Appendix A.

SECTION I
Geodetic Reference Systems

5-2. General

The discipline of surveying consists of locating points of interest on the surface of the earth. The positions of points of interest are defined by coordinate values that are referenced to a predefined mathematical surface. In geodetic surveying, this mathematical surface is called a datum, and the position of a point with respect to the datum is defined by its coordinates. The reference surface for a system of control points is specified by its position with respect to the earth and its size and shape. A datum is a coordinate surface used as reference figure for positioning control points. Control points are points with known relative positions tied together in a network. Densification of the network refers to adding more fixed control points to the network. Both horizontal and vertical datums are commonly used in surveying and mapping to reference coordinates of points in a network. Reference systems can be based on the geoid, ellipsoid, or a plane. The physical earth's gravity force can be modeled to create a positioning reference frame that rotates with the earth. The geoid is such a surface (an equipotential surface of the earth's gravity field) that best approximates Mean Sea Level (MSL). The orientation of this surface at a given point on geoid is defined by the plumb line. The plumb line is oriented tangent to the local gravity vector. Surveying instruments can be readily oriented with respect to the gravity field because its physical forces can be sensed with simple mechanical devices. Such a reference surface is developed from an ellipsoid of revolution that best approximates the geoid. An ellipsoid of revolution provides a well-defined mathematical surface to calculate geodetic distances, azimuths, and coordinates.

5-3. Geodetic Coordinates

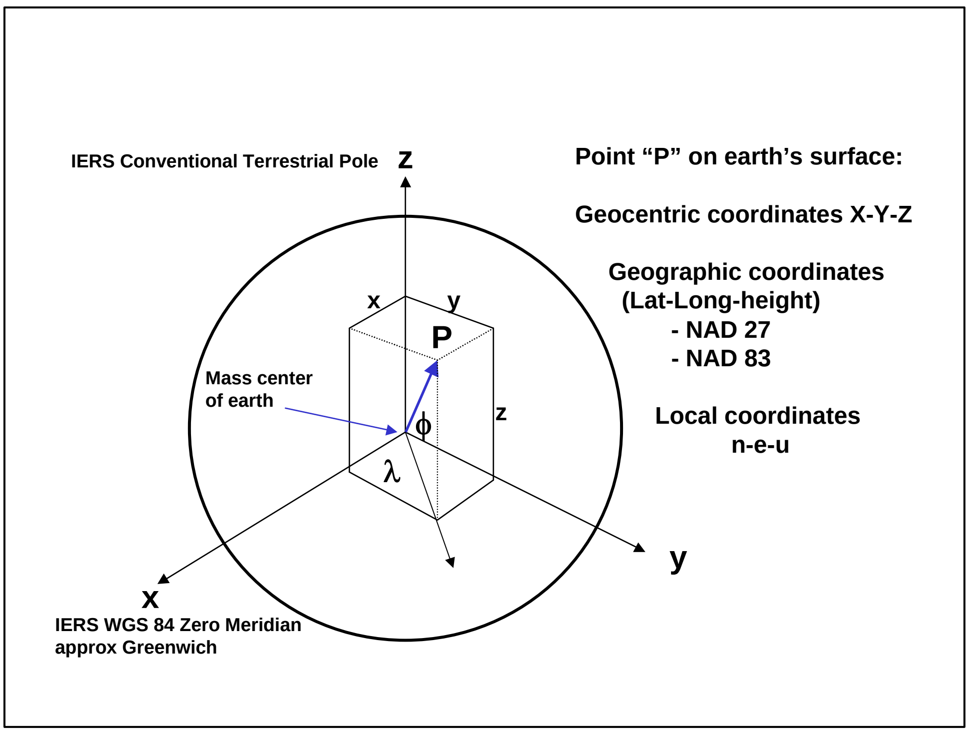

Figure 5-1. Earth-centered earth-fixed coordinate reference frames

A coordinate system is defined by the location of the origin, orientation of its axes, and the parameters (coordinate components) which define the position of a point within the coordinate system. Terrestrial coordinate systems are widely used to define the position of points on the terrain because they are fixed to the earth and rotate with it. The origin of terrestrial systems can be specified as either geocentric (origin at the center of the earth, such as NAD 83) or topocentric (origin at a point on the surface of the earth, such as NAD 27). The orientation of terrestrial coordinate systems is described with respect to its poles, planes, and axes. The primary pole (Z in Figure 5-1 above) is the axis of symmetry of the coordinate system, usually parallel to the rotation axis of the earth, and coincident with the semi-minor axis of the reference ellipsoid. The reference planes that are perpendicular to the primary polar axis are the equator (zero latitude) and the Greenwich meridian plane (zero longitude). Parameters for point positioning within a coordinate system refer to the coordinate components of the system (either Cartesian or curvilinear).

a. Geocentric coordinates. Geocentric coordinates have an origin at the center of the earth, as shown above in Figure 5-1. GPS coordinates are initially observed on this type of reference system. For example, a coordinate on such a system might be displayed on a GPS receiver as:

```
X =    668400.506 m
Y =  -4929214.152 m
Z =   3978967.747 m
```

GPS receivers will transform these geocentric coordinates into a geographic coordinate system described below.

b. Geodetic or Geographic coordinates. Geographic coordinate components consist of:

- latitude (ϕ),
- longitude (λ),
- ellipsoid height (h).

Geodetic latitude, longitude, and ellipsoid height define the position of a point on the surface of the Earth with respect to some "reference ellipsoid." The most common reference ellipsoid used today is the WGS 84, which will be described in more detail in a later section.

(1) Geodetic latitude (ϕ). The geodetic latitude of a point is the acute angular distance between the equatorial plane and the normal through the point on the ellipsoid measured in the meridian plane (Figure 5-1). Geodetic latitude is positive north of the equator and negative south of the equator.

(2) Geodetic longitude (λ). The geodetic longitude is the angle measured counter-clockwise (east), in the equatorial plane, starting from the prime meridian (Greenwich meridian), to the meridian of the defined point (Figure 5-1). In the continental United States, longitude is commonly reported as a west longitude. To convert easterly to westerly referenced longitudes, the easterly longitude must be subtracted from 360 deg.

East-West Longitude Conversion:

$$\lambda (W) = [360 - \lambda (E)] \qquad \text{(Eq 5-1)}$$

For example:

λ (E) = 282 ^{d} 52 ^{m} 36.345 ^{s} E

λ (W) = [360 ^{d} - 282 ^{d} 52 ^{m} 36.345 ^{s} E]
λ (W) = 77 ^{d} 07 ^{m} 23.655 ^{s} W

(3) Ellipsoid Height (h). The ellipsoid height is the linear distance above the reference ellipsoid measured along the ellipsoidal normal to the point in question. The ellipsoid height is positive if the reference ellipsoid is below the topographic surface and negative if the ellipsoid is above the topographic surface.

(4) Geoid Separation (N). The geoid separation (or often termed "geoidal height") is the distance between the reference ellipsoid surface and the geoid surface measured along the ellipsoid normal. The geoid separation is positive if the geoid is above the ellipsoid and negative if the geoid is below the ellipsoid.

(5) Orthometric Height (H). The orthometric height is the vertical distance of a point above or below the geoid.

5-4. Datums

A datum is a coordinate surface used as reference for positioning control points. Both horizontal and vertical datums are commonly used in surveying and mapping to reference coordinates of points in a network.

a. Geodetic datum. Five parameters are required to define an ellipsoid-based datum. The major semi-axis (a) and flattening (f) define the size and shape of the reference ellipsoid; the latitude and longitude of an initial point; and a defined azimuth from the initial point define its orientation with respect to the earth. The NAD 27 and NAD 83 systems are examples of horizontal geodetic datums.

b. Horizontal datum. A horizontal datum is defined by specifying (1) the 2D geometric surface (plane, ellipsoid, sphere) used in coordinate, distance, and directional calculations, (2) the initial reference point (origin), and (3)a defined orientation, azimuth or bearing from the initial point. The “horizontal datum” for most topographic surveys is usually defined relative to the fixed control points (monuments and/or benchmarks) that were used to control the individual shots. These “control points” may, in turn, be referenced to a local installation/compound control network and/or to a regional NSRS CORS station.

c. Project datum. A project datum is defined relative to local control and might not be directly referenced to a geodetic datum. Project datums are usually defined by a system with perpendicular axes, and with arbitrary coordinates for the initial point, and with one (principal) axis oriented toward an assumed north. A chainage-offset system may also be used as a reference, with the PIs (points of intersection) either marked points or referenced to some other coordinate system.

d. Vertical datum. A vertical datum is a reference system used for reporting elevations. The two most common nationwide systems are the National Geodetic Vertical Datum of 1929 (NGVD 29) and the North American Vertical Datum of 1988 (NAVD 88). Vertical elevations used on navigation, flood control, and hydropower projects may also be referenced to a variety of datums, such as:

- Mean Sea Level (MSL)
- Mean Low Water (MLW)
- Mean Lower Low Water (MLLW)
- Mean High Water (MHW)
- International Great Lakes Datum (IGLD)

- Low Water Reference Plane (LWRP)
- Flat Pool Stage
- Local Pool or Reservoir Capacity Reference Point

Mean Sea Level (MSL) based elevations are used for most construction and topographic surveys--in particular those involving flood control or shoreline improvement/protection. It should be noted that MSL elevations are not the same as NGVD 29; and that MSL and NGVD 29 elevations can widely differ from NAVD 88 elevations--as much as 3 ft in western CONUS. MLLW elevations are used in referencing coastal navigation projects. MHW elevations are used in construction projects involving bridges and other crossings over navigable waterways.

e. The National Spatial Reference System (NSRS). The NSRS is that component of the National Spatial Data Infrastructure (NSDI) - [http://www.fgdc.gov/nsdi/nsdi.html] which contains all geodetic control contained in the National Geodetic Survey (NGS) database. This includes: A, B, First, Second and Third-Order horizontal and vertical control, geoid models, precise GPS orbits and Continuously Operating Reference Stations (CORS), and the National Shoreline as observed by NGS as well as data submitted by other Federal, State, and local agencies, academic institutions, and the private sector.

5-5. WGS 84 Reference Ellipsoid

The WGS 84 ellipsoid is used to reference GPS satellite observations and is used to reduce observations onto the NAD 83 system. The origin of the WGS 84 Cartesian system is the earth's center of mass, as shown in Figure 5-1. The Z-axis is parallel to the direction of the Conventional Terrestrial Pole (CTP) for polar motion, as defined by the Bureau International Heure (BIH), and equal to the rotation axis of the WGS 84 ellipsoid. The X-axis is the intersection of the WGS 84 reference meridian plane and the CTP's equator, the reference meridian being parallel to the zero meridian defined by the BIH and equal to the X-axis of the WGS 84 ellipsoid. The Y-axis completes a right-handed, earth-centered, earth-fixed orthogonal coordinate system, measured in the plane of the CTP equator 90 degrees east of the X-axis and equal to the Y-axis of the WGS 84 ellipsoid. The DOD continuously monitors the origin, scale, and orientation of the WGS 84 reference frame and references satellite orbit coordinates to this frame. Updates are shown as WGS 84 (GXXX), where "XXX" refers to a GPS week number starting on 29 September 1996.

Prior to development of WGS 84, there were several reference ellipsoids and interrelated coordinate systems (datums) that were used by the surveying and mapping community. Table 5-1 lists just a few of these reference systems along with their mathematical defining parameters. Note that GRS 80 is the actual reference ellipsoid for NAD 83; however, the difference between GRS-80 and WGS 84 ellipsoids is insignificant. Transformation techniques are used to convert between different datums and coordinate systems. Most GPS software has built in transformation algorithms for the more common datums.

Table 5-1. Reference Ellipsoids and Related Coordinate Systems

Reference Ellipsoid	Coordinate System (Datum/Frame)	Semimajor axis (meters)	Shape (1/flattening)
Clarke 1866	NAD 27	6378206.4	1/294.9786982
WGS 72	WGS 72	6378135	1/298.26
GRS 80	NAD 83 (XX)	6378137	1/298.257222101
WGS 84	WGS 84 (GXXX)	6378137	1/298.257223563
ITRS	ITRF (XX)	6378136.49	1/298.25645

5-6. Horizontal Datums and Reference Frames

The following paragraphs briefly describe the most common datums used to reference CONUS projects.

a. North American Datum of 1927 (NAD 27). NAD 27 is a horizontal datum based on a comprehensive adjustment of a national network of traverse and triangulation stations. NAD 27 is a best fit for the continental United States. The fixed datum reference point is located at Meades Ranch, Kansas. The longitude origin of NAD 27 is the Greenwich Meridian with a south azimuth orientation. The original network adjustment used 25,000 stations. The relative precision between initial point monuments of NAD 27 is by definition 1:100,000, but coordinates on any given monument in the network contain errors of varying degrees. As a result, relative accuracies between points on NAD 27 may be far less than the nominal 1:100,000. The reference units for NAD 27 are US Survey Feet. This datum is no longer supported by NGS, and USACE commands are gradually transforming their project coordinates over to the NAD 83 described below. Approximate conversions of points on NAD 27 to NAD 83 may be performed using CORPSCON, a transformation program developed by ERDC/TEC. Since NAD 27 contains errors approaching 10 m, transforming highly accurate GPS observations to this antiquated reference system is not the best approach.

b. North American Datum of 1983 (NAD 83). The nationwide horizontal reference network was redefined in 1983 and readjusted in 1986 by the National Geodetic Survey. It is known as the North American Datum of 1983, adjustment of 1986, and is referred to as NAD 83 (1986). NAD 83 used far more stations (250,000) and observations than NAD 27, including a few satellite-derived coordinates, to readjust the national network. The longitude origin of NAD 83 is the Greenwich Meridian with a north azimuth orientation. The fixed adjustment of NAD 83 (1986) has an average precision of 1:300,000. NAD 83 is based upon the Geodetic Reference System of 1980 (GRS 80), an earth-centered reference ellipsoid which for most (but not all) practical purposes is equivalent to WGS 84. With increasingly more accurate uses of GPS, the errors and misalignments in NAD 83 (1986) became more obvious (they approached 1 meter), and subsequent refinements outlined below have been made to correct these inconsistencies.

c. High Accuracy Reference Networks (HARN). (Figure 5-2). Within a few years after 1986, more refined GPS measurements had allowed geodesists to locate the earth's center of mass with a precision of a few centimeters. In doing so, these technologies revealed that the center of mass that was adopted for NAD 83 (1986) is displaced by about 2 m from the true geocenter. These discrepancies caused significant concern as the use of highly accurate GPS measurements proliferated. Starting with Tennessee in 1989, each state--in collaboration with NGS and various other institutions--used GPS technology to establish regional reference frames that were to be consistent with NAD 83. The corresponding networks of GPS control points were originally called High Precision Geodetic Networks (HPGN). Currently, they are referred to as High Accuracy Reference Networks (HARN). This latter name reflects the fact that relative accuracies among HARN control points are better than 1 ppm, whereas relative accuracies among pre-existing control points were nominally only 10 ppm. Positional differences between NAD 83 (1986) and NAD 83 (HARN) can approach 1 meter.

