The Right Place

The Promise and the Peril of Using GPS for GIS

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The Global Positioning System (GPS) has become a dominant technology for positioning. GPS is used for a wide variety of mapping and surveying applications and is often employed for populating, verifying, and controlling Geographical Information System (GIS) databases. The software has also become easier to use, so that it is now possible for a user with minimal training to collect and process GPS data. Such "user-friendly" software has made GPS a much more accessible technology, yet this ease of use has come at a price: It is also easy for users with little geodetic knowledge to unwittingly generate erroneous coordinates.

Modern technology is characterized by rapid change, and GPS is no exception. The pace of change has made it difficult to establish GPS positioning standards and specifications. Many users find themselves struggling to understand a tool that is both highly complex and unnervingly easy to use. GPS vendors have attempted to fill this void by developing their own specifications and methods, including their own jargon. While this has propelled the use of GPS, it has also led to confusion about procedures, accuracy, performance, and terminology. This has made it problematic for those seeking positioning services to write meaningful project specifications. The end result of all this is a greatly increased risk for creating or receiving a product that is not correctly georeferenced — that is, not in the right place.

The positioning precision of GPS varies greatly, by as much as a factor of a thousand depending on the types of equipment and procedures used. Regardless of the precision, derivations and manipulations of GPS coordinates are based on the science of geodesy. While poor field procedures can and do contribute to positioning errors, the largest errors, both in number and magnitude, are a consequence of neglecting the geodetic principles behind GPS.

To illustrate this problem, several examples of GPS positioning errors are listed in Table 1. This table was prepared for the situation as it exists in Alaska, but most of the examples apply to other areas in the country, and even elsewhere in the world. Although the list is intended to be comprehensive, it does not cover all possible permutations. It is important to realize that these tabulated errors are not hypothetical; they actually do occur. This fact alone should give pause to surveyors and GIS managers.

Two things in Table 1 specifically warrant comment. One is the large variety of positioning errors, which can occur from diverse sources, and can range from a fraction of a foot to many miles. The other is that the table is dense with arcane terminology and abbreviations. Indeed, most of the error descriptions in the table are probably unfamiliar to many readers (a list of definitions below the table should help in deciphering it). This is a cogent demonstration of what is arguably the central problem of GPS positioning: It is a highly complex technology that requires considerable geodetic knowledge to ensure consistent and correct results. This problem remains despite the efforts of vendors to streamline and simplify the GPS positioning process.

The required positional accuracy of data used to populate a GIS can vary widely. For example, mapping of utilities might require positions accurate to ±5 feet horizontally (with no vertical accuracy specified). In contrast, control for a flood hazard mapping project could require positions accurate to better than ±0.1 foot, both horizontally and vertically. At the other end of the spectrum, mapping of wildlife habitat might only need to achieve a horizontal accuracy of ±100 feet. Despite this wide range, all positioning has some accuracy associated with it, and this accuracy should always be part of the GIS metadata. Even positions with relatively low accuracy requirements can be adversely affected by some of the errors listed in Table 1.

A major challenge facing the geospatial community is the problem of establishing appropriate mapping standards and specifications. In many cases existing standards are preliminary; if not well written or if overly prescriptive they can quickly become obsolete; they may be excessively long and complex; and in some cases they are too vendor-specific to be generally useful. Because of such problems with existing standards, a goal of the geospatial community should be to develop spatial data standards that will enable them to unambiguously define project requirements, whether they are seeking or providing mapping and surveying services. Given the pace of technological change, it is vitally important that any new standards be flexible enough to allow for the inevitable advances in theory and technology. Another critical element of modern standards is that they should be explicitly integrated with current realizations of the National Spatial Reference System (NSRS). The NSRS was developed and is maintained by the National Geodetic Survey (NGS) to provide a uniform and reliable framework for positioning throughout the US. As an illustration of its importance to positioning, consider that most of the errors listed in Table 1 can be attributed to incorrect use of the NSRS.

Although recent high-profile developments (such as Homeland Security) have highlighted the need for consistent and correct spatial information, the problem has existed for some time. The cost for developing a sophisticated GIS is quite high, but it is false economy to attempt to save money by populating a GIS with data of dubious origin — it can be more expensive to evaluate and fix positioning problems than it is to initially capture and document the data correctly. This is not to say that all GIS data should be highly accurate, but rather that *realistic* and *reliable* accuracy estimates (regardless of magnitude) be explicitly linked to the data. It is moreover poor practice to rely solely on the equipment and software vendors for ensuring spatial integrity. In the end, this is the duty of the professional in responsible charge, which also best serves the public welfare. Simply put, geospatial professionals who use GPS should be conversant with geodesy, a point persuasively articulated by Jan Van Sickle (2001, p. 126):

> *Today, GPS has thrust surveyors into the thick of geodesy which is no longer the exclusive realm of distant experts. Thankfully, in the age of microcomputers, the computational drudgery can be handled with software packages. Nevertheless, it is unwise to venture into GPS believing that knowledge of the basics of geodesy is, therefore, unnecessary. It is true that GPS would be impossible without computers, but blind reliance on the data they generate eventually leads to disaster.*

Table 1. Examples of various positioning error sources and their magnitudes for Alaska. Abbreviations and technical terms are defined in the "Abbreviations and definitions" section following this table.

