Additional Discussion of True 3-D Versus Pseudo 3-D

Earl F. Burkholder, PS, PE, F.ASCE
Global COGO, Inc. – Las Cruces, NM 88003
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This is a work in progress - subject to corrections and revision.
Web links are included in the endnotes.

A preliminary discussion of True 3-D Versus Pseudo 3-D is posted on the Global COGO website[1].

This article includes more detail and additional arguments in favor of using ellipsoid (sometimes called geodetic) heights for the third dimension – that is, using True 3-D instead of Pseudo 3-D. True 3-D is computed from Earth-centered Earth-fixed (ECEF) X/Y/Z coordinates while Pseudo 3-D is computed using 2-D plane coordinates and elevation. True 3-D and Pseudo 3-D are quite similar and, in some cases, can be used interchangeably. However, given increasing reliance on 3-D digital spatial data, differences between the two become critical - especially depending on how the data are used - e.g., in applications of artificial intelligence and machine learning (AI/ML). Globally, True 3-D is driven by satellite positioning which uses the ECEF coordinate system for GNSS positioning worldwide. Pseudo 3-D comes from using a horizontal datum for "flat-Earth" eastings and northings while referencing a separate vertical datum for elevation. Such coordinates are called Pseudo 3-D because horizontal and vertical datums do not share a common origin – see definition[2].

Euclid lived several hundred years BCA and is recognized for his contributions to geometry. Descartes formalized analytical geometry in his "*Discourse on the Method*" published in 1637. Although rules of solid geometry are long-standing, modern spatial data manipulation also includes vectors, matrix algebra, and computer processing. Such practices routinely include 3-D digital spatial data, and the term "Digital Twin" is increasingly popular for representing the physical world in a digital database. Understandably, geometrical spatial data computations within the realm of AI/ML can be performed more efficiently if "a 3-D model is used for 3-D data." The global spatial data model (GSDM) is a comprehensive 3-D model based on the ECEF geocentric coordinate system which has a single origin for 3-D data and preserves geometrical integrity by using rules of solid geometry throughout. Those solid geometry equations are in the public domain and computations performed in 3-D space are referred to as True 3-D (no gravity) as opposed to Pseudo 3-D (which includes elevation, influenced by gravity, for the third dimension). The GSDM includes both True 3-D and Pseudo 3-D, but geometrical integrity and computational efficiency are both enhanced by using True 3-D[3].

Surveying and civil engineering share many concepts related to spatial data and both are profoundly affected by the emergence/application of Digital Twins. But it is important to note that the land surveying profession has statutory responsibility (and separate licensure) for establishment and retracement of property lines – primarily 2-D. Beyond that, surveying - also called geomatics - uses 3-D extensively (4-D if time is also included). Typical local surveying and engineering practices routinely express horizontal position with 2-D plane coordinates while the third dimension, vertical, is expressed as elevation (1-D). Even when extending beyond reasonable flat-Earth assumptions and using latitude/longitude (or map projection) coordinates to define horizontal position, elevation is still used for the third dimension and the resulting coordinate system is called Pseudo 3-D.

The 3-D GSDM, defined in 1997[2], is built on the assumption of a single origin for 3-D data and uses public domain solid geometry equations to perform computations in three-dimensional space. The GSDM, and the definition of geospatial Digital Twins, both include curvilinear and rectangular coordinates, thereby accommodating both True 3-D and Pseudo 3-D. This ambiguity may lead to significant economic consequences if either is used inappropriately as the other. Such problems can be avoided by geometrical specificity and discussions to eliminate "the elephant in the room[4]."

GPS emerged as a measuring tool for surveyors in the 1980s and the grid/ground distance difference became a hot topic of discussion among surveyors. While on sabbatical leave from the Oregon Institute of Technology in 1990/91, the author sent an inquiry to all 50 state DOTs asking how they handled the grid/ground distance difference. The replies from 46 out of 50 state DOTs are summarized in Appendix C of, "Using GPS Results in True 3-D Coordinate System," presented at the ASCE GPS '91 Specialty Conference in Sacramento, CA[5]. Figure 1 is a schematic showing the relationship between the True 3-D and Pseudo 3-D coordinate systems. The formal definition of the global spatial data model (GSDM) grew out of that GPS '91 paper.