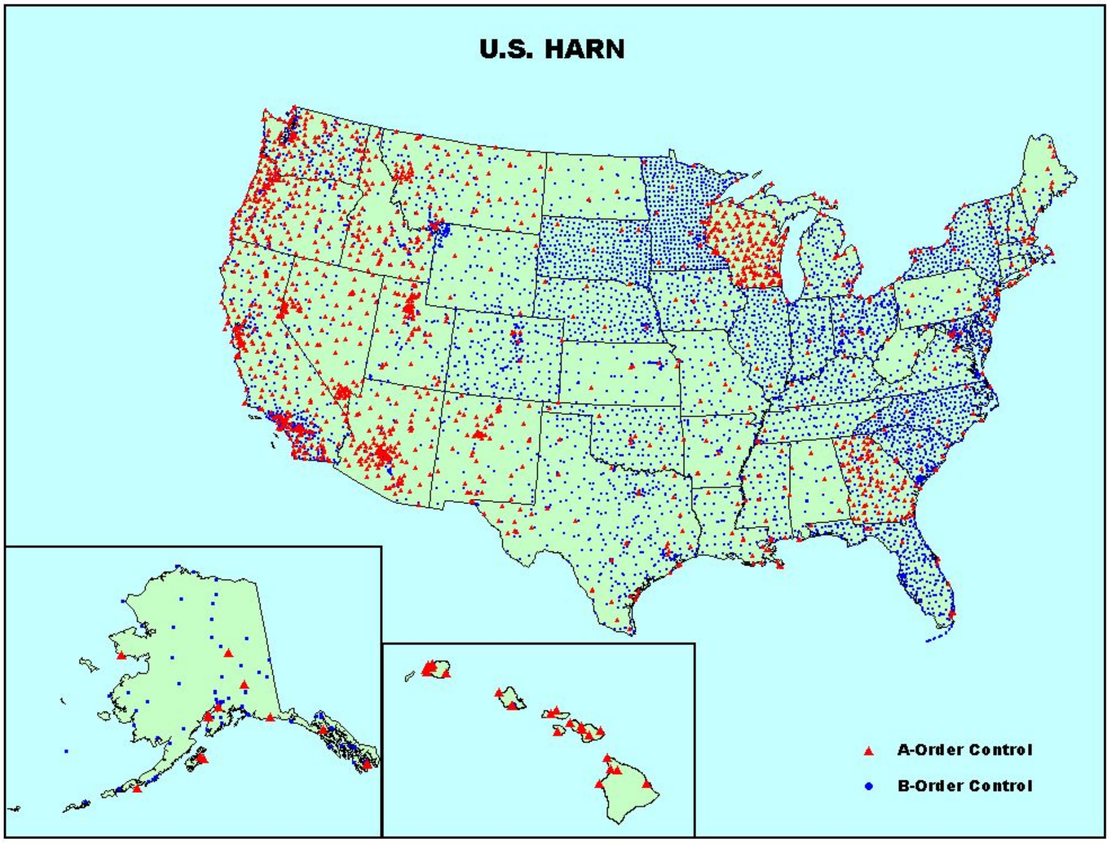

Figure 5-2. High Accuracy Reference Network control points

d. Continuously Operating Reference Stations (CORS). The regional HARNs were subsequently further refined (or "realized") by NGS into a network of Continuously Operating Reference Stations, or CORS. This CORS network was additionally incorporated with the International Terrestrial Reference System (ITRS), i.e. the ITRF. CORS are located at fixed points throughout CONUS and at some OCONUS points--see Figure 5-3 below. This network of high-accuracy points can provide GPS users with centimeter level accuracy where adequate CORS coverage exists. Coordinates of CORS stations are designated by the year of the reference frame, e.g., NAD 83 (CORS 96). Positional differences between NAD 83 (HARN) and NAD 83 (CORS) are less than 10 cm. More importantly, positional difference between two NAD 83 (CORSxx) points is typically less than 2 cm. Thus, GPS connections to CORS stations will be of the highest order of accuracy. USACE commands can easily connect and adjust GPS-observed points directly with CORS stations using a number of methods, including the NGS on-line program OPUS (On-Line Positioning User Service)--see EM 1110-1-1003. CORS are particularly useful when precise control is required in a remote area, from which a topographic survey may be performed. With only 1 to 2 hours of static DGPS observations, reference points can often be established to an ellipsoid accuracy better than ± 0.2 ft in X-Y-Z.

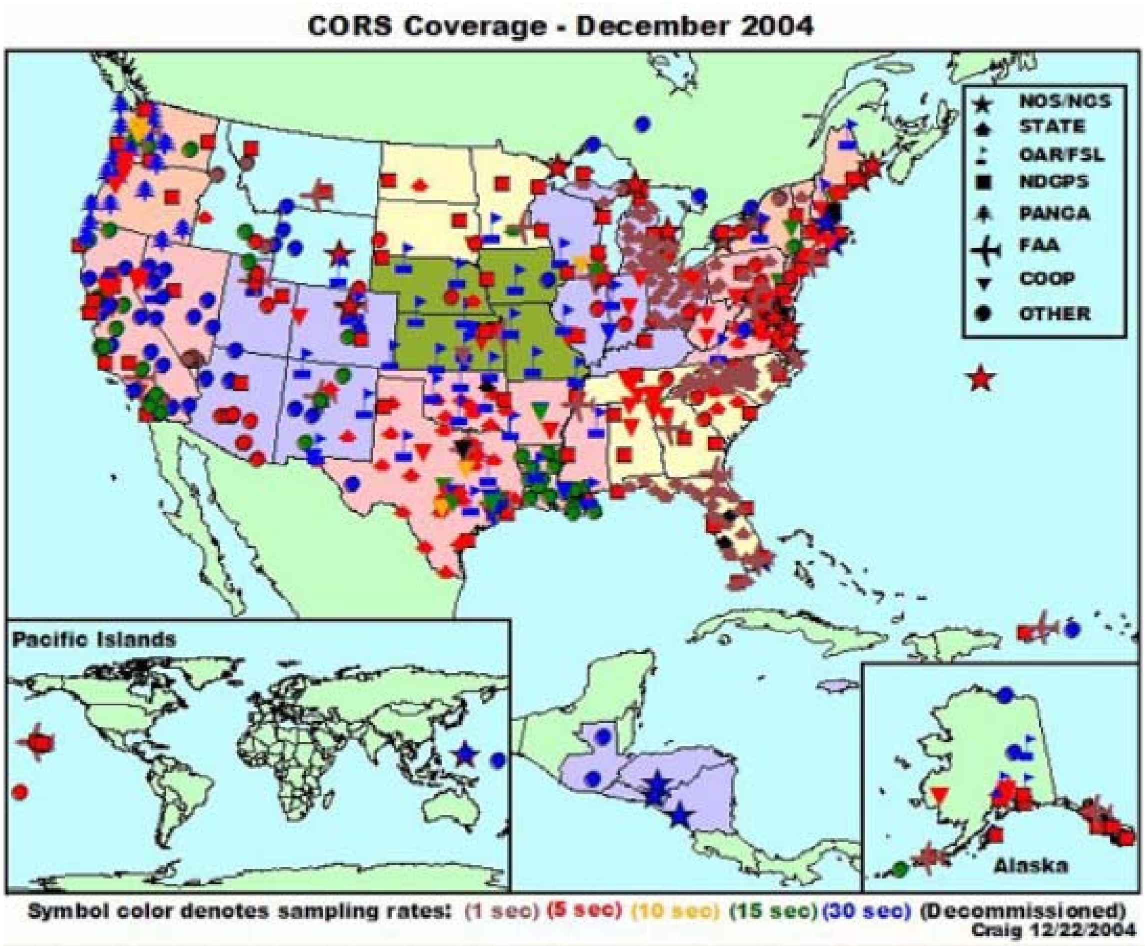

Figure 5-3. Continuously Operating Reference Stations as of 2001 (NGS)

e. International Terrestrial Reference Frame (ITRF). The ITRF is a highly accurate geocentric reference frame with an origin at the center of the earth's mass. The ITRF is continuously monitored and updated by the International Earth Rotation Service (IERS) using very-long-baseline-interferometry (VLBI) and other techniques. These observations allow for the determination of small movements of fixed points on the earth's surface due to crustal motion, rotational variances, tectonic plate movement, etc. These movements can average 10 to 20 mm/year in CONUS, and may become significant when geodetic control is established from remote reference stations. These refinements can be used to accurately determine GPS positions observed on the basic WGS 84 reference frame. NAD 83 coordinates are defined based on the ITRF year/epoch in which it is defined, e.g., ITRF 89, ITRF 96, ITRF 2000. For highly accurate positioning where plate velocities may be significant, users should use the same coordinate reference frame and epoch for both the satellite orbits and the terrestrial reference frame. USACE requirements for these precisions on control surveys would be rare, and would never be applicable to local facility mapping surveys. Those obtaining coordinates from NGS datasheets must take care not to use ITRF values. The relationship between ITRF, NAD 83, and the geoid is illustrated in Figure 5-4 below.

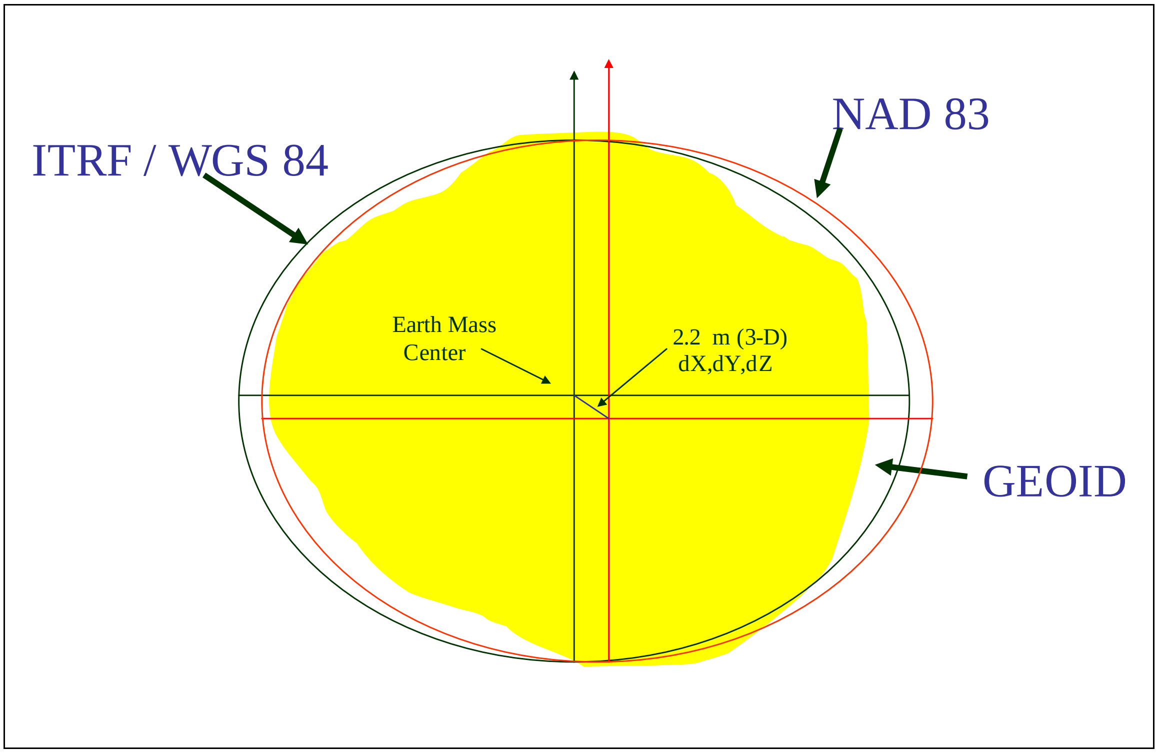

Figure 5-4. Relationship between ITRF, NAD 83, and the geoid

SECTION II
Horizontal Coordinate Systems

5-7. General

Geocentric, geographic, or geodetic coordinates described above are rarely used to reference site plan topographic surveys or maps. Engineering site plan drawings are normally referenced to a local state plane coordinate system (SPCS), or in some cases a metric-based UTM system. In rare cases, they may be referenced to an arbitrary coordinate system relative to some point on the project--a monument, corner, road intersection, etc. In most cases, control surveys performed for setting project control will be computed and adjusted using the SPCS. The following paragraphs describe horizontal coordinate systems commonly used on facility site plan mapping and related control surveys.

