Elevations and the Global Spatial Data Model (GSDM)

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BIOGRAPHY:

Earl F. Burkholder is a licensed professional surveyor and engineer (PS, PE) who teaches geodesy and other topics in the Surveying Engineering Department at New Mexico State University, Las Cruces, New Mexico. He received a BSCE from the University of Michigan in 1973, worked 5 years for an international engineering design firm, earned a MSCE from Purdue University in 1980, taught surveying at Oregon's Institute of Technology from 1980 to 1993, and was self-employed from 1993 until he joined the faculty at NMSU in August, 1998. During 1990-91, he was on sabbatical leave and spent most of the year at the University of Maine learning more about applications of GPS technology to modern surveying practice. Since 1985 he served two non-consecutive 4-year terms as Editor of the ASCE Journal of Surveying Engineering and is currently Past Chair of the Applied Science Accreditation Commission (ASAC) of the Accreditation Board for Engineering and Technology (ABET). In 1997, he incorporated Global COGO, Inc., a firm formed to promote use of 3-D spatial data and the Global Spatial Data Model (GSDM). He continues to write about various features of the GSDM.

ABSTRACT:

Spatial data are three-dimensional (3-D). Modern measurement systems collect spatial data in a 3-D environment and computer data bases store digital spatial data in 3-D. The WGS84 earth-centered earth-fixed (ECEF) geocentric coordinate system defined by the Defense Mapping Agency (now NIMA) can be viewed as a coherent 3-D geodetic datum which has a single origin at the earth's center of mass. With the advent of GPS, and other technologies, many spatial data computations can be performed more efficiently in the ECEF environment. The global spatial data model (GSDM) is a collection of geometrical relationships and error propagation procedures (functional & stochastic models) that incorporates the ECEF system and describes a comprehensive environment for working with 3-D spatial data. Previously, horizontal and vertical data were considered separately, in part, because they are assigned different origins. Horizontal data are referenced by latitude/longitude on a mathematical ellipsoid while elevation is taken to be the distance from sea level (the geoid). Geoid height is the difference between those two origins, the ellipsoid and the geoid. But, globally, the geoid defies precise location and absolute elevation suffers accordingly. The approach here is to define the terms concisely, put the pieces together carefully, and to suggest that elevation (along with horizontal) should also be referenced to the earth's center of mass via the mathematical ellipsoid. That will provide a single origin for 3-D data and the need for incidental geoid modeling will be enormously reduced – especially for routine use of GPS technology. Making that change will not diminish the value of previous geoid modeling and on-going efforts to locate the elusive geoid should continue because there are identifiable scientific and engineering applications for which knowledge of the equipotential surfaces is still required.

INTRODUCTION:

Spatial data are 3-dimensional (3-D). Modern measurement systems collect spatial data in 3-D. Computer data bases store digital spatial data in 3 dimensions. Human perception of spatial relationships and the world at large is primarily visual and intuitively related to 2-D horizontal and 1-D vertical. Spatial data are manipulated using rules of solid geometry that reflect the geometry of the model being used to represent the data. Locally, the world appears to be flat and 3-D rectangular cartesian coordinates are used to describe the size, shape, and location of most objects. But, the world is not flat and geodetic datums provide models for referencing spatial data in a global context. The problem is, traditional horizontal and vertical datums do not share a common origin.

The earth-centered earth-fixed (ECEF) geocentric rectangular coordinate system defined by the Defense Mapping Agency (DMA 1991) is called the World Geodetic System 1984 (WGS84) and can be viewed as a coherent 3-D geodetic datum which has a single origin at the earth's center of mass. Many GPS related computations are performed using ECEF coordinates and the global spatial data model (GSDM), described at a previous ION meeting (Burkholder 1998), can be used to move back and forth easily between local and global coordinate systems. That means local "flat-earth" relationships (coordinate differences) can be readily related to the world at large. But, the issue of elevation, distance above sea level, needs more attention.