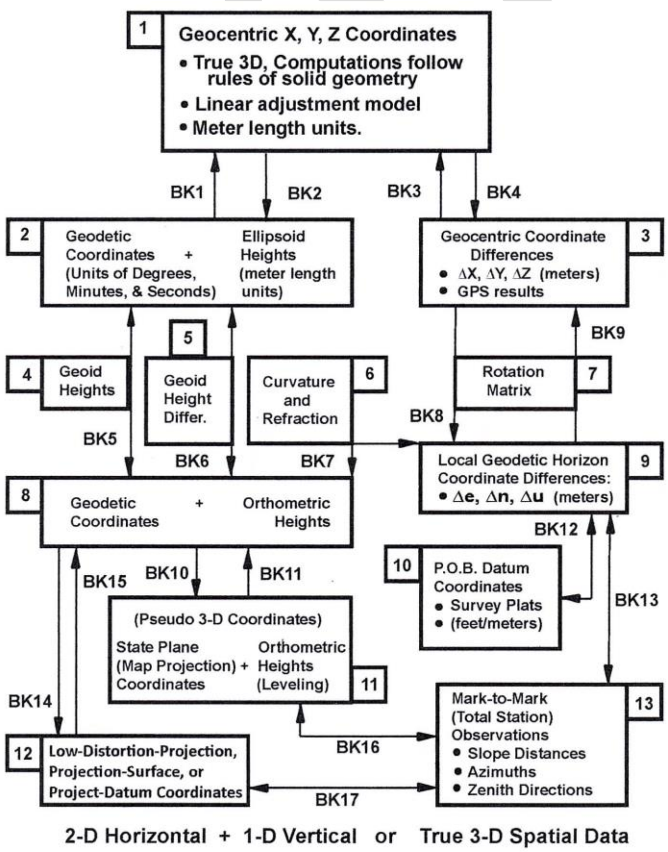

Figure 1 True 3-D and Pseudo 3-D (Fig. 6 in True 3-D paper[5])

A separate, but related, issue is the difference between spatial data and geospatial data. The generic term "spatial data" includes elements of geometry relating to the size, shape, and location of objects and may include geodetic considerations while the term "geospatial data" refers specifically to those spatial data referenced to the Earth and presumes inclusion of geodetic concepts as needed. Given existing ambiguity, it could be argued either way - spatial data are a sub-component of geospatial data or geospatial data are a sub-component of spatial data. It can also be said that P.O.B. Datum coordinates (Box 10 in Figure 1) are spatial data, having been obtained by rotating ECEF (geospatial) differences to local (spatial) differences. The components in Box 9 are the same flat-Earth differences plane surveyors have been using for generations. The rotation between boxes 3 and 9 is bi-directional - meaning local spatial data can be converted to geospatial data if the local differences are rotated to ECEF differences and those $\Delta X/\Delta Y/\Delta Z$ components added to the ECEF coordinates of the vector anchor point.

Some Features of Google Earth are Compatible with the GSDM

Of many things that could be said about Google Earth and True 3-D, the point here is that the "Zoom" feature of Google Earth uses a moveable perspective (origin) with results similar to those obtained using Boxes 3, 7, 9, and 10 of Figure 1. The images on a Google Earth screen contain much information. The Google Earth "ruler feature" enables the user to find distances (and other geometrical properties) extracted from features displayed on the screen. However, if the user is given a choice of displaying either map distance or ground distance, Pseudo 3-D is implicit, and definitions of horizontal distance become relevant.[6]

Generically, Google Earth is an excellent 3-D tool. It is, however, the user's responsibility to verify which reference frame (and/or datum) is implicit and whether the third dimension is based on elevations or ellipsoid heights. For elevations obtained from Google Earth data, questions of datums and geoid models also need to be addressed to assure the 3-D geometrical integrity and compatibility of data being used. Understandably (for various reasons), Google Earth derived spatial data are not recommended for engineering design.

Ultimately, Google Earth may evolve to using True 3-D, i.e., displaying distances computed directly from the ECEF data base values – Figure 1. Various horizontal distance options[6] based on True 3-D are available. The 3-D (geodetic) azimuth from one point to another is also available directly from the stored X/Y/Z values[7]. If or when Google Earth supports geometrical computations compatible with the GSDM, the quality (standard deviation) of a derived quantity can also be available to the user based upon the variance/covariances in the database via the stochastic features of the GSDM[8 and 9].

Accommodating the Impact of Gravity

It can be said that gravity is responsible for the difference between generic spatial data and those geospatial data referenced to the Earth. That difference is also manifest by "deflection-of-the-vertical," a comparison of the direction of the plumb line (defined by gravity at a point) and the direction of the ellipsoid normal (defined as perpendicular to the ellipsoid at a point). The "deflection-of-the-vertical" is directly related to the slope of the geoid. Under flat-Earth assumptions (associated with spatial data), the deflection-of-the-vertical is assumed to be zero and gravity is not a factor in computations using rectangular spatial data components. Many virtual reality computer graphics applications (e.g., modeling, gaming, walk-throughs, and visualizations) are based on spatial data and flat-Earth assumptions. Software and equations for spatial data computations using simple local rectangular components (Δx/Δy/Δz or Δe/Δn/Δu) can legitimately be called True 3-D only to the extent flat-Earth assumptions are acceptable.