5-8. Geographic Coordinates

The use of geographic coordinates as a system of reference is accepted worldwide. It is based on the expression of position by latitude (parallels) and longitude (meridians) in terms of arc (degrees, minutes, and seconds) referred to the equator (north and south) and a prime meridian (east and west). The degree of accuracy of a geographic reference (GEOREF) is influenced by the map scale and the accuracy requirements for plotting and scaling. Examples of GEOREFs are as follows:

40° N 132° E (referenced to degrees of latitude and longitude).
40°21' N 132°14' E (referenced to minutes of latitude and longitude).
40°21'12" N 132°14'18" E (referenced to seconds of latitude and longitude).
40°21'12.4" N 132°14'17.7" E (referenced to tenths of seconds of latitude and longitude).
40°21'12.45" N 132°14'17.73" E (referenced to hundredths of seconds of latitude and longitude).

US military maps and charts include a graticule (parallels and meridians) for plotting and scaling geographic coordinates. Graticule values are shown in the map margin. On maps and charts at scales of 1:250,000 and larger, the graticule may be indicated in the map interior by lines or ticks at prescribed intervals (for example, scale ticks and interval labeling at the corners of 1:50,000 at 1minute [in degrees, minutes, and seconds] and again every 5 minutes).

5-9. State Plane Coordinate Systems

a. General. State Plane Coordinate Systems (SPCS) were developed by the National Geodetic Survey (NGS) to provide plane coordinates over a limited region of the earth's surface. To properly relate geodetic coordinates (ϕ-λ-h) of a point to a 2D plane coordinate representation (Northing, Easting), a conformal mapping projection must be used. Conformal projections have mathematical properties that preserve differentially small shapes and angular relationships to minimize the errors in the transformation from the ellipsoid to the mapping plane. Map projections that are most commonly used for large regions are based on either a conic or a cylindrical mapping surface (Figure 5-5 below). The projection of choice is dependent on the north-south or east-west areal extent of the region. Areas with limited east-west dimensions and indefinite north-south extent use the Transverse Mercator (TM) type projection. Areas with limited north-south dimensions and indefinite east-west extent use the Lambert projection. The SPCS is designed to minimize the spatial distortion at a given point to approximately one part in ten thousand (1:10,000). To satisfy this criteria, the SPCS has been divided into zones that have a maximum width or height of approximately one hundred and fifty eight statute miles (158 miles). Therefore, each state may have several zones or may employ both the Lambert (conic) and Transverse Mercator (cylindrical) projections. The projection state plane coordinates are referenced to a specific geodetic datum (i.e. the datum that the initial geodetic coordinates are referenced to must be known).

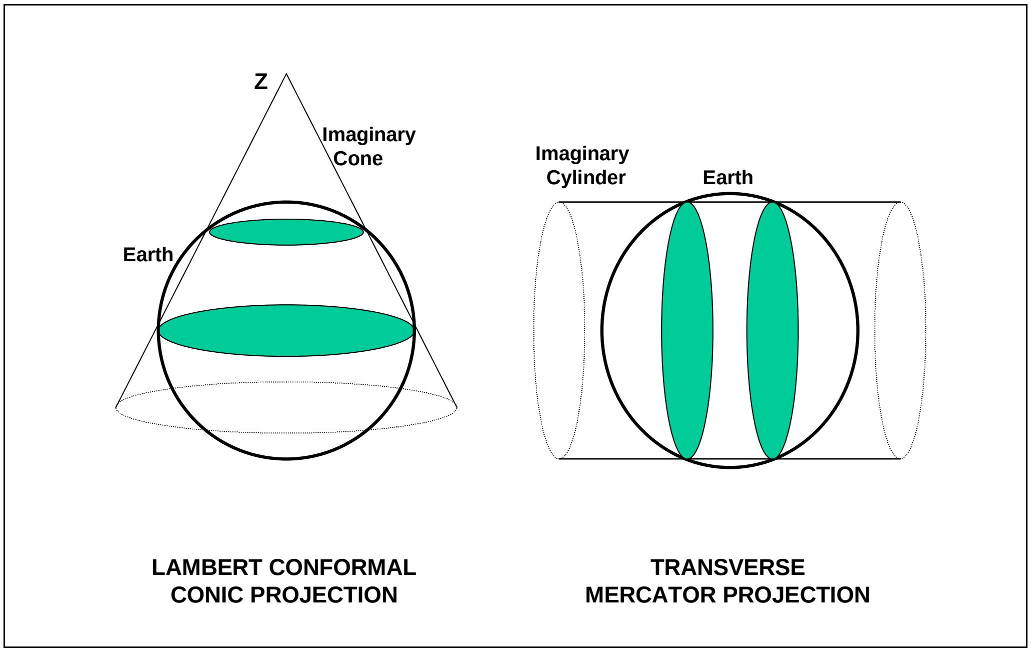

Figure 5-5. Common map projections

b. Transverse Mercator (TM). The Transverse Mercator projection uses a cylindrical surface to cover limited zones on either side of a central reference longitude. Its primary axis is rotated perpendicular to the symmetry axis of the reference ellipsoid. Thus, the TM projection surface intersects the ellipsoid along two lines equidistant from the designated central meridian longitude (Figure 5-6). Distortions in the TM projection increase predominantly in the east-west direction. The scale factor for the Transverse Mercator projection is unity where the cylinder intersects the ellipsoid. The scale factor is less than one between the lines of intersection, and greater than one outside the lines of intersection. The scale factor is the ratio of arc length on the projection to arc length on the ellipsoid. To compute the state plane coordinates of a point, the latitude and longitude of the point and the projection parameters for a particular TM zone or state must be known.

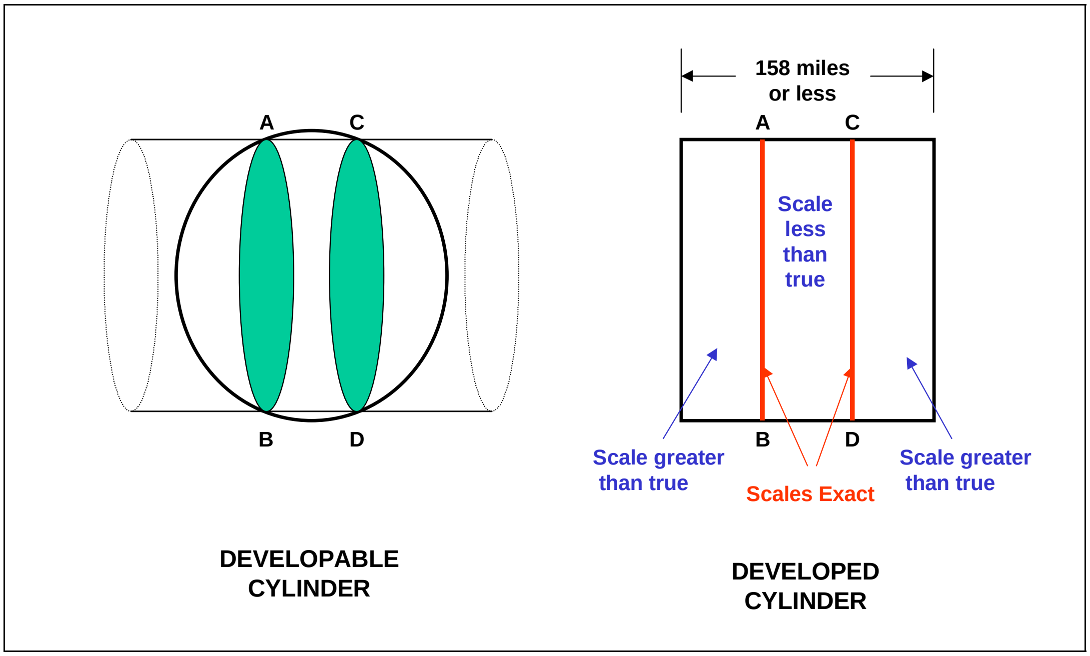

Figure 5-6. Transverse Mercator Projection

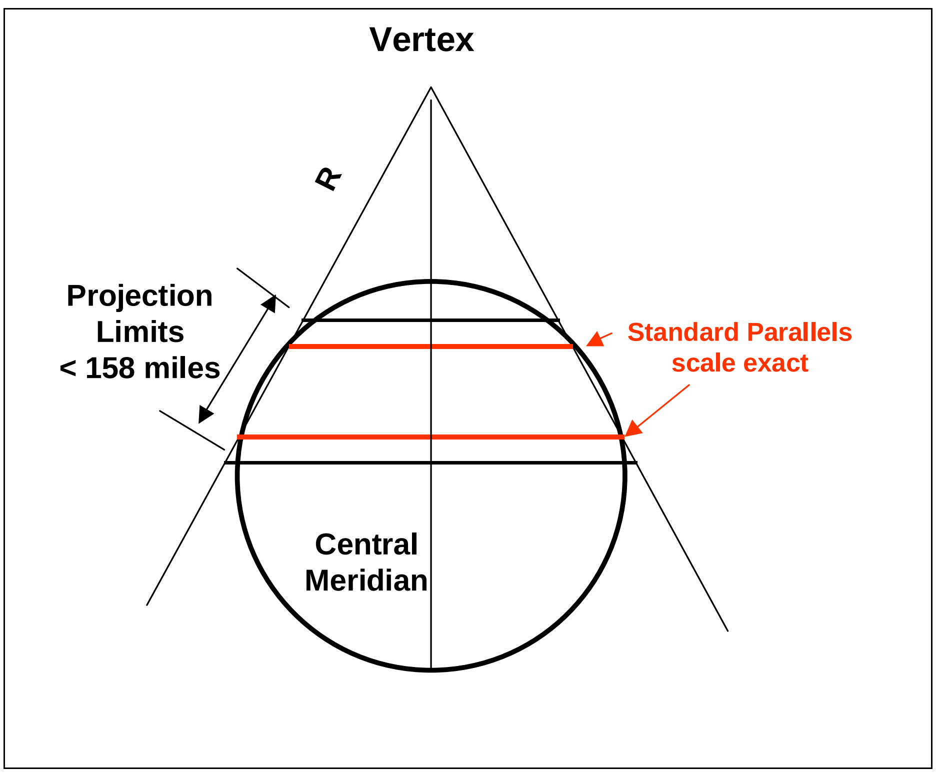

Figure 5-7. Lambert Projection

c. Lambert Conformal Conic (LCC). The Lambert projection uses a conic surface to cover limited zones of latitude adjacent to two parallels of latitude. Its primary axis is coincident with the symmetry axis of the reference ellipsoid. Thus, the LCC projection intersects the ellipsoid along two standard parallels (Figure 5-7). Distortions in the LCC projection increase predominantly in the north-south direction. The scale factor for the Lambert projection is equal to unity at each standard parallel and is less than one inside, and greater than one outside the standard parallels. The scale factor remains constant along the standard parallels.

d. SPCS zones. Figure 5-8 depicts the various SPCS zones in the US. The unique state zone number provides a standard reference when using transformation software developed by NGS and the COE. The state zone number remains constant in both NAD27 and NAD83 coordinate systems.

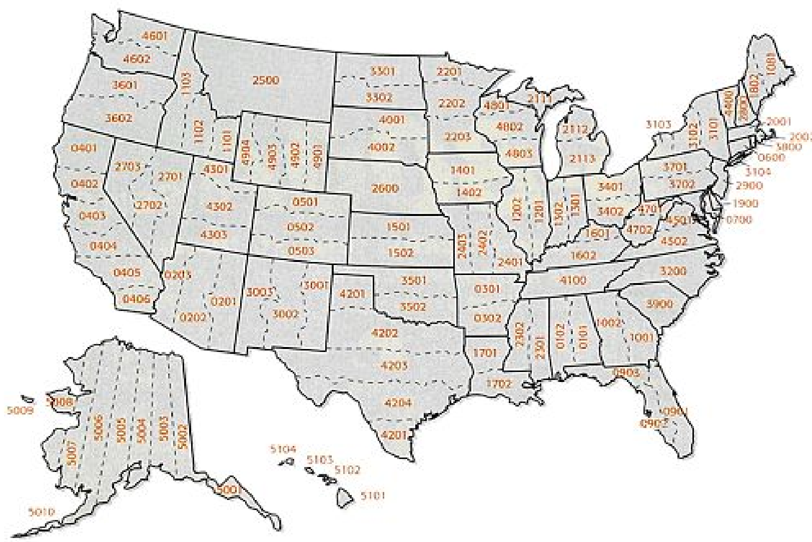

Figure 5-8. SPCS zones identification numbers for the various states

e. Scale units. State plane coordinates can be expressed in both feet and meters. State plane coordinates defined on the NAD 27 datum are published in feet. State plane coordinates defined on the NAD 83 datum are published in meters; however, state and federal agencies can request the NGS to provide coordinates in feet. If NAD 83 based state plane coordinates are defined in meters and the user intends to convert those values to feet, the proper meter-feet conversion factor must be used. Some states use the International Survey Foot rather than the US Survey Foot in the conversion of feet to meters.

International Survey Foot:

1 International Foot = 0.3048 meter (exact)

US Survey Foot:

1 US Survey Foot = 1200 / 3937 meter (exact)

5-10. Grid Elevations, Scale Factors, and Convergence

In all planer grid systems, the grid projection only approximates the ellipsoid (or roughly the ground), and "ground-grid" corrections must be made for measured distances or angles (directions). Measured ground distances must be corrected for (1) elevation (sea level factor), and (2) ground to grid plane (scale factor). Figure 5-9 below illustrates a reduction of a measured distance (D) down to the ellipsoid distance (S). Not shown is the subsequent reduction from the ellipsoid length to a grid system length. Observed directions (or angles) must also be corrected for grid convergence. Also shown on the figure is the relationship between ellipsoid heights (h), geoid heights (N), and orthometric heights (H).