This paper looks closely at the definition for elevation, vertical datums, equipotential surfaces, and absolute/ relative quantities. The solution proposed herein is that elevation be re-defined in terms of distance from the mathematical ellipsoid (related to a precise common 3-D origin) instead of the geoid (which defies precise location). An analogy is drawn with the shift from defining time by the rotation of the earth to defining time by the oscillations of an atom. The Equation-of-Time is used routinely by astronomers and others who need it, but the fact that the sun does not cross a local meridian at exactly 12:00:00 noon is inconsequential to most people. Similarly, those needing precise orthometric heights, dynamic heights, or equipotential surfaces will still have access to same using existing tools and procedures. But with elevation defined as the distance from the ellipsoid, elevation will share a common origin with 3-D spatial data and the computational effort of many spatial data users will be greatly simplified.

DEFINITIONS:

The following definitions are intended to be consistent with common usage, recent publications, e.g. (Burkholder 2001 and 2002), and standard references such as (NGS 1986) and (ASPRS/ACSM/ASCE 1994).

Spatial data: The spatial data primitive is taken to be the distance between the endpoints of a line in Euclidean space. The line can be curved (latitude/longitude coordinates) or straight (rectangular coordinates). An endpoint can be an origin or an axis of a coordinate system. Endpoints can also represent a location described by coordinates. Other spatial data entities such as surfaces or objects are created by an aggregation of lines. Geospatial data are those referenced to the physical earth.

Geodetic coordinates: Geodetic coordinates are 2-dimensional latitude and longitude (sexagesimal units) as expressed on a mathematical ellipsoid and 1-dimensional distance (in meters) above or below the same ellipsoid.

Geocentric coordinates: Geocentric coordinates are ECEF rectangular X/Y/Z coordinates having their origin at the earth's center of mass, X/Y are in the equatorial plane, the X axis is on the Greenwich Meridian, and the Z axis coincides (very nearly) with the earth's rotation axis.

Elevation (generic): Elevation is the distance above or below a reference surface. The geoid is an equipotential surface that has been used as the reference surface and is closely approximated by mean sea level. Note that the origin for elevation (the geoid) is different from the origin for ellipsoid height (earth's center of mass).

Absolute: Absolute spatial data are given by coordinates of a point in a defined reference system. Latitude and longitude are 2-dimensional absolute spatial data. Geocentric ECEF X/Y/Z coordinates are 3-dimensional absolute spatial data.

Relative: Relative spatial data are given by differences within the same coordinate system. A 3-D GPS vector is defined by ECEF coordinate differences, $\Delta X/\Delta Y/\Delta Z$. Plane surveying latitudes (Δ northings) and departures (Δ eastings) are 2-D local plane coordinate differences.

Equipotential surface: An equipotential surface is a continuous surface defined in units of work with regard to its physical environment. Mean sea level is often given as an example. Moving an object from one equipotential surface to another either requires the expenditure of work or gives up work. Two objects at rest having the same mass and located on the same equipotential surface store the same amount of potential energy.

Dynamic Height: Dynamic height is computed as the geo-potential number of an equipotential surface divided by normal gravity at latitude 45°. Dynamic heights are given by numbers that look like elevations, but they reflect the true hydraulic head associated with an equipotential surface rather than distance from sea level.

Helmert orthometric height (H): Orthometric height is the curved distance along the plumb line from the geoid to a point or surface in question. Few users make the distinction between the curved plumb line distance and a straight-line distance between the plumb line endpoints. Orthometric height is computed (very nearly) as the geo-potential number of the equipotential surface divided by gravity at that point (Zilkoski et al 1992).

Ellipsoid height (h): Ellipsoid height is the distance below or above the ellipsoid and measured along , or as an extension of, the ellipsoid normal (a straight line).

Geoid height (N): Geoid height, ignoring the curved plumb line difference, is the difference between ellipsoid height and orthometric height. Using the commonly accepted symbols:

$$N = h - H \qquad \text{Eq (1)}$$

Vertical datum: A vertical datum is a system of elevations referenced to a common surface.

Horizontal datum: A horizontal datum is system of 2-dimensional coordinates parallel to the earth referenced to a common defined origin.

3-D geodetic datum: A 3-D geodetic datum is system of 3-dimensional coordinates referenced to the earth's center of mass and further defined by orientation and scale of the associated reference frame. Examples include the WGS84 datum, the International Terrestrial Reference Frame (ITRF), and the NAD83 datum. The GSDM is a comprehensive collection of geometrical relationships that can be used with any 3-D geodetic datum.