A point of clarification is that, in terms of the GSDM, ΔX/ΔY/ΔZ components represent ECEF differences while local differences are given by Δe/Δn/Δu (both systems are right-handed). Many existing applications use Δx/Δy/Δz for (flat-Earth) spatial data differences. Traditional practices, such as cadastral surveying, construction layout, or photogrammetric mapping, often associate the Z direction with elevation. As used in the GSDM, the Z axis is perpendicular to the Equator. That difference in visualizing the "Z" direction can be unsettling. Context can help eliminate confusion but when working with 3-D digital spatial data, ambiguity can best be avoided by using specific consistent coordinate system declarations.

What about error propagation and accuracy? When using standard deviation to judge spatial data quality, each spatial data user deserves to know "accuracy with respect to what?" Answering that question is not attempted here – several sources include.[8 and 9] Error propagation in terms of Pseudo 3-D is more challenging than it is with True 3-D. The point being since gravity is not a factor in True 3-D geometrical computations, rules of solid geometry are globally applicable and 3-D error propagation is succinctly handled using matrices. For "local flat-Earth" spatial data computations, a geocentric ΔX/ΔY/ΔZ vector is rotated to a local Δe/Δn/Δu perspective (Box 9 and 10 in Figure 1). Changing the perspective of a vector does not alter its underlying stochastic properties – meaning no geometrical integrity is lost. Viewing standard deviations in a local (n/e/u) perspective is preferred to the geocentric perspective of sigma X, sigma Y, and sigma Z. Local-perspective standard deviations for e/n/u are readily available using equation 5 in the accuracy paper.[8]

Justifications for using Pseudo 3-D include arguments about which way "water will run." Actually, the question relates to the slope of the geoid (related to deflection-of-the-vertical), not geoid height. Of course, slope of the geoid is computed as the difference in geoid height between two points divided by the distance between the same two points. To a first approximation, the direction "water will run" can be computed using geodetic (ellipsoid) heights rather than orthometric heights, i.e., using True 3-D rather than Pseudo 3-D. But, in "big picture" applications where hydraulic gradient is critical (e.g., the Great Lakes System in the U.S.), dynamic heights (not orthometric heights) are needed to define the geopotential surface precisely[10]. Corrections are available to and used by high-level professionals needing them[11]. Concepts of geopotential surfaces and the impact of gravity remain enormously important in scientific applications but, for many spatial data applications, the "direction water will run" can be acceptably approximated using ellipsoid heights. Two possible exceptions include:

1. The Union Pacific Railroad sorting yard in North Platte, Nebraska[12]. The yard is 8 miles long and strings of railroad cars "drift downhill" toward various switches -

routing each car to its correct destination. Other factors are also involved to control rolling speed, but it appears that the Union Pacific has solved those problems.

2. Alignment of high-energy particle beams such as at CERN. The video “Particle Fever” is a fascinating story of discovering the Higgs Boson[13] and includes incidental discussions of both horizontal and vertical beam alignment. The implication in several other related articles[14 and 15] is that local beam displacements are measured in a local system, but reference is also made to global compatibility. No mention of deflection-of-the-vertical issues was found.

The impact of gravity[16] for spatial data users can be mitigated by using ellipsoid height instead of orthometric height. Comments about the gravity article include:

1. The subject of gravity is enormously important and deserves considerable scientific and professional attention. At the risk of over-simplification, the location of a point is a “solved problem.” Location is the purview of spatial data users. But gravity has everything to do with “why” a point is where it is or predicting “where” a point was in the past or “where” it will be in the future.

2. The goal in the gravity paper is to honor existing scientific/professional efforts but to look for ways that the spatial data community can find answers and solve location-based problems more efficiently without sacrificing geometrical rigor.

3. Corrections to ellipsoid height are readily available for applications in which location of the geoid is essential.

4. It is acknowledged that the user community has a huge investment in using separate horizontal and vertical datums. The transition to using true 3-D (an integrated 3-D datum) will be hastened by disruptive innovations driven by the digital revolution.