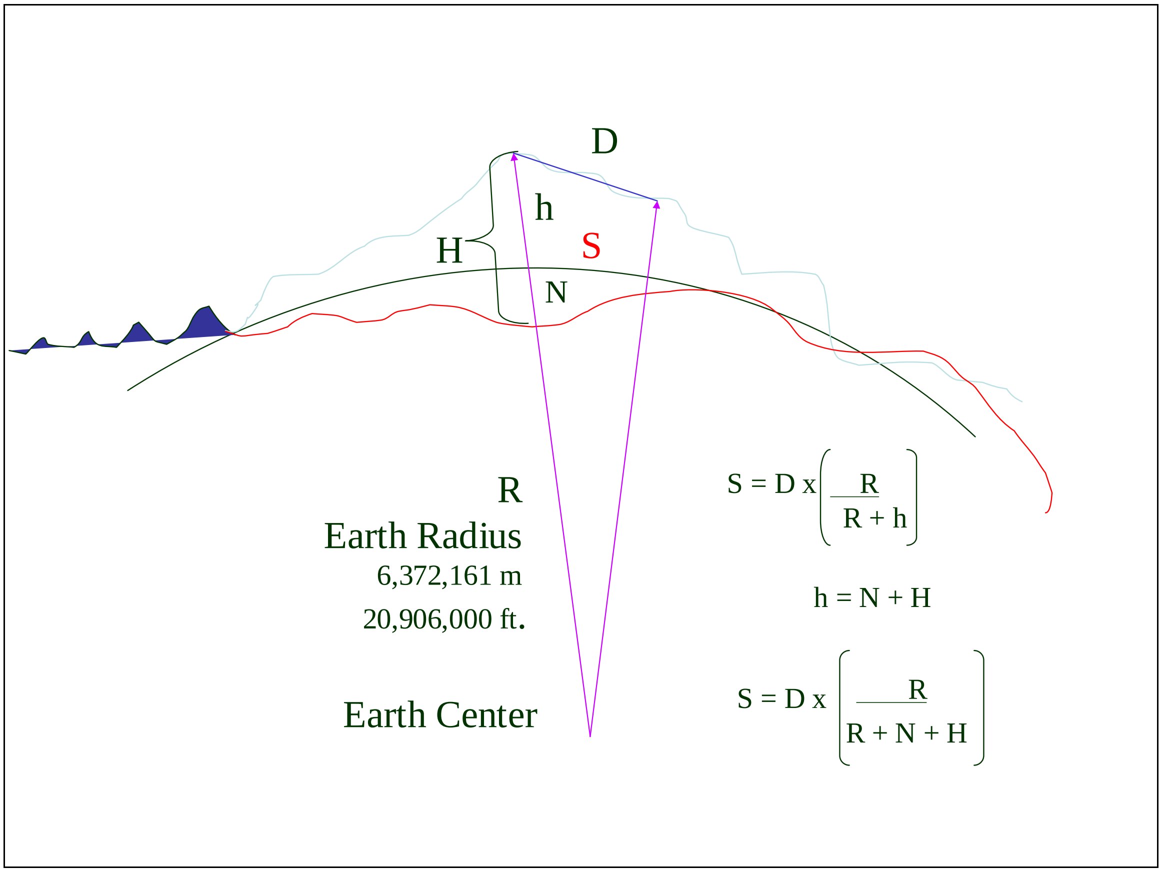

Figure 5-9. Reduction of measured slope distance D to ellipsoid distance S (NGS)

a. Grid factor. For most topographic surveys covering a small geographical site, these two factors can be combined into a constant "grid factor"--reference Kavanagh 1997:

Grid factor = Sea Level Factor x Scale Factor

then: *Ground Distance = Grid Distance / Grid Factor*

or

Grid Distance = Ground Distance x Grid Factor

b. Convergence. Between two fixed points, the geodetic azimuth will differ from the grid azimuth. This difference is known as "convergence" and varies with the distance from the central meridian of the projection. Thus, if a geodetic azimuth is given between two fixed points (inversed from published geographic coordinates, astronomic, or GPS), then it must be corrected for convergence to obtain an equivalent grid azimuth. If lengthy control traverses are being computed on a SPCS or UTM grid, then additional second term corrections to observed angles may be required--e.g., the ”t-T” correction used in older survey manuals at Appendix A-4 (TM 5-237 and TM 5-241-2).

c. Use of data collectors. The above grid corrections should rarely have to be performed when modern survey data collectors are being used. These total station or RTK data collectors (with full COGO and adjustment capabilities) will automatically perform all the necessary geographic to grid coordinate translations, including sea level reductions and local grid system conversions that are later transformed and adjusted into an established SPCS grid at a true elevation. If for some reason you are not using a data collector that seamlessly performs these translation functions, and you are performing a survey in higher elevations, then you must correct original distance observations for the sea level reduction. If you transfer these observed distances and angles to a SPCS or UTM grid, then you must correct for grid scale factor and convergence described above. Consult any of the referenced surveying textbooks at Appendix A-2 for procedures and examples.

5-11. Universal Transverse Mercator Coordinate System

Universal Transverse Mercator (UTM) coordinates are used in surveying and mapping when the size of the project extends through several state plane zones or projections. UTM coordinates are also utilized by the US Army, Air Force, and Navy for tactical mapping, charting, and geodetic applications. It may also be used to reference site plan engineering surveys if so requested in CONUS or OCONUS installations. The UTM projection differs from the TM projection in the scale at the central meridian, origin, and unit representation. The scale at the central meridian of the UTM projection is 0.9996. In the Northern Hemisphere, the northing coordinate has an origin of zero at the equator. In the Southern Hemisphere, the southing coordinate has an origin of ten million meters (10,000,000 m). The easting coordinate has an origin five hundred thousand meters (500,000 m) at the central meridian. The UTM system is divided into sixty (60) longitudinal zones. Each zone is six (6) degrees in width extending three (3) degrees on each side of the central meridian. UTM coordinates are always expressed in meters. USACE program CORPSCON can be used to transform coordinates between UTM and SPCS systems. Additional details on UTM grids and survey computations thereon may be found in the older DA references listed at Appendix A-4.

5-12. The US Military Grid-Reference System (FM 3-34.331)

The US Military Grid-Reference System (MGRS) is designed for use with UTM grids. For convenience, the earth is generally divided into 6° by 8° geographic areas, each of which is given a unique grid-zone designation. These areas are covered by a pattern of 100,000-meter squares. Two letters (called the 100,000-meter-square letter identification) identify each square. This identification is unique within the area covered by the grid-zone designation.

a. The MGRS is an alphanumeric version of a numerical UTM grid coordinate. Thus, for that portion of the world where the UTM grid is specified (80° south to 84° north), the UTM grid-zone number is the first element of a military grid reference. This number sets the zone longitude limits. The next element is a letter that designates a latitude bond. Beginning at 80° south and proceeding northward, 20 bands are lettered C through X. In the UTM portion of the MGRS, the first three characters designate one of the areas within the zone dimensions.

b. A reference that is keyed to a gridded map (of any scale) is made by giving the 100,000-meter-square letter identification together with the numerical location. Numerical references within the

100,000-meter square are given to the desired accuracy in terms of the easting and northing grid coordinates for the point.

c. The final MGRS position coordinate consists of a group of letters and numbers that include the following elements:

- The grid-zone designation.
- The 100,000-meter-square letter identification.
- The grid coordinates (also referred to as rectangular coordinates) of the numerical portion of the reference, expressed to a desired refinement.
- The reference is written as an entity without spaces, parentheses, dashes, or decimal points.

Examples are as follows:

18S (locating a point within the grid-zone designation).
18SUU (locating a point within a 100,000-meter square).
18SUU80 (locating a point within a 10,000-meter square).
18SUU8401 (locating a point within a 1,000-meter square).
18SUU836014 (locating a point within a 100-meter square).

d. To satisfy special needs, a reference can be given to a 10-meter square and a 1-meter square. Examples are as follows:

8SUU83630143 (locating a point within a 10-meter square).
18SUU8362601432 (locating a point within a 1-meter square).

e. There is no zone number in the polar regions. A single letter designates the semicircular area and the hemisphere. The letters A, B, Y, and Z are used only in the polar regions. An effort is being made to reduce the complexity of grid reference systems by standardizing a single, worldwide grid reference system.

5-13. US National Grid System

A US National Grid (USNG) system has been developed to improve public safety, commerce, and aid the casual GPS user with an easy to use geoaddress system for identifying and determining location with the help of a USNG gridded map and/or a USNG enabled GPS system. The USNG can provide for whatever level of precision is desired. Many users may prefer to continue using the UTM format for applications requiring precision greater than 1 meter.

a. Grid Zone Designation (GZD). The US geographic area is divided into 6-degree longitudinal zones designated by a number and 8-degree latitudinal bands designated by a letter. Each area is given a unique alphanumeric Grid Zone Designator--e.g., 18S.

b. 100,000-meter square identification. Each GZD 6x8 degree area is covered by a specific scheme of 100,000-meter squares where each square is identified by two unique letters--e.g., 18SUJ identifies a specific 100,000-meter square in the specified GZD.

c. Grid coordinates. A point position within the 100,000-meter square shall be given by the UTM grid coordinates in terms of its Easting (E) and Northing (N). An equal number of digits shall be used for

E and N where the number of digits depends on the precision desired in position referencing. In this convention, the reading shall be from left with Easting first and then Northing.

Examples:

18SUJ20 - Locates a point with a precision of 10 km

18SUJ2306 - Locates a point with a precision of 1 km

18SUJ234064 - Locates a point with a precision of 100 meters

18SUJ23480647 - Locates a point with a precision of 10 meters

18SUJ2348306479 - Locates a point with a precision of 1 meter

The number of digits in Easting and Northing can vary, depending on specific requirements or application.

5-14. Chainage-Offset Coordinate Systems

Most linear engineering and construction projects (roads, railways, canals, navigation channels, levees, floodwalls, beach renourishment, etc.) are locally referenced using the traditional engineering chainage-offset system--Figure 5-10. Usually, SPCS coordinates are provided at the PIs, from which (given the alignment between PIs) a SPCS coordinate can then be computed for any given station-offset point. Chainage-offset systems are used for locating cross-sections along even centerline stations. Topographic elevation and feature data is then collected along each section relative to the centerline. Likewise, road, canal, levee alignments can be staked out relative to station-offset parameters, and internally in a total station or RTK system data collector, these offsets may actually be transformed from a SPCS.

a. Station. Alignment stationing (or chainage) zero references are arbitrarily established for a given project or sectional area. Stationing on a navigation project usually commences offshore on coastal projects and runs inland or upstream. Stationing follows the channel centerline alignment. Stationing may be accumulated through each PI or zero out at each PI or new channel reach. Separate stationing is established for widener sections, turning basins, levees, floodwalls, etc. Each district may have its own convention. Stationing coordinates use "+" signs to separate the second- and third-place units (XXX + XX.XX). Metric chainage often separates the third and fourth places (XXX + XXX.XX) to distinguish the units from English feet; however, some districts use this convention for English stationing units.

b. Offsets. Offset coordinates are distances from the centerline alignment. Offsets carry plus/minus coordinate values. Normally, offsets are positive to the right (looking toward increasing stationing). Some USACE Districts designate cardinal compass points (east-west or north-south) in lieu of a coordinate sign. On some navigation projects, the offset coordinate is termed a "range," and is defined relative to the project centerline or, in some instances, the channel-slope intersection line (toe). Channel or canal offsets may be defined relative to a fixed baseline on the bank or levee.

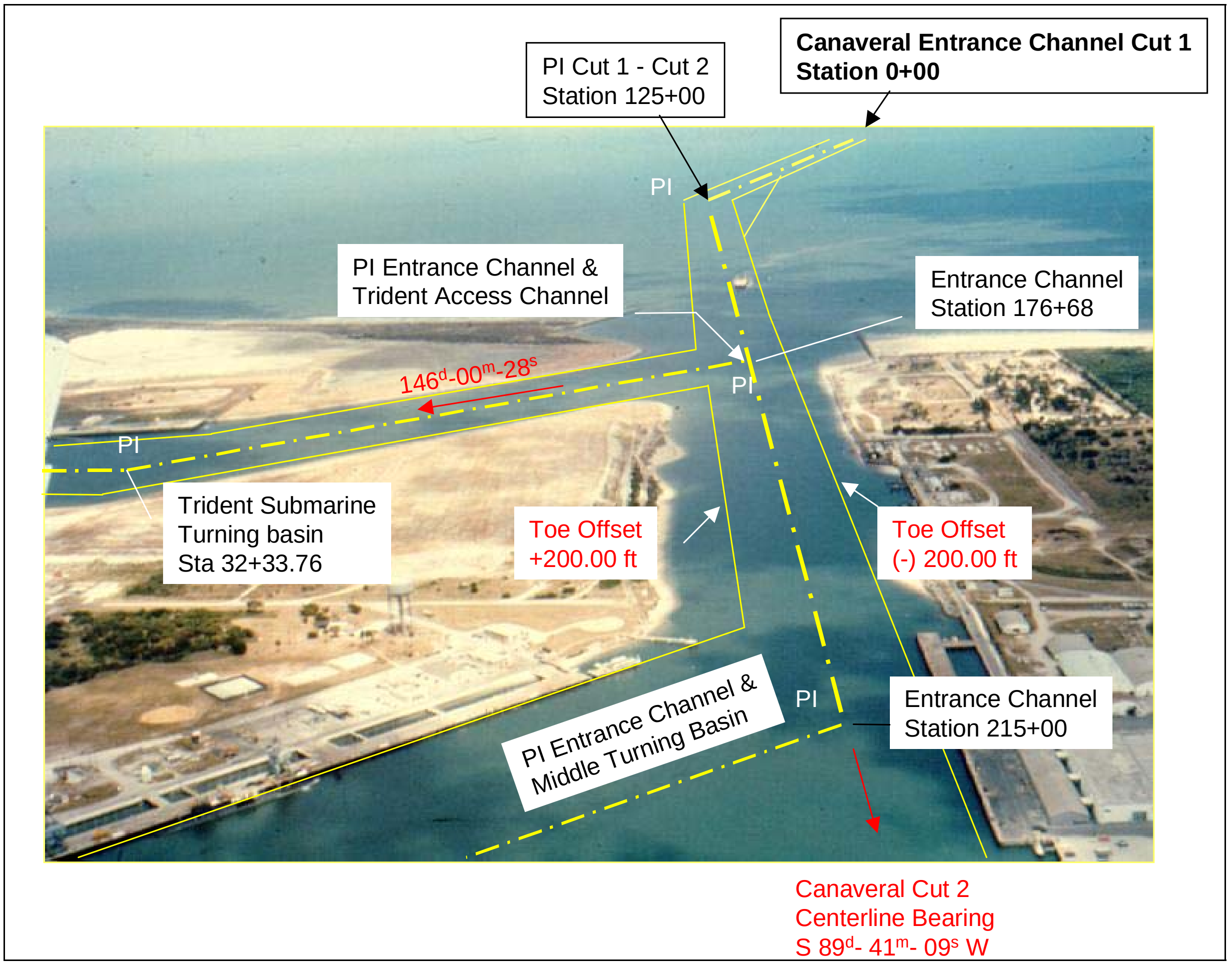

Figure 5-10. Chainage-offset project control scheme for a typical deep-draft navigation project--Cape Canaveral, FL (Jacksonville District)

c. Azimuth. Azimuths are computed relative to the two defining PIs. Either 360-deg azimuth or bearing designations may be used. Azimuths should be shown to the nearest second.