Spatial data accuracy: Spatial data accuracy is given by the standard deviation of each coordinate, distance, or direction. It is the right and responsibility of the user to know at all times, "with respect to what." Spatial data accuracy is often quoted at the 95% confidence level.

Datum accuracy: Datum accuracy is the standard deviation of each coordinate value with respect to the underlying datum (as chosen by the user). A zero standard deviation means the quantity is errorless and/or used as being fixed.

Local accuracy: Local accuracy is the standard deviation of a direction and/or distance of a directly connected point-pair (measurement) and is computed using the full covariance matrix of equation (9) in Burkholder (1999).

Network accuracy: Network accuracy is the standard deviation of a computed direction and/or distance between two points on the same datum that are statistically independent. It is computed using equation (9) of Burkholder (1999) with zero's in the off-diagonal correlation matrices.

CONSEQUENCES OF THE DEFINITIONS:

1. The ECEF geocentric coordinates are strictly 3-D spatial. With the origin at the earth's center of mass, all directions are "up" from the origin and there is no definition of elevation.

2. If and when one computes latitude/longitude/height from the X/Y/Z coordinates, height is governed by the datum of the coordinates and the ellipsoid chosen by the user. The standard deviation of the computed ellipsoid height is obtained directly from the covariance matrix of the X/Y/Z coordinates.

3. Elevation with respect to sea level is a valuable intuitive concept that is understood and used world-wide. But, because it is very difficult to locate mean sea level precisely over large areas it could be argued that **high accuracy absolute elevations do not exist**.

4. Elevation differences are determined very precisely using high-accuracy differential leveling (Δ orthometric height), GPS (Δ ellipsoid height) or hydrostatic leveling (Δ dynamic height). Therefore, elevations must be considered a relative quantity. Question: Is elevation accuracy absolute or relative?

5. Since equipotential surfaces are in all cases perpendicular to the plumb line and since the plumb line is curved, the implication is level surfaces are not parallel. That means precise leveling requires more than just measuring vertical distances between surfaces. The orthometric height correction is required for precise leveling over long distances in order to stay on the same equipotential surface.

6. With GPS measurements, ellipsoid height can be readily obtained and proven – complete with rigorous statistics. Therefore, the first question for spatial data users with regard to vertical is not, "How far is this point from sea level?" but "How far is this point from the ellipsoid and what is the accuracy of that number:

   a. with respect to the ellipsoid, and
   b. with respect to some adjacent or nearby point?

   Subsequent questions by the researcher or hydraulic engineer (looking for relative or absolute answers) could be, "Where is the geoid with respect to this point and what is its shape? or "What is the hydraulic head associated with this point?" Questions of accuracy should also addressed.

7. Finally, regardless of whether measurements are made of absolute quantities or relative quantities, whether directly or indirectly, the model chosen for handling any spatial data should be judged by:

   a. Its simplicity and appropriateness.
   b. How well it preserves the integrity of 3-D data.
   c. Its ability to reflect any chosen perspective.
   d. Its ability to handle spatial data accuracy issues.
   e. Its global applicability.

THE WAY THINGS ARE:

Because humans walk erect (and for other reasons), the world is viewed in terms of horizontal and vertical. Locally the world is seen as being flat and maps showing location are 2-D. As understanding of the world matured, it became obvious that the earth is not flat and the system of latitude/longitude became the preferred method for defining location on the curved earth. And, because plane coordinates are easier to use than latitude/longitude, map projections were developed to facilitate depicting the curved earth on a flat map. However, a major disadvantage of map projections is that they are strictly 2-D and spatial data are 3-dimensional. Vertical has, therefore, been treated separately and elevation is shown on many maps using shading, hachures, or contour lines.

It is a statement of the obvious to say that mean sea level is the best reference for elevation. It is also intuitive and elegant to say that absolute elevation is distance above (or below) mean sea level. The problem is, mean sea level defies precise location. Although the physical definition of the geoid as an equipotential surface is both simple and rigorous, the fact is, the precise location of mean sea level (the geoid) has yet to be found. That may be an overstatement, but that is essentially the reason that the name of the vertical datum was changed in May 1973 from Mean Sea Level Datum of 1929 to the National Geodetic Vertical Datum of 1929. Changing the name was recognition of the fact that zero elevation is not necessarily mean sea level.