Positioning errors and examples for Alaska	**Error magnitudes**
Geodetic datum definitions and reference coordinates	
Using NAD 27 when NAD 83 required	Varies from ~200 to 780 feet (horizontal)
Using "WGS 84" when NAD 83 required (e.g., by using WAAS corrections or CORS ITRF coordinates)	3.6 to 4.4 feet (horizontal) −0.4 to 3.3 feet (vertical)
Using published three-parameter datum transformation between NAD 27 and WGS 84 for NAD 83 projects	~60 to −180 feet (horizontal)
Using NADCON to transform coordinates between NAD 27 and NAD 83 (at 95% confidence)	~4 feet (horizontal)
Using NAD 83 (1986) coordinates when NAD 83 (1992) coordinates required	~1.7 to 3.3 feet (horizontal) in Anchorage
Autonomous (uncorrected) GPS single-point positioning precision (at 95% confidence)	~10 to 20 ft (horizontal) ~20 to 50 ft (vertical)
Grid coordinate systems and computations	
Using SPCS 27 projection parameters for SPCS 83 projects (easting coordinate differences)	216 ***miles*** (Zones 2-9) 53.2 ***miles*** (Zone 10) *Zero* (Zone 1)
Determining State Plane coordinates in US Survey Feet when International Feet are required	Up to 13 feet (horizontal)
Determining UTM coordinates in US Survey Feet when International Feet are required	Up to 52 feet (horizontal)
Using linear coordinates from a geographic "projection" to compute distances	Up to ~3500 feet horizontal per mile (67% error)
Using SPCS grid distances when "ground" distances are required (example here is for point on projection axis)	Apprx −1.8 feet horizontal per mile at height of 1500 ft
Using UTM grid distances when "ground" distances are required (example here is for point on central meridian)	Apprx −3.4 feet horizontal per mile at height of 1500 ft
Using planar computation methods to transform geodetically-derived horizontal coordinates (example here is for converting from UTM to SPCS over a 10 mi × 10 mi area using planar scaling, rotation, and translation based on two common points)	Varies, but increases rapidly with size of area (~1 foot horizontal for this example)

continued on next page

Error Table. (*continued*)

Positioning errors and examples for Alaska	**Error magnitudes**
Vertical datums and height systems	
Using NGVD 29 when NAVD 88 required	~5.7 to 6.8 feet too low in Anchorage vicinity (vertical)
Using ellipsoid heights for elevations	Varies from −20 feet to +69 feet (vertical)
Neglecting geoid slope when transferring elevations with GPS	Up to 1.3 feet vertical per mile horizontal (up to 0.7 ft/mi in Anchorage area)
Using leveling without orthometric corrections to “correct” GPS-derived elevations	Can exceed 0.05 ft vertical per mile horizontal
Accuracy estimation and reporting	
Documenting geodetic datum as “WGS-84” when it is not	Perpetuates confusion about “equivalence” of WGS-84 and NAD 83
Listing grid coordinates (such as SPCS) as “NAD 83”	NAD 83 is a geodetic datum, not a grid coordinate system
Documenting geodetic datum as “GRS-80”	GRS-80 is a reference ellipsoid, not a datum
Documenting vertical datum as “Mean Sea Level” (MSL)	There is no MSL datum in the US (name changed to NGVD 29 in 1976)
Using precision as an accuracy estimate with data containing systematic errors (e.g., incorrect reference coordinates)	Accuracy estimate is meaningless
Reporting horizontal error using unscaled standard deviation, rather than at the 95% confidence level (as specified by the FGDC)	Gives error estimates at 39% confidence level
Reporting vertical error using unscaled standard deviation, rather than at the 95% confidence level (as specified by the FGDC)	Gives error estimates at 68% confidence level
Using radial and circular estimates for horizontal error rather than semi-major axis of horizontal error ellipse	Typically makes errors appear less than actual
Using trivial vectors in GPS network adjustments	Varies, but always makes errors appear less than actual

Abbreviations and definitions

Below is a list that includes abbreviations and terms used in this handout. In the interest of brevity, the definitions are highly general and simplified. Please note also that this list gives only a portion of the terms and abbreviations frequently encountered in GPS positioning and geodesy. Terms in *italics* within the definitions are also defined in this list. Cited references are listed at the end of the handout.