d. Other local alignments. Different station-offset reference grids may be established for individual portions of a project. River sections and coastal beach sections are often aligned perpendicular to the project/coast. Each of these sections is basically a separate local datum with a different reference point and azimuth alignment. Beach sections may also be referenced to an established coastal construction setback line. Circular and transition (spiral) curve alignments are also found in some rivers, canals, and flood control projects such as spillways and levees. Surveys will generally be aligned to the chainage and offsets along such curves. Along inland waterways, such as the Mississippi River, stationing is often referenced to either arbitrary or monumented baselines along the bank. In many instances, a reference baseline for a levee is used, and surveys for revetment design and construction are performed from offsets to this line. Separate baselines may exist over the same section of river, often from levees on opposite banks or as the result of revised river flow alignments. Baseline stationing may increase either upstream or downstream. Most often, the mouth of a river is considered the starting point (Station 0 + 00), or the river reaches are summed to assign a station number at the channel confluence. Stationing may increase consecutively through PIs or reinitialize at channel turns. In addition, supplemental horizontal reference may also be made to a river mile designation system. River mile systems established years ago may no longer be exact if the river course has subsequently realigned itself. River mile designations can be used to specify geographical features and provide navigation reference for users.

5-15. Datum Conversions and Transformation Methods

a. General. Federal Geodetic Control Subcommittee (FGCS) members, which includes USACE, have adopted NAD 83 as the standard horizontal datum for surveying and mapping activities performed or financed by the Federal government. To the extent practicable, legally allowable, and feasible, USACE should use NAD 83 in its surveying and mapping activities. Transformations between NAD 27 coordinates and NAD 83 coordinates are generally obtained using the CORPS Convert (CORPSCON) software package or other North American Datum Conversion (e.g., NADCON) based programs.

b. Conversion techniques. USACE survey control published in the NGS control point database has been already converted to NAD 83 values. However, most USACE survey control was not originally in the NGS database and was not included in the NGS readjustment and redefinition of the national geodetic network. Therefore, USACE will have to convert this control to NAD 83. Coordinate conversion methods considered applicable to USACE projects are discussed below.

(1) Resurvey from NAD 83 Control. A new survey using NGS published NAD 83 control could be performed over the entire project. This could be either a newly authorized project or one undergoing major renovation or maintenance. Resurvey of an existing project must tie into all monumented points. Although this is not a datum transformation technique, and would not normally be economically justified unless major renovation work is being performed, it can be used if existing NAD 27 control is of low density or accuracy.

(2) Readjustment of Survey. If the original project control survey was connected to NGS control stations, the survey may be readjusted using the NAD 83 coordinates instead of the NAD 27 coordinates originally used. This method involves locating the original field notes and observations, and completely readjusting the survey and fixing the published NAD 83 control coordinates.

(3) Mathematical Transformations. Since neither of the above methods can be economically justified on most USACE projects, mathematical approximation techniques for transforming project control data to NAD 83 have been developed. These methods yield results which are normally within ± 1 ft of the actual values and the distribution of errors are usually consistent within a local project area. Since these coordinate transformation techniques involve approximations, they should be used with caution when real property demarcation points and precise surveying projects are involved. When mathematical transformations are employed they should be adequately noted so that users will be aware of the conversion method.

c. Horizontal datum transformation methods. Coordinate transformations from one geodetic reference system to another can be most practically made either by using a local seven-parameter transformation or by interpolation of datum shift values across a given region.

(1) Seven parameter transformations. For worldwide (OCONUS) and local datum transformations, one of the referenced textbooks at Section A-2 should be consulted.

(2) Grid-shift transformations. Current methods for interpolation of datum shift values use the difference between known coordinates of common points from both the NAD 27 and NAD 83 adjustments to model a best-fit shift in the regions surrounding common points. A grid of approximate

datum shift values is established based on the computed shift values at common points in the geodetic network. The datum shift values of an unknown point within a given grid square are interpolated along each axis to compute an approximate shift value between NAD 27 and NAD 83. Any point that has been converted by such a transformation method should be considered as having only approximate NAD 83 coordinates.

(3) NADCON/CORPSCON. NGS developed the transformation program NADCON, which yields consistent NAD 27 to NAD 83 coordinate transformation results over a regional area. This technique is based on the above grid-shift interpolation approximation. NADCON was reconfigured into a more comprehensive program called CORPSCON. Technical documentation and operating instructions for CORPSCON can be obtained at the following ERDC Web site: http://crunch.tec.army.mil. This software converts between:

NAD 27	NAD 83	SPCS 27	SPCS 83
UTM 27	UTM 83	NGVD 29	NAVD 88
GEOID03	HARN		

Since the overall CORPSCON datum shift (from point to point) varies throughout North America, the amount of datum shift across a local project is also not constant. The variation can be as much as 0.1 ft per mile. Examples of some NAD 27 to NAD 83 based coordinate shift variations that can be expected over a 10,000-ft section of a project are shown below:

Project Area	SPCS Reference	Per 10,000 feet
Baltimore, MD	1900	0.16 ft
Los Angeles, CA	0405	0.15 ft
Mississippi Gulf Coast	2301	0.08 ft
Mississippi River (IL)	1202	0.12 ft
New Orleans, LA	1702	0.22 ft
Norfolk, VA	4502	0.08 ft
San Francisco, CA	0402	0.12 ft
Savannah, GA	1001	0.12 ft
Seattle, WA	4601	0.10 ft

Such local scale changes will cause project alignment data to distort by unequal amounts. Thus, a 10,000-ft tangent on NAD 27 project coordinates could end up as 9,999.91 feet after mathematical transformation to NAD 83 coordinates. Although such differences may not be appear significant from a lower-order construction survey standpoint, the potential for such errors must be recognized. Therefore, the transformations will not only significantly change absolute coordinates on a project and the datum transformation process will slightly modify the project's design dimensions and/or construction orientation and scale. For example, on a navigation project, an 800.00-ft wide channel could vary from 799.98 to 800.04 feet along its reach. This variation could also affect grid alignment azimuths. Moreover, if the local SPCS 83 grid was further modified, then even larger dimension changes can result. Correcting for distortions may require recomputation of coordinates after conversion to ensure original project dimensions and alignment data remain intact. This is particularly important for property and boundary surveys. A less accurate alternative is to compute a fixed shift to be applied to all data points over a limited area. Determining the maximum area over which such a fixed shift can be applied is important. Computing a fixed conversion factor with CORPSCON can be made to within ±1 foot. Typically, this fixed conversion would be computed at the center of a sheet or at the center of a project and the conversions in X and Y from NAD 27 to NAD 83 and from SPCS 27 to SPCS 83 indicated by notes on the sheets or data sets. Since the conversion is not constant over a given area, the fixed conversion amounts must be explained in the note. The magnitude of the conversion factor change across a sheet is a function of location and the drawing scale. Whether the magnitude of the distortion is significant depends on the nature of the project. For example, a 0.5-ft variation on an offshore navigation project may be acceptable for converting depth sounding locations, whereas a 0.1-ft change may be intolerable for construction layout on an installation. In any event, the magnitude of this gradient should be computed by CORPSCON at each end (or corners) of a sheet or project. If the conversion factor variation exceeds the allowable tolerances, then a fixed conversion factor should not be used. Two examples of using Fixed Conversion Factors follow:

Example 1. Assume a 1 inch = 40 ft scale site plan map on existing SPCS 27 (VA South Zone 4502). Using CORPSCON, convert existing SPCS 27 coordinates at the sheet center and corners to SPCS 83 (US Survey Foot), and compare SPCS 83-27 differences.

SPCS 83		SPCS 27	SPCS 83 - SPCS 27
Center	N 3,527,095.554	Y 246,200.000	dY = 3,280,895.554
of Sheet	E 11,921,022.711	X 2,438,025.000	dX = 9,482,997.711
NW	N 3,527,595.553	Y 246,700.000	dY = 3,280,895.553
Corner	E 11,920,522.693	X 2,437,525.000	dX = 9,482,997.693
NE	N 3,527,595.556	Y 246,700.000	dY = 3,280,895.556
Corner	E 11,921,522.691	X 2,438,525.000	dX = 9,482,997.691
SE	N 3,526,595.535	Y 245,700.000	dY = 3,280,895.535
Corner	E 11,921,522.702	X 2,438,525.000	dX = 9,482,997.702
SW	N 3,526,595.535	Y 245,700.000	dY = 3,280,895.535
Corner	E 11,920,522.704	X 2,437,525.000	dX = 9,482,997.704

Since coordinate differences do not exceed 0.03 feet in either the X or Y direction, the computed SPCS 83-27 coordinate differences at the center of the sheet may be used as a fixed conversion factor to be applied to all existing SPCS 27 coordinates on this drawing.

Example 2. Assuming a 1inch = 1,000 ft base map is prepared of the same general area, a standard drawing will cover some 30,000 feet in an east-west direction. Computing SPCS 83-27 differences along this alignment yields the following:

SPCS 83		SPCS 27	SPCS 83 - SPCS 27
West	N 3,527,095.554	Y 246,200.000	dY = 3,280,895.554
End	E 11,921,022.711	X 2,438,025.000	dX = 9,482,997.711
East	N 3,527,095.364	Y 246,200.000	dY = 3,280,895.364
End	E 11,951,022.104	X 2,468,025.000	dX = 9,482,997.104

The conversion factor gradient across this sheet is about 0.2 ft in Y and 0.6 ft in X. Such small changes are not significant at the plot scale of 1 inch = 1,000 ft; however, for referencing basic design or construction control, applying a fixed shift across an area of this size is not recommended -- individual points should be transformed separately. If this 30,000-ft distance were a navigation project, then a fixed conversion factor computed at the center of the sheet would suffice for all bathymetric features. Caution should be exercised when converting portions of projects or military installations or projects that are adjacent to other projects that may not be converted. If the same monumented control points are used for several projects or parts of the same project, different datums for the two projects or parts thereof could lead to surveying and mapping errors, misalignment at the junctions and layout problems during construction.

d. Dual grids ticks. Depicting both NAD 27 and NAD 83 grid ticks and coordinate systems on maps and drawings should be avoided where possible. This is often confusing and can increase the chance for errors during design and construction. However, where use of dual grid ticks and coordinate systems is unavoidable, only secondary grid ticks in the margins will be permitted.

e. Field survey methods. If GPS is used to set new control points referenced to higher order control many miles from the project (e.g., CORS networks), inconsistent data may result at the project site. If the new control is near older control points that have been converted to NAD 83 using CORPSCON, two slightly different network solutions can result, even though both have NAD 83 coordinates. In order to avoid these situations, it is recommended that all project control (old and new) be tied into the same reference system--preferably the NSRS.

f. Local project datums. Local project datums that are not referenced to NAD 27 cannot be mathematically converted to NAD 83 with CORPSCON. Field surveys connecting them to other stations that are referenced to NAD 83 are required.

5-16. Horizontal Transition Plan from NAD 27 to NAD 83

a. General. Not all maps, engineering site drawings, documents, and associated products containing coordinate information will require conversion to NAD 83. To insure an orderly and timely transition to NAD 83 is achieved for the appropriate products, the following general guidelines should be followed:

(1) Initial surveys. All initial surveys should be referenced to NAD 83.

(2) Active projects. Active projects where maps, site drawings or coordinate information are provided to non-USACE users (e.g., NOAA, USCG, FEMA, and others in the public and private sector) coordinates should be converted to NAD 83 the next time the project is surveyed or maps or site drawings are updated for other reasons.

(3) Inactive projects. For inactive projects or active projects where maps, site drawings or coordinate information are not normally provided to non-USACE users, conversion to NAD 83 is optional.