The 1929 vertical adjustment was computed holding the average elevation at 26 tide gages scattered along both the east and west coasts of the United States (Zilkoski et al 1992). Since then, it was discovered that precise level loops throughout the U.S. have a greater internal consistency than could be achieved by holding the mean sea level elevations for the tide gage stations. Therefore, when the vertical network was adjusted for the North American Vertical Datum of 1988, only one tide-gage derived elevation was held for all of North America – a point in the St Lawrence Seaway near Rimouski, Quebec, Canada. So, technically, those numbers we call elevations (in North America) are not tied to mean sea level and the reference surface is an arbitrary one.

THE SOLUTION:

The solution proposed herein is to re-define (generic) elevation as the distance above or below the mathematical ellipsoid of the 3-D datum being used. All other definitions remain the same. But, with that simple change in definition, the realization of elevation (and the estimate of its accuracy) will be greatly facilitated. Other height quantities can still be computed as needed with reference to the ellipsoid instead of the geoid. Is such a recommendation consistent with a point made over 10 years ago by Zilkoski et al (1992) on page 143 where they say, “Space-derived ellipsoid height differences over long lines are probably more precise than leveling-derived orthometric heights differences over the same distances.”? The questions now might be, What is a <u>long</u> line? What equipment/procedures are being used? And, “What is the accuracy associated with the bench marks, the observations, the model, and/or the results?

EQUATION (1) REVISITED:

The fact remains that GPS delivers ellipsoid height differences and differential leveling delivers orthometric height differences. Equation (1) still holds but with elevation being defined as ellipsoid height, equation (1) is not needed when using GPS to get elevations. When using differential leveling, equation (1) will not be required for many applications because the slope of the geoid over the distance involved is inconsequential. That is good news for spatial data users in many non-precise applications.

In those cases where he slope of the geoid (with respect to the ellipsoid) is severe and/or where the accuracy of the work warrants it, equation (1) remains valid as the basis for converting differential leveling differences into ellipsoid height (elevation) differences. And, in those applications requiring rigorous computation of hydraulic head, dynamic heights should be used regardless of the definition of elevation.

ANALOGY:

Time is also a relative quantity and, over the years, as the measure of time became more precise, a better reference was needed. The sun crossing the local meridian at 12 noon each day is a simple physical global reference. But, due to motion of the earth about the sun as well as the earth spinning on its axis, the interval from one local noon to another varies from day to day. The difference between a uniform time interval and the changing interval is known as the equation-of-time. John Flamsteed was the first Royal Astronomer of the Greenwich Observatory which was built in 1675. Ancient Greeks recognized the existence of the equation-of-time but it was not until reliable clocks were available and Flamsteed made the necessary observations that the equation-of-time was quantified. Is there an analogy with geoid modeling?

Even after the equation-of-time was quantified, most people still reckoned time from the transit of the sun over the local meridian at 12:00:00 noon each day. The problem was the instant of noon varied according to which meridian one was on and each railroad station had its own version of the correct time. Establishing and maintaining reliable train schedules was an enormous challenge. The problem was solved in the United States in 1883 by adopting a system of standard time zones as devised by Charles F. Dowd of Saratoga Springs, New York (Howse 1980). The world-wide time zone system was adopted at the International Meridian Conference in Washington, D.C. in 1884. With Britain's promise of support for the decimal meter as the international length standard, the French supported, and the conference adopted, the Greenwich Meridian in England as the reference meridian for the world. Now, most people take the world time zone system for granted and the fact that the sun crosses the local meridian before or after 12:00 noon is of little consequence. But, for scientific and other purposes, the equation-of-time and other time scale differences are known, documented, and used by those for whom the difference matters.

IMPLEMENTATION:

Changing the definition of elevation to distance from the ellipsoid should be viewed as a win-win proposal. Spatial data users world-wide stand to benefit.

1. The word "elevation" enjoys excellent recognition and wide spread use. Should the word "elevation" be in the datum name? Several possible names for an ellipsoid based vertical datum are: World Elevation System (WES), Global Elevation System (GES), World Vertical Datum (WVD), Global Vertical Datum (GVD), etc. Regardless of the datum name, the datum epoch should be given by two digits immediately following the name, e.g. WES12.