Autonomous position. A *GPS* position obtained with a single receiver using only the ranging capability of the *GPS* code (i.e., with no *differential correction*).

Cartesian coordinates. Coordinates based on a system of two or three mutually perpendicular axes. *Map projection* and *ECEF* coordinates are examples two- and three-dimensional Cartesian coordinates, respectively.

Confidence interval or level. A computed probability that the "true" value will fall within a specified region (e.g., 95% confidence level). Applies only to randomly distributed errors.

CORS (Continuously Operating Reference Stations). A nation-wide system of permanently mounted *GPS* antennas and receivers that collect *GPS* data continuously. The CORS network is extremely accurate and constitutes the primary survey control for the US. CORS data can be used to correct *GPS* survey and mapping results, and the data are freely available over the Internet.

Datum transformation. Mathematical method for converting one *geodetic* or *vertical datum* to another (there are several types, and they vary widely in accuracy).

Differential correction. A method for removing much of the error in an autonomous *GPS* position. Typically requires at least two simultaneously operating *GPS* receivers, with one of the two at a location of known geodetic coordinates.

ECEF (Earth-Centered, Earth-Fixed). Refers to a global three-dimensional (X, Y, Z) *Cartesian coordinate* system with its origin at the Earth's center of mass, and "fixed" so that it rotates with the solid Earth. The Z-axis corresponds to the Earth's conventional spin axis, and the X- and Y-axes lie in the equatorial plane. Widely used for geodetic and *GPS* computations.

Ellipsoid. A simple mathematical model of the Earth corresponding to mean sea level (the *geoid*) and used as part of a *geodetic datum* definition. Constructed by rotating an ellipse about its semi-minor axis. Also referred to as a "spheroid".

Ellipsoid height. Straight-line height above and perpendicular to the *ellipsoid*. This is the type of height determined by *GPS*, and it does not equal elevation. Can be converted to orthometric heights ("elevations") using a *geoid* model.

Ellipsoid normal. A line perpendicular to the reference *ellipsoid* along which *ellipsoid heights* are measured.

FBN (Federal Base Network). Nationwide network of *GPS* control stations observed and adjusted by the *NGS*. A nation-wide readjustment of the FBN is scheduled for 2007.

FGDC (Federal Geographic Data Committee). Develops and promulgates information on spatial data formats, accuracy, specifications, and standards. Widely referenced by other organizations. Includes the Federal Geodetic Control Subcommittee (FGCS) and the *NSSDA*.

Geodetic datum. Reference frame for computing geodetic coordinates (latitude, longitude, and ellipsoid height) of a point. A datum always refers to a particular *ellipsoid* and a specific adjustment (e.g. the 1992 adjustment of *NAD 83* for the Alaska *GPS* stations).

Geographic "projection". This is not a true *map projection* in the sense that it does not transform geodetic coordinates (latitude and longitude) into linear units. However, it is a projection in the sense that it represents geodetic coordinates on a regular flat grid, such that the difference in angular units (e.g., decimal degrees) is equal in all directions. Because of meridian convergence, this results in an extremely distorted coordinate system, especially at high latitudes, and the distortion varies greatly with direction.

Geoid. Surface of constant gravitational equipotential (a level surface) that best corresponds to global mean sea level. Often used as a reference surface for *vertical datums*.

GPS (Global Positioning System). A constellation of satellites used for navigation, mapping, surveying, and timing. Microwave signals transmitted by the satellites are observed by GPS receivers to determine a three-dimensional position. Accuracy varies greatly depending on the type of receiver and methods used.

Grid distance. The horizontal distance between two points on a flat plane. This is the type of distance obtained from *map projections*.

Ground distance. The horizontal distance between two points as measured on the curved Earth surface.

GRS-80 (Geodetic Reference System of 1980). The reference *ellipsoid* currently used for many *geodetic datums* throughout the world, including *NAD 83* and *ITRF*.

HARN (High Accuracy Reference Network). Network of *GPS* stations adjusted by the *NGS* on a state-by-state basis. For example, the Arizona HARN was adjusted in 1992. In some states it is referred to as a High Precision *GPS* (or Geodetic) Network (HPGN). Although there is no "official" HARN for Alaska, GPS stations in Alaska have datum tags of 1992, which implies a HARN-type adjustment.