(4) Datum notes. Whenever maps, site drawings or coordinate information (regardless of type) are provided to non-USACE users, it should contain a datum note, such as the following:

> THE COORDINATES SHOWN ARE REFERENCED TO NAD *[27/83] AND ARE IN FEET BASED ON THE SPCS *[27/83] *[STATE, ZONE]. DIFFERENCES BETWEEN NAD 27 AND NAD 83 AT THE CENTER OF THE *[SHEET/DATASET] ARE *[dLat, dLon, dX, dY]. DATUM CONVERSION WAS PERFORMED USING THE COMPUTER PROGRAM “CORPSCON.” METRIC CONVERSIONS WERE BASED ON THE *[US SURVEY FOOT = 1200/3937 METER] [INTERNATIONAL FOOT = 30.48/100 METER].

b. Levels of effort. For maps and site drawings the conversion process entails one of three levels of effort:

(1) Conversion of coordinates of all mapped details to NAD 83, and redrawing the map,

(2) Replace the existing map grid with a NAD 83 grid,

(3) Simply adding a datum note.

For surveyed points, control stations, alignment, and other coordinated information, conversion must be made either through a mathematical transformation or through readjustment of survey observations.

c. Detailed instructions.

(1) Initial surveys on Civil Works projects. The project control should be established on NAD 83 relative to NGS's National Spatial Reference System (NSRS) using conventional or GPS surveying procedures. The local SPCS 83 grid should be used on all maps and site drawings. All planning and design activities should then be based on the SPCS 83 grid. This includes supplemental site plan mapping, core borings, project design and alignment, construction layout and payment surveys, and applicable boundary or property surveys. All maps and site drawings shall contain datum notes. If the local sponsor requires the use of NAD 27 for continuity with other projects that have not yet converted to NAD 83, conversion to NAD 27 could be performed using the CORPSCON transformation techniques.

(2) Active Civil Works Operations and Maintenance projects undergoing maintenance or repair. These projects should be converted to NAD 83 during the next maintenance or repair cycle in the same manner as for newly initiated civil works projects. However, if resources are not available for this level of effort, either redraw the grids or add the necessary datum notes. Plans should be made for the full conversion during a later maintenance or repair cycle when resources can be made available.

(3) Military Construction and master planning projects. All installations and master planning projects should remain on NAD 27 or the current local datum until a thoroughly coordinated effort can be arranged with the MACOM and installation. An entire installation's control network should be transformed simultaneously to avoid different datums on the same installation. The respective MACOMs are responsible for this decision. However, military operations may require NAD 83, including SPCS 83 or UTM metric grid systems. If so, these shall be performed separate from facility engineering support. A dual grid system may be required for such operational applications when there is overlap with normal facilities engineering functions. Coordinate transformations throughout an installation can be computed using the procedures described herein. Care must be taken when using transformations from NAD 27 with new control set using GPS methods from points remote from the installation. Installation boundary surveys should adhere to those outlined under real estate surveys listed below.

(4) Real Estate. Surveys, maps, and plats prepared in support of civil works and military real estate activities should conform as much as possible to state requirements. Since most states have adopted NAD 83, most new boundary and property surveys should be based on NAD 83. The local authorities should be contacted before conducting boundary and property surveys to ascertain their policies. It should be noted that several states have adopted the International Foot for their standard conversion from meters to feet. In order to avoid dual coordinates on USACE survey control points that have multiple uses, all control should be based on the US Survey Foot, including control for boundary and property surveys. In states where the International Foot is the only accepted standard for boundary and property surveys, conversion of these points to NAD 83 should be based on the International foot, while the control remains based on the US Survey foot.

(5) Regulatory functions. Surveys, maps, and site drawings prepared in support of regulatory functions should begin to be referenced to NAD 83 unless there is some compelling reason to remain on NAD 27 or locally used datum. Conversion of existing surveys, maps, and drawings to NAD 83 is not necessary. Existing surveys, maps, and drawings need only have the datum note added before distribution to non-USACE users. The requirements of local, state and other Federal permitting agencies should be ascertained before site specific conversions are undertaken. If states require conversions based on the International foot, the same procedures as described above for Real Estate surveys should be followed.

(6) Other existing projects. Other existing projects, e.g., beach nourishment, submerged offshore disposal areas, historical preservation projects, etc., need not be converted to NAD 83. However, existing surveys, maps, and drawings should have the datum note added before distribution to non-USACE users.

(7) Work for others. Existing projects for other agencies will remain on NAD 27 or the current local datum until a thoroughly coordinated effort can be arranged with the sponsoring agency. The decision to convert rests with the sponsoring agency. However, existing surveys, maps, and drawings should have the datum note added before distribution to non-USACE users. If sponsoring agencies do not indicate a preference for new projects, NAD 83 should be used. The same procedures as described above for initial surveys on Civil Works projects should be followed.

SECTION III
Vertical Reference Systems

A vertical datum is the surface to which elevations or depths are referred to or referenced. There are many vertical datums used within CONUS. The surveyor should be aware of the vertical control datum being used and its practicability to meet project requirements. .

5-17. National Geodetic Vertical Datum of 1929 (NGVD 29)

NGVD 29 was established by the United States Coast and Geodetic Survey (USC&GS) 1929 General Adjustment by constraining the combined US and Canadian First Order leveling nets to conform to Mean Sea Level (MSL). It was determined at 26 long-term tidal gage stations that were spaced along the east and west coast of North American and along the Gulf of Mexico, with 21 stations in the US and 5 stations in Canada. NGVD 29 was originally named the Mean Sea Level Datum of 1929. It was known at the time that the MSL determinations at the tide gages would not define a single equipotential surface because of the variation of ocean currents, prevailing winds, barometric pressures, and other physical causes. The name of the datum was changed from the Mean Sea Level Datum to the NGVD 29 in 1973 to eliminate the reference to sea level in the title. This was a change in name only; the definition of the datum established in 1929 was not changed. Since NGVD 29 was established, it has become obvious that the geoid based upon local mean tidal observations would change with each measurement cycle. Estimating the geoid based upon the constantly changing tides does not provide a stable estimate of the shape of the geoid.

5-18. North American Vertical Datum of 1988 (NAVD 88)

The NAVD 88 datum is the product of a vertical adjustment of leveled height difference measurements made across North America. This reference system supersedes the NGVD 29 vertical reference framework. NAVD 88 was constrained by holding fixed the orthometric height of a single primary tidal benchmark at Father's Point / Rimouski, Quebec, Canada and performing a minimally constrained general adjustment of US-Canadian-Mexican leveling observations. Most Third Order benchmarks, including those of other Federal, state and local government agencies, were not included in the NAVD 88 adjustment. The vertical reference surface is therefore defined by the surface on which the gravity values are equal to the control point value. NAVD 88 elevations are published orthometric heights that represent the geometric distance from the geoid to the terrain measured along the plumb line. Orthometric height corrections were used to enforce consistency between geopotential based vertical coordinates and measured leveled differences. NAVD 88 is the most compatible vertical reference frame available to relate GPS ellipsoidal heights to orthometric heights. Note also that NGVD 29 is no longer supported by NGS; thus, USACE commands should be transitioning all older project vertical control to NAVD 88. The differences in orthometric elevations between the superseded NGVD 29 and NAVD 88 references are significant--upwards of 1.5 meters in places, as depicted in Figure 5-11 below. Therefore, it is important that these two reference systems not be confused. Given the local variations shown in Figure 5-14, there is no direct transformation between the two systems, and a site calibration/transformation must be performed as explained in subsequent sections.

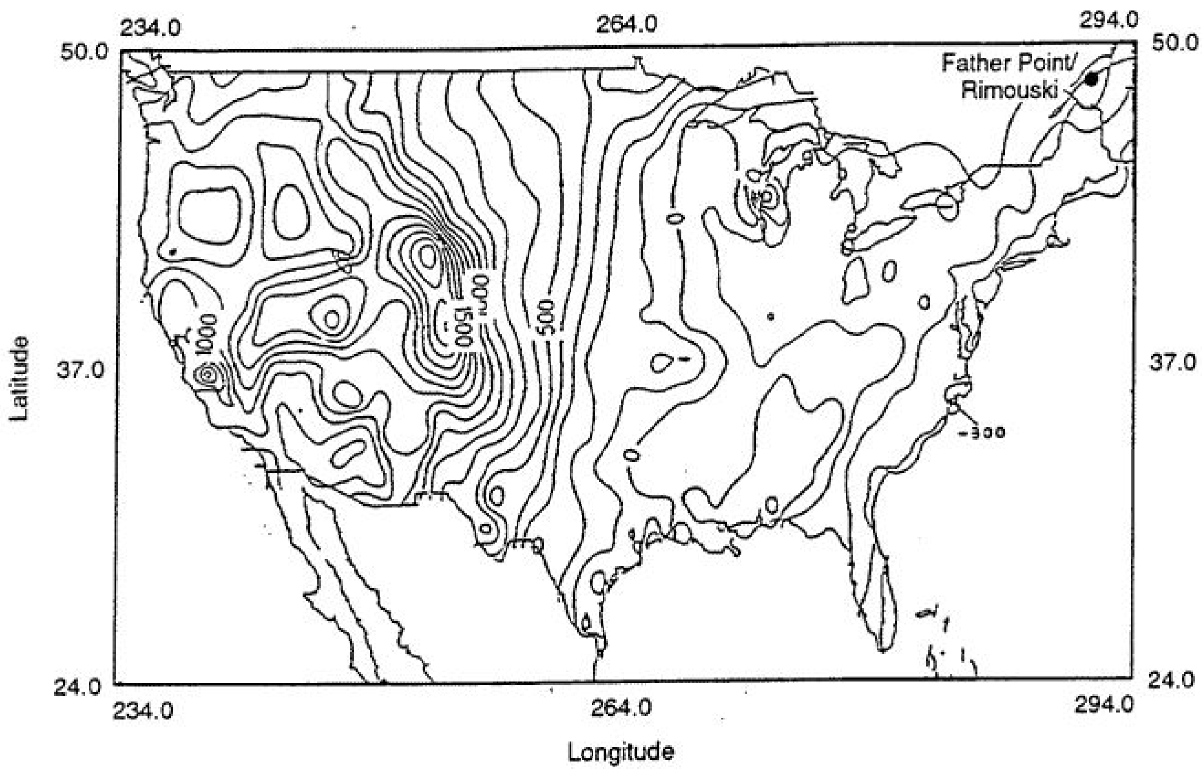

Figure 5-11. NGVD 29-NAVD 88 elevation differences in mm

The Federal Geodetic Control Subcommittee (FGCS) of the Federal Geographic Data Committee (FGDC) has affirmed that NAVD 88 shall be the official vertical reference datum for the US. The FGDC has prescribed that all surveying and mapping activities performed or financed by the Federal Government make every effort to begin an orderly transition to NAVD 88, where practicable and feasible. Further technical details on NAVD 88 are in Appendix C, "*Development and Implementation of NAVD 88*."

5-19. Other Vertical Reference Datums and Planes

a. Mean Sea Level datums. Some vertical datums are referenced to mean seal level. Such datums typically are maintained locally or within a specific project area. The theoretical basis for these datums is local mean sea level. Local MSL is a vertical datum based on observations from one or more tidal gaging stations. NGVD 29 was based upon the assumption that local MSL at 21 tidal stations in the US and 5 tidal stations in Canada averaged 0.0 ft on NGVD 29. The value of MSL as measured over the Metonic cycle of 19 years shows that this assumption is not valid and that MSL varies from station to station.

b. Great Lake datums. Depths in the Great Lakes and connecting channels are referenced to the International Great Lakes Datum (IGLD) of 1985. IGLD 85 represents a low water datum from which navigation is maintained. A separate datum is established for each of the Great Lakes. The datum must be adjusted for slope in the connecting channels between the Great Lakes. These datums undergo periodic adjustment. For example, the IGLD 55 was adjusted in 1985 to produce IGLD 85. IGLD 85 has been directly referenced to NAVD 88 and originates at the same point as NAVD 88. Additional details are provided in Appendix C.

c. Other vertical datums. Other areas may maintain and employ specialized vertical datums. For instance, vertical datums maintained in Alaska, Puerto Rico, Hawaii, the Virgin Islands, Guam, and other islands and project areas. Specifications and other information for these particular vertical datums can be obtained from the particular District responsible for survey related activities in these areas, or the National Ocean Service (NOS).

d. Tidal areas. Tidal datums usually are defined by the range and phase of the tide and usually are referenced to a mean lower low water elevation, or MLLW. In offshore coastal areas, CONUS navigation projects are generally referenced to a MLLW datum established by NOS or the Corps from long-term gage observations. This MLLW reference plane is not a flat surface but slopes as a function of the tidal range in the area. Tidal range can increase or decrease near coastal entrances; thus the MLLW must be accurately modeled throughout the navigation project. The required grade at all points on the navigation project is dependent on tidal modeling--requiring determination of the elevation of the MLLW datum plane from a series of gage observations at each point. For further information on these and other tidal datum related terms, refer to Appendix B, "*Requirements and Procedures for Referencing Coastal Navigation Projects to Mean Lower Low Water (MLLW) Datum"* and EM 1110-2-1003 (*Hydrographic Surveying*)

e. Inland river areas. River datums are usually referenced to a low water reference plane (LWRP), such as the LWRP 1974 reference used in the unregulated portion of the Mississippi River. Like tidal MLLW, the low water river datum must be determined from gage/staff observations at sufficient points along the river to adequately define the surface. The spacing of these observations must be sufficient to allow linear interpolation between staff gage points. For a river like the Mississippi that drops 0.5 ft/mile, gages or benchmarks may be required at least every quarter- to half-mile in order to reference hydrographic surveys.

f. Controlled river pools. Between river control structures, low water pools are used to reference maintained navigation depths. Since these pools themselves may exhibit some slope, sufficient gages/benchmarks within the pools should be established to account for any minor slope.

g. Reservoir pools. Depths in controlled reservoirs are usually referenced to a national vertical datum (e.g., NGVD 29 or NAVD 88).