2. All the pieces are already in place. The ECEF system is defined and operational, the GSDM provides a comprehensive 3-D computational environment and ellipsoid heights are the primary representation of the third dimension when using GPS data.

3. Precedents have already been set by:

    a. Switching from a well-defined physical reference for time (local noon) to an "arbitrary" atomic uniform reference (mean time).

    b. Establishing the Greenwich Meridian as a common arbitrary standard reference meridian for world-wide use.

    c. Adopting a system of time zones world-wide.

    d. Breaking the formal connection of elevation with mean sea level.

    e. Adopting an arbitrary reference surface for elevations – the NAVD88.

4. An appropriate international scientific body or government will need to host a meeting of delegates representing affected disciplines and/or nations to officially adopt the change. Such a meeting should also formally adopt the GSDM as the standard model for handling spatial data.

5. Unofficially, spatial data users will simply begin using ellipsoid height as elevation – possible, but not recommended. Isn't it true that some spatial data users already use (quite successfully) ellipsoid height differences as elevation differences when working with GPS in the RTK mode?

IMPORTANT CONSIDERATIONS:

A common statement in surveying education is that differential leveling is the simplest surveying concept to teach and perform, but leveling is the most difficult surveying operation to do well. Gravity, equipotential surfaces, deflection-of-the-vertical, and dynamic heights are some of the concepts which make that statement true. The goal in making this proposal to re-define elevation is not to solve the gravity related issues facing scientists and researchers but to recommend adoption of the simplest comprehensive set of 3-D spatial data principles which will enable spatial data users world-wide to perform their tasks more efficiently.

Technical issues which need additional study and documentation include, but are not limited to:

1. A careful analysis of those applications which require use of orthometric height differences as opposed to ellipsoid height differences. The first to come to mind is the hydraulic head computations for the Great Lakes System. But dynamic heights are already being used for those computations.

    Some engineers will insist that accurate grades are needed on highways and for water in gravity sewers to flow down hill properly. Highway grades can be readily expressed in ellipsoid height differences with little or no impact and most sewer line grades are not sensitive to the slope of the geoid from one manhole to the next. In areas where the slope of the geoid is severe, an appropriate sewer grade could be established using differential levels instead of GPS to stake out critical slopes or by computing and applying the geoid height correction. Case studies need to be developed.

2. Establishing true planes in 3-D space for beam alignment in particle accelerators. Two examples include Ruland (1994) and Robinson et al (1995).

3. Converting existing data bases such as the USGS National Map, the NASA Digital Earth, the BLM NILS program, FEMA flood plain maps, or the NGS National Spatial Reference System to a true 3-D spatial data base. Maybe this is the reason the change will never be made. If they would have had computers in the 1800's, train schedules would have been optimized ad infinitum and my guess is every town, village, and home today would still have its own time.

4. Accommodating new categories of spatial data users such as:

    a. Many transportation modes and models.
    b. Administering near-earth airspace.
    c. Population demographics of many kinds.
    d. Tracking the flow of goods and services.
    e. Military applications.

CONCLUSION:

The future of spatial data is digital and 3-D. More and more segments of society are becoming intelligent competent users of spatial data. A comprehensive global 3-D ECEF datum is already in place but digital spatial data users world-wide need to discuss and agree upon a common spatial data model that best accommodates all users. I'm convinced that using the global spatial data model and re-defining elevation as the distance from the ellipsoid is the correct thing to do.

Adopting WES12 will put all spatial data users all over the world on the same elevation basis and provide standard efficient tools for assessing absolute elevation accuracy. Will there be an impact? Yes. The difference is that the uncertainty associated with elevation will be in the derived quantity only (statistically identifiable) instead of having to worry about uncertainty in the reference.

Although the change will be invisible to most spatial data users, the following problems being addressed by various disciplines will still need to be addressed:

1. Impact of severe slope of the geoid.
2. Tectonic up-lift.
3. Subsidence due to various reasons.
4. Earth tides.

More information on the Global Spatial Data Model can be found at: www.zianet.com/globalcogo/refbyefb.html.

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