International Foot. Linear unit adopted by the US in 1959, and defined such that one foot equals exactly 0.3048 meter. Shorter than the *US Survey Foot* by 2 *parts per million* (ppm).

ITRF (International Terrestrial Reference Frame). Global geodetic reference system that takes into account plate tectonics (continental drift) and is used mainly in scientific studies. A new ITRF "epoch" is computed periodically and is referenced to a specific time (e.g., ITRF 2000 1997.0). Each epoch is a realization of the International Terrestrial Reference System (ITRS). See Soler (2004), and Soler and Snay (2004) for information on its relationship to *NAD 83* and *WGS 84*.

Local geodetic horizon. A "northing", "easting", and "up" planar coordinate system defined at a point such that the northing-easting plane is perpendicular to the *ellipsoid normal*, north corresponds to true geodetic north, and "up" is in the direction of the *ellipsoid normal* at that point.

Map projection. A functional (one-to-one) mathematical relationship between geodetic coordinates (latitude, longitude) on the curved *ellipsoid* surface, and grid coordinates (northings, eastings) on a planar (flat) map surface. All projections are distorted, in that the relationship between projected coordinates differs from that between their respective geodetic coordinates. See Snyder (1987) for details.

NAD 27 (North American Datum of 1927). *Geodetic datum* of the US prior to *NAD 83*, and superseded by *NAD 83* in 1986. This is the datum of *SPCS* 27 and *UTM* 27.

NAD 83 (North American Datum of 1983). Current official *geodetic datum* of the US. Replaced *NAD 27* in 1986, which is the year of the initial NAD 83 adjustment. This is the datum of *SPCS* 83 and *UTM* 83. See Schwarz (1986) for details.

NADCON. *Datum transformation* computer program developed by the NGS for transforming coordinates between *NAD 27* and *NAD 83*, and also between the *NAD 83* 1986 adjustment and the various *HARN* adjustments. See Dewhurst (1990) for details.

NAVD 88 (North American Vertical Datum of 1988). Current official vertical datum of the US. Replaced *NGVD 29* in 1991. See Zilkoski et al. (1992) for details.

NDGPS (National Differential GPS). A nation-wide system of "beacons" (permanently mounted *GPS* receivers and radio transmission equipment) that transmits real-time *differential corrections* which can be used by *GPS* receivers equipped with the appropriate radio receivers. Operated and maintained by the US Coast Guard. See US Coast Guard (2004) for details.

NGS (National Geodetic Survey). Federal agency within the Department of Commerce responsible for defining, maintaining, and promulgating the *NSRS* within the US and its territories.

NGVD 29 (National Geodetic Vertical Datum of 1929). Previous *vertical datum* of the US, superseded by *NAVD 88* in 1991. Not referenced to the *geoid* or mean sea level, and not as compatible with *GPS*-derived elevations as *NAVD 88*. Called "Mean Sea Level" (MSL) datum prior to 1976.

NSRS (National Spatial Reference System). The framework for latitude, longitude, height, scale, gravity, orientation and shoreline throughout the US. Consists of geodetic control point coordinates and sets of models describing relevant geophysical characteristics of the Earth, such as the *geoid* and surface gravity. Defined, maintained, and promulgated by the *NGS* (see Doyle, 1994, for details).

NSSDA (National Standard for Spatial Data Accuracy). *FGDC* methodology for determining the positional accuracy of spatial data (see Federal Geographic Data Committee, 1998).

OPUS (Online Positioning User Service). A free *NGS* service that computes *NSRS* and *ITRF* coordinates with respect to the *CORS* using raw *GPS* data submitted via the Internet.

Orthometric correction. A correction applied to leveled height differences which reduces systematic errors due to variation in gravitational potential. See Dennis (2004) for details.

Parts per million (ppm). A method for conveniently expressing small numbers, accomplished by multiplying the number by 1 million (e.g., 0.00001 = 10 ppm). Exactly analogous to percent, which is "parts per hundred".

SPCS (State Plane Coordinate System). A system of standardized *map projections* covering each state with one or more zones such that a specific distortion criterion is met (usually 1:10,000). Projection parameters (including units of length) are independently established by the legislature of each state. Can be referenced to either the *NAD 83* or *NAD 27* datums (SPCS 83 and SPCS 27, respectively). See Stem (1989) for details.

Triangulation. A method for determining positions from angles measured between points (requires at least one distance to provide scale).

Trilateration. A method for determining positions from measured distances only.

Trivial vector. A *GPS* vector (computed line connecting two *GPS* stations) that is not statistically independent from other *GPS* vectors observed at the same time.