5-20. Orthometric Elevations

Orthometric elevations are those corresponding to the earth's irregular geoidal surface, as illustrated in Figure 5-12 below. Measured differences in elevation from spirit leveling are generally relative to the local geoidal surface--a spirit level bubble (or pendulum) positions the instrument normal to the direction of gravity, and thus parallel with the local slope of the geoid, which approximates mean sea level near coastal points. The orthometric height of a point is the distance from the geoid (or a related reference surface) to the point on the earth's surface, measured along the line perpendicular to every equipotential surface in between. A series of equipotential surfaces can be used to represent the gravity field. One of these surfaces, the geoid, is specified as the reference system from which orthometric heights are measured. The geoid itself is defined as an equipotential surface. Natural variations in gravity induce a smooth, continuous, curvature to the plumb line, and therefore physical equipotential surfaces which are normal to gravity do not remain geometrically parallel over a given vertical distance (the plumb line is not quite parallel to the ellipsoidal normal). Elevation differences between two points are orthometric differences, a distinction particularly important in river/channel hydraulics. Orthometric heights for the continental United States (CONUS) are generally referenced to the NGVD 29 or the updated NAVD 88. The NGVD 29 reference datum more closely approximates mean sea level--the NAVD 88 does not. Tidal reference datums (e.g., MLLW) vary geographically over short distances and must be accurately related to NAVD 88 and/or NGVD 29 orthometric heights. GPS derived ellipsoidal heights shown in Figure 5-12 below must be converted to local orthometric elevations in order to have useful engineering and construction value--see EM 1110-1-1003 for details. This transformation is usually done by a form of "site calibration" using known orthometric elevations of fixed benchmarks and/or geoid undulation models for the project area. These transforms are further explained below.

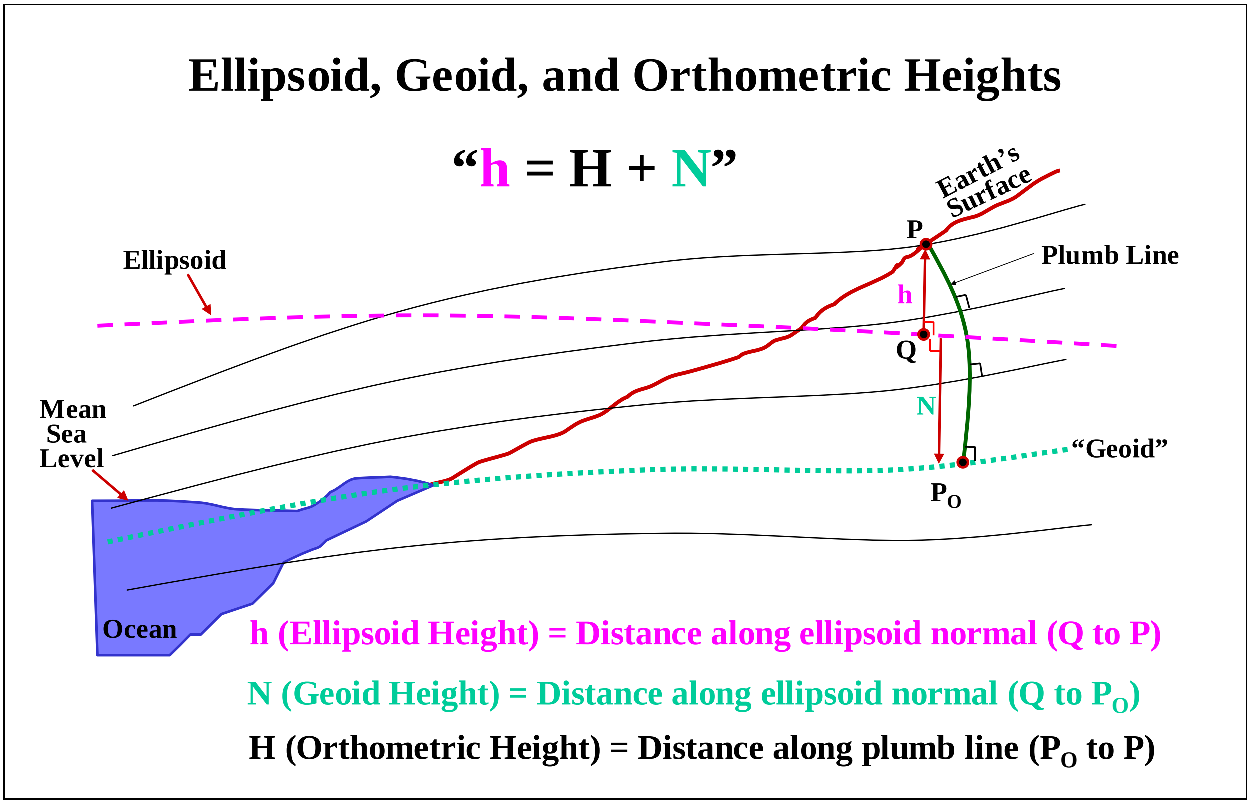

Figure 5-12. Ellipsoid, geoid, and orthometric surface definitions and relationships (NGS)

5-21. WGS 84 Ellipsoidal Heights

GPS-determined heights (or height differences) are referenced to an idealized mathematical ellipsoid which differs significantly from the geoid; thus, GPS heights are not the same as the orthometric heights needed for standard USACE projects (local engineering, construction, and hydraulic measurement functions). Accordingly, any WGS 84 referenced ellipsoidal height obtained using GPS must be transformed or calibrated to the local orthometric vertical datum. This requires adjusting and interpolating GPS-derived heights relative to fixed orthometric elevations. Over short distances--less than 1 km--elevation differences determined by GPS can usually be assumed to be orthometric differences. These elevation differences would then be of sufficient accuracy for topographic site plan mapping, such as those acquired using RTK total station methods. However, at greater distances, a site calibration with surrounding benchmarks must be performed in order to adjust RTK ellipsoidal heights down to the local vertical datum. For some surveys (e.g., offshore navigation), a predicted geoid model may be used if no other vertical control is available to calibrate the model.

5-22. Orthometric Height and WGS 84 Ellipsoidal Elevation Relationship

Geoidal heights represent the geoid-ellipsoid separation distance and are obtained by taking the difference between ellipsoidal and orthometric height values. Knowledge of the geoid height enables the evaluation of vertical positions in either the geodetic (ellipsoid based) or the orthometric height system. The relationship between a WGS 84 ellipsoidal height and an orthometric height relative to the geoid can be obtained from the following equation, and depicted graphically in Figure 5-12 above.

$$h = H + N \qquad \text{(Eq 5-2)}$$

where

h = ellipsoidal height (WGS 84)
H = elevation (orthometric--normal to geoid)
N = geoidal undulation above or below the WGS 84 ellipsoid

and by convention the geoid undulation *"N"* being a positive height above the ellipsoid.

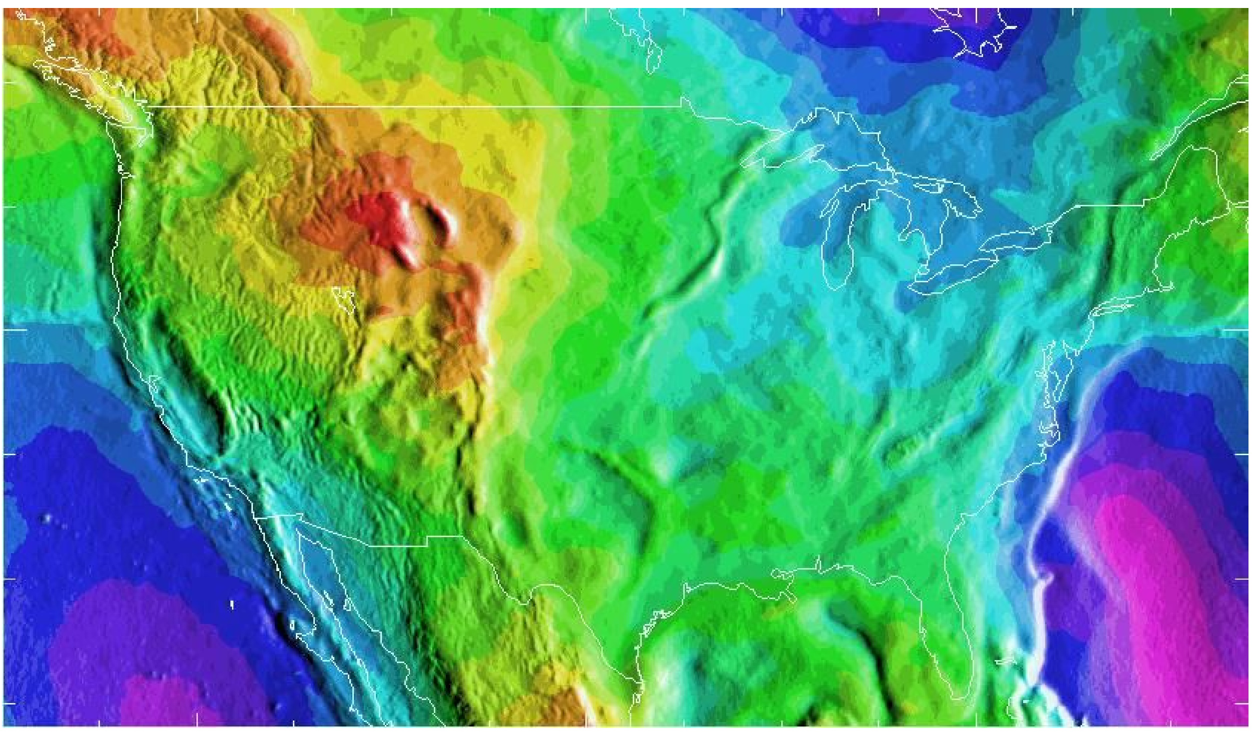

Figure 5-13. Geoid undulation model of North America--depicts geoid undulation *N* relative to the WGS 84 ellipsoid

5-23. Geoid Undulations and Geoid Models

Due to significant variations in the geoid, sometimes even over small distances, elevation differences obtained by GPS cannot be directly equated to orthometric (or spirit level) differences. This geoid variation is depicted as a surface model in Figure 5-13 above. Geoid modeling techniques are used to obtain the parameter *"N"* in the above equation from which ellipsoidal heights can be converted to orthometric elevations. These geoid models (e.g., Geoid 90, Geoid 93, Geoid 96, Geoid 99, Geoid 03, etc.) are approximations based on observations by the NGS. Each successive geoid model is more accurate. In time, these models may improve to centimeter-level accuracy. On some small project areas where the geoid stays relatively constant, elevation differences obtained by GPS can be directly used without geoid correction. Geoid models are not compatible with the superseded NGVD 29.

a. Geoid height values at stations where either only " h "or " H " is known can be obtained from geoid models which are mathematical surfaces representing the shape of the earth's gravity field. The geoid model is constructed from a truncated functional series approximation using a spherical harmonics expansion and an extensive set of globally available gravity data. The model is determined from the unique coefficients of the finite series representing the geoid surface. Its accuracy depends on the coverage and accuracy of the gravity measurements used as boundary conditions. Former geoid models produced for general use limit absolute accuracies for geoid heights to no less than 1 meter. More recent geoid models have shown a significant increase in absolute accuracy for geoid heights to a few centimeters.

b. In practice the shape of the geoid surface is estimated globally as a function of horizontal coordinates referenced to a common geocentric position. Specific geoid height values are extracted from the model surface at the node points of a regular grid (e.g., a 2-minute x 2-minute grid spacing). Biquadratic interpolation procedures can be used within a grid cell boundary to approximate the geoid height at a given geodetic latitude and longitude. For example, the NGS GEOID 96 model for the United States indicates geoid heights (N) range from a low of (-) 51.6 meters in the Atlantic to a high of -7.2 meters in the Rocky Mountains. For more information on geoid modeling, see the references in Appendix A or the National Geodetic Survey web site.

c. GPS surveys can be designed to provide elevations of points on any local vertical datum. This requires connecting to a sufficient number of existing orthometric benchmarks from which the elevations of unknown points can be "best-fit" or "site calibrated" by some adjustment method--usually a least squares minimization. This is essentially an interpolation process and assumes linearity in the geoid slope between two established benchmarks. If the geoid variation is not linear--as is typically the case--then the adjusted (interpolated) elevation of an intermediate point will be in error. Depending on the station spacing, location, local geoid undulations, and numerous other factors, the resultant interpolated/adjusted elevation accuracy is usually not suitable for accurate (i.e., ± 0.01 ft) construction surveying purposes; however, GPS-derived elevations may be adequate for small-scale topographic mapping control and hydrographic surveying applications where ± 0.1 ft accuracy is sufficient.

5-24. Using GPS to Densify Orthometric Elevations

DGPS observation sessions produce 3-D geodetic coordinate differences that establish the baseline between two given stations. The expected accuracy of ellipsoidal height difference measurements is based on several factors, such as GPS receiver manufacture type, observation session duration, and the measured baseline distance, but it does not depend greatly on prior knowledge of the absolute vertical position of either occupied station. Dual frequency, carrier phase measurement based GPS surveys are usually able to produce 3-D relative positioning accuracies under 30 mm at the 95% confidence level over baseline distances less than 20 km, depending on the type of GPS surveying method used. This situation exists mainly because GPS range biases are physically well correlated over relatively short distances and tend to cancel out as a result of forming double differences for carrier phase data processing. In contrast, GPS absolute code positioning accuracy will contain the full effects of any GPS range measurement errors. Geoidal height differences describe the change in vertical position of the geoid with respect to the ellipsoid between two stations. These relative geoidal heights can be more accurate than the modeled absolute separation values within extended areas because the relative geoidal height accuracy is based on the continuous surface characteristics of the geoid model, where only small deviations between closely spaced points would be expected. The regional trend or slope of the geoid at a given point will not be highly sensitive to local gravity anomalies especially in non-mountainous areas. Differential GPS can accurately measure ellipsoidal height differences from GPS satellites. GPS surveys output vertical positions in geodetic coordinates defined with respect to the WGS 84 reference ellipsoid. The ellipsoidal height value at a given point is based on the distance measured along the normal vector from the surface of the reference ellipsoid to the unknown point. The practical accuracy of WGS 84 as a vertical reference frame for collecting elevation data depends on the actual ellipsoidal height values assigned to benchmarks or other physically defined control points.

5-25. Vertical Datum Transformations

Appendix C (*Development and Implementation of NAVD 88)* contains a detailed discussion on the development and implementation of NAVD 88, and the rationale for converting projects from NGVD 29 to this updated vertical datum. There are several reasons for USACE commands to convert authorized and future projects to NAVD 88--these are summarized from Appendix C.

- Differential leveling surveys will close better.
- NAVD 88 height values are available in convenient form from the NGS database.
- Federal surveying and mapping agencies will stop publishing on NGVD 29.
- NAVD 88 is recommended by ACSM and FGCS.
- Surveys performed for the Federal government require use of NAVD 88.
- NAVD 88 provides a reference to estimate GPS derived orthometric heights.

The last bullet above is a primary reason for transforming project control to NAVD 88. The conversion process entails one of two levels of effort that are covered in detail in Appendix C:

(1) Conversion of all elevations to NAVD 88 by readjustment or releveling.

(2) Adding a datum note based on an approximate conversion (VERTCON).

a. VERTCON. VERTCON is a software program developed by NGS that converts elevation data from NGVD 29 to NAVD 88. Although the VERTCON software has been fully incorporated into the software application package CORPSCON, it will be referred to below as a separate program. VERTCON uses benchmark heights to model the shift between NGVD 29 and NAVD 88 that is applicable to a given area. In general, it is only sufficiently accurate to meet small-scale mapping requirements. VERTCON should not be used for converting benchmark elevations used for site plan design or construction applications. Users input the latitude and longitude for a point and the vertical datum shift between NGVD 29 and NAVD 88 is reported. The root-mean-square (RMS) error of NGVD

29 to NAVD 88 conversion, when compared to the stations used to create the conversion model, is ±1 cm; with an estimated maximum error of ± 2.5 cm. Depending on network design and terrain relief, larger differences (e.g., 5 to 50 cm) may occur the further a benchmark is located from the control points used to establish the model coefficients. For this reason, VERTCON should only be used for approximate conversions where these potential errors are not critical.

b. Datum note. Whenever maps, site drawings, or spatial elevation data are provided to non-USACE users, they should contain a datum note that provides, at minimum, the following information:

> The elevations shown are referenced to the *[NGVD 29] [NAVD 88] and are in *[feet] [meters]. Differences between NGVD 29 and NAVD 88 at the center of the project sheet/data set are shown on the diagram below. Datum conversion was performed using the *[program VERTCON] [direct leveling connections with published NGS benchmarks] [other]. Metric conversions are based on *[US Survey Foot = 1200/3937 meters] [International Survey Foot = 0.3048 meters].

5-26. Vertical Transition Plan from NGVD 29 to NAVD 88

a. General. A change in the vertical datum on a project will affect USACE engineering, construction, planning, and surveying activities. The cost of conversion could be substantial at the onset. There is a potential for errors in conversions inadvertently occurring. The effects of the vertical datum change can be minimized if the change is gradually applied over time; being applied to future projects and efforts, rather than concentrated on changing already published products. In order to insure an orderly and timely transition to NAVD 88 is achieved for the appropriate products, the following general guidelines should be followed.

b. Conversion criteria. Maps, engineering site drawings, documents, and associated spatial data products containing elevation data may require conversion to NAVD 88. Specific requirements for conversion will, in large part, be based on local usage--e.g., that of the local sponsor, installation, etc. Where applicable and appropriate, this conversion should be recommended to local interests.

c. Newly authorized construction projects. Generally, initial surveys of newly authorized projects should be referenced to NAVD 88. In addition to design/construction, this would include wide-area master plan mapping work. The project control should be referenced to NAVD 88 using conventional or GPS surveying techniques. All planning and design activities should be based upon NAVD 88. All maps and site drawings shall contain datum notes as described below. If the sponsor/installation requires the use of NGVD 29 or some other local vertical reference datum for continuity, the relationship between NGVD 29 and NAVD 88 shall be clearly noted on all maps, engineering site drawings, documents, and associated products.

d. Active projects. On active projects where maps, site drawings, or elevation data are provided to non-USACE users, the conversion to NAVD 88 should be performed. This conversion to NAVD 88 may be performed the next time the project is surveyed or when the maps/site drawings are updated for other reasons. Civil works projects may be converted to NAVD 88 during the next maintenance or repair cycle in the same manner as for newly initiated civil works projects. However, if resources are not available for this level of effort, redraw the maps or drawings and add the necessary datum note. Plans should be made for the full conversion during a later maintenance or repair cycle when resources can be made available. Military installations should remain on NGVD 29 or the local vertical datum until a thoroughly coordinated effort can be arranged with the MACOM and installation. An entire installation's control network should be transformed simultaneously to avoid different datums on the same installation. MACOMs should be encouraged to convert to NAVD 88. However, the respective MACOMs are responsible for this decision.

e. Inactive projects. For inactive projects or active projects where maps, site drawings, or elevation data are not normally provided to non-USACE users, conversion to NAVD 88 is optional.

f. Work for others. Projects for other agencies will remain on NGVD 29 or the current local vertical datum until a thoroughly coordinated effort can be arranged with the sponsoring agency. Other agencies should be encouraged to convert their projects to NAVD 88, although the decision to convert rests with the sponsoring agency. However, surveys, maps, and drawings should have the datum note described below added before distribution to non-USACE users. If sponsoring agencies do not indicate a preference for new projects, NAVD 88 should be used.

g. Miscellaneous projects. Other projects referenced to strictly local datum, such as, beach nourishment, submerged offshore disposal areas, historical preservation projects, etc., need not necessarily be converted to NAVD 88. However, it is recommended that surveys, maps and drawings have a clear datum reference note added before distribution to non-USACE users.

h. Real Estate. Surveys, maps, and plats prepared in support of civil works and military real estate activities should conform as much as possible to state requirements. Many states are expected to adopt NAVD 88 (by statute) as an official vertical reference datum. This likewise will entail a transition to NAVD 88 in those states. State and local authorities should therefore be contacted to ascertain their current policies. Note that several states have adopted the International Foot for their standard conversion from meters to feet. In order to avoid dual elevations on USACE survey control points that have multiple uses, it is recommended that published elevations be based on the US Survey Foot. In states where the International Foot is the only accepted standard for boundary and property surveys, conversion of these elevations to NAVD 88 should be based on the International Foot while the control remains based on the US Survey Foot.

5-27. Vertical Control in Areas Subjected to Subsidence or Sea Level Rise

Published elevations relative to the vertical datums in high subsidence areas must be used with caution. This is due to the uneven temporal and spatial movement of the land. Thus, any geodetic or terrestrial-based elevation is not constant and must be periodically observed and adjusted for local subsidence. Likewise, hydraulic or sea level based reference datums are subject to variations due to subsidence and sea level rise at each gage site. Sea level datums also have time varying astronomical components making their reference definition more complex than terrestrial based datums. Hydraulic low water reference datums used to define navigation and flood protection elevations on the Mississippi River may also be subject to subsidence and other long-term variations, and thus these datums are spatially and temporally variable.

Subsidence is the lowering or sinking of Earth’s surface, often quantified relative to non-sinking portions of the Earth’s crust. It is especially pronounced in portions of California, Texas, and Louisiana. In Southern Louisiana, subsidence is occurring at a rate of up to 0.1 foot every three years in some areas. There are many potential factors that contribute to subsidence, such as the geologic composition of the area and withdrawal of ground water and oil. The rate of subsidence is not always constant and can vary from epoch to epoch (survey to survey) due to many factors, such as compaction, removal of subsurface fluids, and geologic events. Therefore, one cannot predict future subsidence with any degree of accuracy. Table 1 below illustrates the large variability in subsidence rates of change occurring over a relatively small region in Louisiana. These rates were determined from periodic First-Order, Class II leveling surveys by NOAA.

Table 1 **Apparent Benchmark Movement Rates**	
Benchmark Designation	**Rates of Movement in Millimeters per year**
A 148 (AU0429)	-11.01
PIKE RESET (BH1164)	-6.99
231 LAGS (BH1073)	-16.08
A 92 (BH1136)	-7.39

Subsidence can be measured and/or periodically monitored using either conventional leveling procedures or GPS techniques contained in NOAA 1997 (Guidelines for Establishing GPS-Derived Ellipsoid Heights (Standards: 2 cm and 5 cm)). Determining subsidence rates requires long-term observations and considerable analysis. As an example, Figure 5-14 below contains a map showing the estimated amount of subsidence along the route between New Orleans and Venice, LA. The leveling for this line was performed by NOAA in 1984 and adjusted to the NGVD 29 datum at that time. In 1991, NGS adjusted the entire CONUS to the NGVD 29 datum in preparation for the NAVD 88 adjustment. In Southern Louisiana, an extensive “GPS Derived Height” network was completed establishing new heights (elevations) for 85 benchmarks in Southern Louisiana. This adjustment, known as NAVD 88 (2004.65), held control outside of the subsidence area to establish new NAVD88 adjusted heights for the 85 benchmarks. Because the 1991 NAVD 88 adjustment held control outside of the area, as did the NAVD 88 (2004.65) adjustment, the change in the heights reflects the apparent movement of the marks between the observation periods. In order to determine the amount of subsidence from the time the original leveling was done, it is necessary to determine the amount of movement between the original adjustment and the 1991 national readjustment of the NGVD 29 and then the amount of movement between the original NAVD 88 adjustment and the NAVD 88 (2004.65) adjustment.

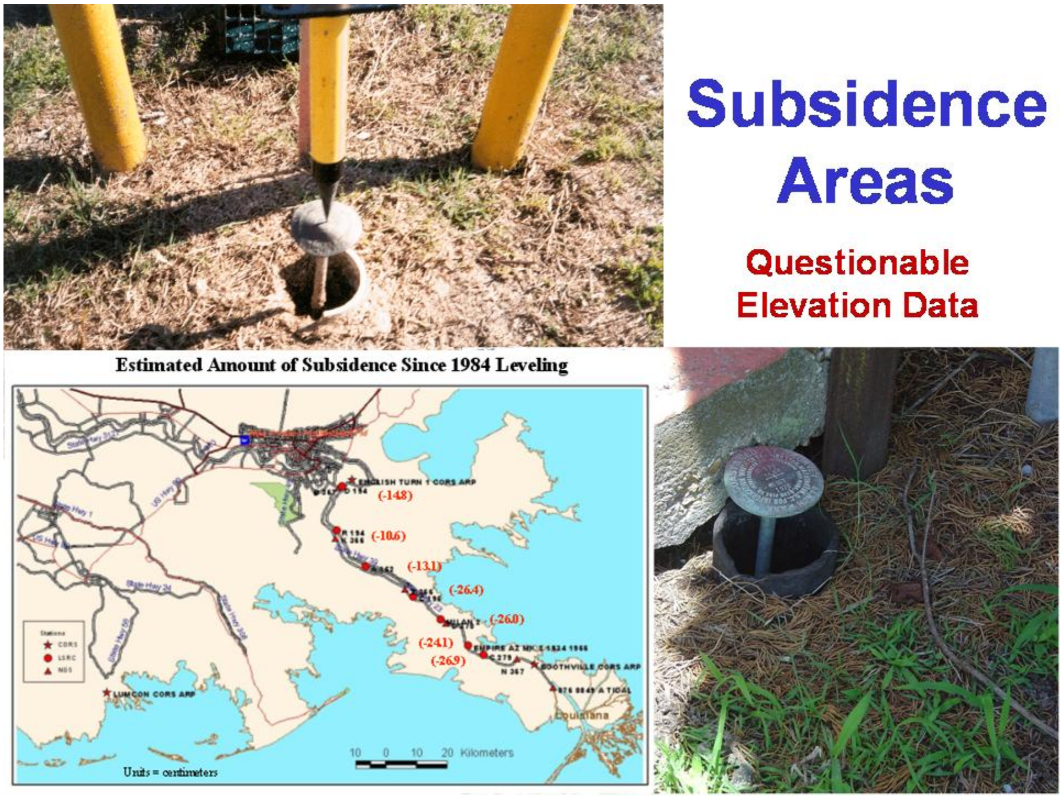

Figure 5-14. Estimated subsidence (in centimeters) in the New Orleans to Venice region. Photos depict relative ground subsidence of benchmarks attached to deep driven rods.

Monitoring subsidence or sea level changes on flood control, hurricane protection, or coastal (tidal) navigation projects requires continuous leveling or GPS surveys between water level recording gages and fixed benchmarks. Vertical datums (NAVD 88 and tidal lower low water datums) must be periodically updated to reflect changes due to subsidence or sea level rise.

5-28. Mandatory Standards

Spatial data collected for projects shall be referenced to the updated NAD 83 and NAVD 88 reference datums established by the National Oceanic and Atmospheric Administration (NOAA). Navigation projects referenced to tidal datums shall be updated to the latest tidal epoch (currently 1983-2001) in accordance with the statutory requirements in Section 224 of the Water Resources Development Act of 1992 (see Appendix B). Flood control or hurricane protection structure elevations shall be referred to the hydrodynamic surface model datum used in the design analysis.