US Survey Foot. Linear unit of the US prior to 1959, and defined such that one foot equals exactly 1200 / 3937 meter. Longer than the *International Foot* by 2 *parts per million* (ppm).

UTM (Universal Transverse Mercator). A grid coordinate system based on the Transverse Mercator *map projection* which divides the Earth (minus the polar regions) into 120 zones in order to keep map scale error within 1:2500. Can be referenced to either the *NAD 83* or *NAD 27* datums (UTM 83 and UTM 27, respectively). See Hager et al. (1989) for details.

Vertical datum. Reference system for determining "elevations", typically through optical leveling. Modern vertical datums typically use the *geoid* as a reference surface and allow elevation determination using *GPS* when combined with a *geoid* model.

WAAS (Wide Area Augmentation System). A system of geosynchronous satellites and ground *GPS* reference stations developed and managed by the Federal Aviation Administration and used to provide free real-time *differential corrections*. See Federal Aviation Administration (2003) for details.

WGS 84 (World Geodetic System of 1984). Reference *ellipsoid* and *geodetic datum* of *GPS*, defined and maintained by the US Department of Defense. Current realizations of WGS 84 are considered identical to *ITRF* 2000 at the 2 cm level. See National Imagery and Mapping Agency (1997) for details, and Merrigan et al. (2002) for information on the most recent realization.

Surveying & mapping spatial data requirements & recommendations

These should be explicitly specified in surveying and mapping projects

1. **Completely define the coordinate system**
    a. Linear unit (e.g., International foot, U.S. Survey foot, meter)
        i. Use same linear unit for horizontal and vertical coordinates
    b. Geodetic datum (recommend North American Datum of 1983)
        i. Should include datum "epoch" (date), e.g., 1986, 1992 (HARN), 2002.0 (CORS)
        ii. WGS 84, ITRF, and NAD 27 are **NOT** recommended
    c. Vertical datum (e.g., North American Vertical Datum of 1988)
        i. If GPS used for elevations, recommend using a modern geoid model (e.g., GEOID03)
        ii. Recommend using NAVD 88 rather than NGVD 29 when possible
    d. Map projection type and parameters (e.g., Transverse Mercator, Lambert Conical)
        i. Special attention required for low-distortion grid (a.k.a. "ground") coordinate systems
            1) Avoid scaling of existing coordinate systems (e.g., "modified" State Plane)
2. **Require *direct* referencing of the NSRS (National Spatial Reference System)**
    a. Ties to published control strongly recommended (e.g., National Geodetic Survey control)
        i. Relevant component of control must have greater accuracy than positioning method used
            1) E.g., B-order (or better) stations for GPS control, 2nd order (or better) for vertical control
    b. NGS Continuously Operating Reference Stations (CORS) can be used to reference the NSRS
        i. Free Internet GPS post-processing service: OPUS (Online Positioning User Service)
3. **Specify *accuracy* requirements (*not* precision)**
    a. Use objective, defensible, and robust methods (published ones are recommended)
        i. Mapping and surveying: National Standard for Spatial Data Accuracy (NSSDA)
            1) Require occupations ("check shots") of known high-quality control stations
        ii. Surveys performed for establishing control or determining property boundaries:
            1) Appropriately constrained and over-determined least-squares adjusted control network
            2) Beware of "cheating" (e.g., using "trivial" GPS vectors in network adjustment)
4. **Documentation is *essential* (metadata!)**
    a. Require a report detailing methods, procedures, and results for developing final deliverables
        i. This must include any and all post-survey coordinate transformations
            1) E.g., published datum transformations, computed correction surfaces, "rubber sheeting"
    b. Documentation should be complete enough that someone else can reproduce the product
    c. For GIS data, recommend that accuracy and coordinate system information be included as feature attributes (not just as separate, easy-to-lose and easy-to-ignore metadata files)

Example of surveying and mapping documentation (*metadata*)

Basis of Bearings and Coordinates

Linear unit: International foot

Geodetic datum: North American Datum of 1983 (1992)

Vertical datum: North American Vertical Datum of 1988 (see below)

System: Shephard-Wesnitzer

Zone: Sedona

Projection: Transverse Mercator
Latitude of grid origin: 34° 44’ 00” N
Longitude of central meridian: 111° 48’ 00” W
Northing at grid origin: 0.000 ft
Easting at central meridian: 50,000.000 ft
Scale factor on central meridian: 1.000206 (exact)

All distances and bearings shown hereon are grid values based on the preceding projection definition. The projection was defined such that grid distances are equivalent to “ground” distances in the project area.

The basis of bearings is true geodetic north. Note that the grid bearings shown hereon (or implied by grid coordinates) do not equal geodetic bearings due to meridian convergence.

Orthometric heights (elevations) were transferred to the site from NGS control station “Y 492” (PID ES0652) using GPS with NGS geoid model “GEOID03” referenced to the current published NAVD 88 height of this station (1353.20 m).

The survey was conducted using GPS referenced to the National Spatial Reference System. A partial list of point coordinates is given below (additional coordinates are available upon request). Local network accuracy estimates are given at the 95% confidence level and are based on an appropriately constrained least-squares adjustment of over-determined and statistically independent observations.

Point #28 “VORTEX” (PID AJ5367), aluminum cap in concrete, fixed NGS control (off site)

Latitude = 34° 50' 46.53509” N	Northing = 41,111.003 ft	*Estimated accuracy*
Longitude = 111° 49' 41.94400” W	Easting = 41,501.190 ft	Horizontal = Fixed
Ellipsoid height = 4384.121 ft	Elevation = 4465.001 ft	Vertical = Fixed

Point #2019, 1/2” rebar with aluminum cap, derived coordinates (on site)

Latitude = 34° 51' 47.13683" N	Northing = 47,238.377 ft	*Estimated accuracy*
Longitude = 111° 47' 07.78081" W	Easting = 54,352.494 ft	Horizontal = ±0.034 ft
Ellipsoid height = 4343.842 ft	Elevation = 4423.869 ft	Vertical = ±0.046 ft

Point #3006, 1/2” rebar with plastic cap, derived coordinates (on site)

Latitude = 34° 51' 50.45539" N	Northing = 47,573.933 ft	*Estimated accuracy*
Longitude = 111° 47' 10.25560" W	Easting = 54,146.172 ft	Horizontal = ±0.047 ft
Ellipsoid height = 4353.976 ft	Elevation = 4433.996 ft	Vertical = ±0.057 ft

SELECTED GPS AND GEODESY REFERENCES

Primary resource: The National Geodetic Survey (http://www.ngs.noaa.gov/)

Some NGS web pages of particular interest

Control station datasheets: http://www.ngs.noaa.gov/cgi-bin/datasheet.prl
The Geodetic Tool Kit: http://www.ngs.noaa.gov/TOOLS/
Online Positioning User Service (OPUS): http://www.ngs.noaa.gov/OPUS/
Continuously Operating Reference Stations (CORS): http://www.ngs.noaa.gov/CORS/
The Geoid Page: http://www.ngs.noaa.gov/GEOID/

Documents (categorized as *introductory*, *intermediate*, *advanced*, or *reference*)

American Congress on Surveying and Mapping, (2005) *Definitions of Surveying and Associated Terms*, American Congress on Surveying and Mapping , 314 pp. *[reference]*

American Land Title Association, American Congress on Surveying & Mapping, and National Society of Professional Surveyors (2005) *2005 Minimum Standard Detail Requirements for ALTA/ACSM Land Title Surveys*, 6 pp., http://www.acsm.net/alta.html. *[reference]*

Anderson, M.A., D'Onofrio, D., Helmer, G.A. and Wheeler, W.W. (1996) Specifications for geodetic control networks using high-production GPS surveying techniques, version 2. California Geodetic Control Committee, http://www.rbf.com/cgcc/hpgps21.htm. *[reference]*

Bureau of the Budget (1947) *National Map Accuracy Standards*, Office of Management and Budget, Washington, D.C., 1 p. http://rockyweb.cr.usgs.gov/nmpstds/acrodocs/nmas/NMAS647.PDF. ***Note: These standards NOT recommended for use (superseded by FGDC 1998 standards)*** *[reference]*

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Defense Mapping Agency (1984) *Geodesy for the Layman*, DMA Technical Report 80-003, U.S. Defense Mapping Agency, Washington D.C., USA, 96 pp., www.ngs.noaa.gov/PUBS_LIB/Geodesy4Layman/geo4lay.pdf *[introductory]*

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Dennis, M.L. (2004) A question of gravity: What effect does gravity have on elevations determined by differential leveling?, *The Arizona Surveyor*, Arizona Professional Land Surveyors Association, Vol. 4, No. 1 (Winter 2004), p. 6, http://www.azpls.org/displaynewsletter.cfm] *[intermediate]*

Dewhurst, W.T. (1990) NADCON: The application of minimum-curvature-derived surfaces in the transformation of positional data from the North American Datum of 1927 to the North American Datum of 1983, *NOAA Technical Memorandum NOS NGS-50*, National Geodetic Survey, Silver Springs, MD, USA, 32 pp., http://www.ngs.noaa.gov/PUBS_LIB/NGS50.pdf *[advanced]*

Doyle, D.R. (1994) *Development of the National Spatial Reference System*, National Geodetic Survey, Silver Spring, Maryland,. http://www.ngs.noaa.gov/PUBS_LIB/develop_NSRS.html *[intermediate]*

Federal Aviation Administration (2005) FAA Wide Area Augmentation System, *Fact Sheets*, http://gps.faa.gov/Library/indexWAAS-f.htm *[introductory]*

Federal Emergency Management Agency (2005) *Guidelines and Specifications for Flood Hazard Mapping Partners*, FEMA Map Modernization Program, April 2003 version. Consists of 3 volumes (337 pp.), 13 appendices (1207 pp.), and 5 supporting documents (85 pp.), for a total of 1629 pp., http://www.fema.gov/fhm/dl_cgs.shtm. *[reference]*

Federal Geographic Data Committee (1998) *Geospatial Positioning Accuracy Standards*, FGDC-STD-007.2-1998, Federal Geographic Data Committee, Reston, Virginia, USA, 128 pp., http://www.fgdc.gov/standards/documents/standards/accuracy/, [includes National Standard for Spatial Data Accuracy (NSSDA), Chapter 3]. *[reference]*

Hager, J.W., Behensky, J.F., and Drew, B.W. (1989) The Universal Grids: Universal Transverse Mercator (UTM) and Universal Polar Stereographic (UPS), *DMA Technical Manual 8358.2*, Defense Mapping Agency, Fairfax, Virginia, USA, 49 pp., "TM8358_2.pdf" *in* ftp://164.214.2.65/pub/gig/tm8358.2/. *[reference]*

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Appendix A: Putting It on the Ground

Design and documentation of low-distortion map projections

Abstract. GPS positioning yields geodetic coordinates (latitude, longitude, and ellipsoid height) which, by themselves, are of limited utility in many surveying and mapping applications. In order to render geodetic coordinates useful — e.g., plot them on paper, display them on a computer screen, utilize them in engineering design software — they must be converted to a Cartesian grid system using some type of map projection. This process always distorts the relative position of the geodetic coordinates, both in scale (linear distortion) and orientation (angular distortion).

Often in GPS surveys, the intent is to generate so-called "ground" coordinates — that is, to minimize linear distortion such that the distance between a pair of (projected) grid coordinates essentially equals the actual horizontal ground distance. Linear distortion generally increases with ellipsoid height, and can become significant in high-elevation areas. For example, in Flagstaff, Arizona (elevation of about 7000 feet), the distance between a pair of State Plane coordinates is less than the actual ground distance by approximately 2.3 feet per mile (440 parts per million). Conventional instruments can readily detect this magnitude of distortion, and it can lead to confusion about which distances are "correct". This is a problem for many types of geospatial products and services, such as survey plats, legal descriptions, engineering plans, as-built surveys, and construction staking.

What is map projection distortion?

Map projection distortion is an *unavoidable* consequence of attempting to represent a curved surface on a flat surface. It can be thought of as a change in the "true" relationship between points located on the surface of the Earth and the *representation* of their relationship on a plane. Distortion cannot be eliminated — it is a ***F***act of ***L***ife. The best we can do is decrease the effect.

There are two general types of map projection distortion:

1. Linear distortion. Difference in distance between a pair of grid (map) coordinates when compared to the true ("ground") distance, denoted here by $\boldsymbol{\delta}$.
    - Can express as a ratio of distortion length to ground length:
        - E.g., feet of distortion per mile; parts per million; mm per km
        - *Note:* 1 foot / mile = 189 ppm = 189 mm / km
    - Linear distortion can be positive or negative:
        - NEGATIVE distortion means the grid (map) length is SHORTER than the "true" horizontal (ground) length.
        - POSITIVE distortion means the grid (map) length is LONGER than the "true" horizontal (ground) length.
2. Angular distortion. For conformal projections (e.g., Transverse Mercator, Lambert Conformal Conic), it equals the *convergence* (*mapping*) *angle*, $\boldsymbol{\gamma}$. It is the difference between grid (map) north and true (geodetic) north.
    - Magnitude increases with increasing latitude (in Anchorage, it changes by approximately 01'35" per mile east or west).
    - Usually not as much of a concern as linear distortion, and can only be minimized be staying close to the projection central meridian.

Total linear distortion of grid (map) coordinates is a combination of distortion due to both Earth curvature and ground height above the ellipsoid. Distortion due to variation in ground height is often greater than that due to curvature. This is illustrated in the diagrams and tables below.

Table 2. Horizontal distortion of grid coordinates due to Earth curvature.

Maximum zone width for secant projections (miles)	Maximum linear horizontal distortion, δ		
	Parts per million	Feet per mile	Ratio (absolute value)
16 miles	±1 ppm	±0.005 ft/mile	1 : 1,000,000
50 miles	±10 ppm	±0.05 ft/mile	1 : 100,000
71 miles	**±20 ppm**	**±0.1 ft/mile**	**1 : 50,000**
112 miles	±50 ppm	±0.3 ft/mile	1 : 20,000
159 miles (e.g., SPCS)*	±100 ppm	±0.5 ft/mile	1 : 10,000
318 miles (e.g., UTM)†	±400 ppm	±2.1 ft/mile	1 : 2500

* State Plane Coordinate System; zone width shown is valid between ~45° and 85° latitude

† Universal Transverse Mercator; zone width shown is valid between ~60° and 85° latitude

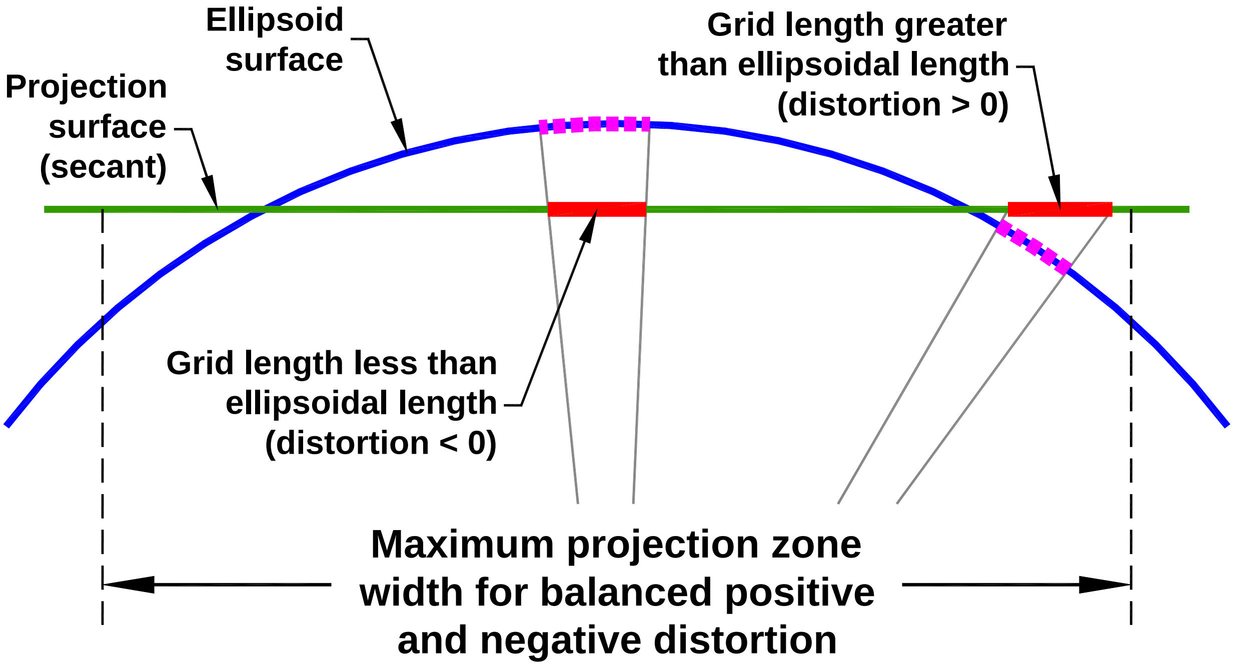

Table 3. Horizontal distortion of grid coordinates due to ground height above the ellipsoid.

Height below (–) and above (+) projection surface	**Maximum linear horizontal distortion, δ**		
	Parts per million	**Feet per mile**	**Ratio (absolute value)**
–100 feet, +100 feet	±4.8 ppm	±0.03 ft/mile	~1 : 209,000
–400 feet, +400 feet	**±19 ppm**	**±0.1 ft/mile**	**~1 : 52,000**
–1000 feet, +1000 feet	±48 ppm	±0.3 ft/mile	~1 : 21,000
+1500 feet*	–72 ppm	–0.4 ft/mile	~1 : 14,000
+3000 feet	–143 ppm	–0.8 ft/mile	~1 : 7000
+10,000 feet	–477 ppm	–2.5 ft/mile	~1 : 2100
+20,000 feet†	–953 ppm	–5.0 ft/mile	~1 : 1000

* Approximate average topographic height in Alaska

† Approximate maximum topographic height in Alaska

Rule of Thumb:

A 100-ft change in height causes a 4.8 ppm change in distortion