5. Many users in the United States have expressed preference for continued use of the U.S. Survey Foot. Under forward-looking leadership of the National Geodetic Survey (NGS), the U.S. Survey Foot has been deprecated to join the ranks of other legacy length units[17]. Can or should the talent and resources of NGS be instrumental in making a similar transition to use of an integrated 3-D datum (True 3-D)?

Importance of a High-Definition Map

The use of autonomous vehicles has emerged as a vital application of geospatial data. Selected excerpts from Wikipedia[18] include. . .

> *A high-definition map (HD map) is a highly accurate map used in autonomous driving, containing details not normally present on traditional maps. Such maps can be precise at a centimetre level.*

High-definition maps for self-driving cars usually include map elements such as road shape, road marking, traffic signs, and barriers. Maintaining high accuracy is one of the biggest challenges in building HD maps of real-world roads. With regard to accuracy, there are two main focus points that determine the quality of an HD map:

- *Global accuracy (positioning of a feature on the surface of the Earth) and*

- *Local accuracy (positioning of a nearby feature in relation to road elements around it).*

The Wikipedia article includes numerous references and acknowledges the importance of (and the difference between) network accuracy and local accuracy which expresses the relative location of one feature with respect to nearby features, e.g., lane changes or front porch package delivery. Those concepts are a standard part of the stochastic portion of the GSDM[7].

An added feature of using the stochastic model portion of the GSDM is that the user, by selecting a numerical filter, can control the quality (positional uncertainty) of data drawn from the database.

All of those high-definition map features are directly supported by the GSDM. Can the GSDM be used with Pseudo 3-D? Yes, but that requires substantially more effort for geoid modeling etc. Ideally, the meta data associated with a high-definition map will state specifically whether the map is based on True 3-D or Pseudo 3-D.

High-level agency distinction between True 3-D and Pseudo 3-D

The difference between True 3-D and Pseudo 3-D is not new at "high levels" of policy as implemented by federal agencies. Without being critical, the current practice of using separate horizontal and vertical datums reflects prudent decisions based on "pre-digital" technology. Disruptive Innovation spawned by the digital revolution affects many sectors of society – maybe none more dramatically than the use of 3-D digital spatial/geospatial data. The espoused goal is to plan ahead in a way that appropriately exploits the benefits of new technology. Communication, standard practice, teamwork, and common geometry all contribute to the world of tomorrow – the world we build and leave to our grandkids etc.

- National Academies Press, 2018, "Thriving on Our Changing Planet: A Decal Strategy for Earth Observations from Space[19]." Although the document is quite comprehensive, a take-away is that requirements vary from agency to agency. For example, it seems that some agencies tend more toward using True 3-D while others appear to be committed to continued use of Pseudo 3-D.

- National Academies Press, 2020, "Evolving the Geodetic Infrastructure[20]." This document references the 2018 document and provides more detail. For example, in discussing Modernization of the National Spatial Reference System, the statement is made (labels in paratheses added). . .

> *"These changes will enable GNSS-based ellipsoid heights (True 3-D) to be related to orthometric heights (Pseudo 3-D) used for local vertical control. Although widely used by surveyors, the NSRS is not sufficiently precise to meet the science requirements of the Decal Survey."*

According to a subsequent paragraph. . .

> *"A precise geodetic infrastructure is essential for studies of (1) absolute sea-level change (sea level measured with respect to the Earth's center of mass or other suitable reference surface), which is important for understanding climate change; and (2) relative sea level (sea level measured with respect to the possibly moving land surface), which is important for assessing the impacts along the coast."*

- FGDC, 2020, "National Spatial Data Infrastructure Strategic Plan[21]." This document describes the National Spatial Data Infrastructure (NSDI) as impacted by the Geospatial Data Act of 2018. The Vision of NSDI is "Empowering a geo-enabled nation and world for place-based decision making. Mission" The NSDI provides a national network of geospatial resources that seamlessly integrates location-based information to serve the needs of the Nation and wider global interests. Here again, it seems that inclusion of specific meta data on use of True 3-D or Pseudo 3-D could be very helpful. Presumably, "seamless integration" is more compatible with True 3-D.

- The U.S. Geological Survey (USGS) is a scientific agency with a long history of developing topographic maps (and other products) for the entire nation. Years ago, contour maps were generated using plane table field surveys and manual drafting techniques. Mapping practices have evolved radically during the digital revolution and now include a plethora of sensors and automated processing of digital spatial/geospatial data. The 3D Elevation Program (3DEP)[22] includes various spatially related products and services provided in support of commerce throughout the nation (and the world).

  Does 3DEP include True 3-D, Pseudo 3-D, neither, or both? One simple answer is that elevations have always been referenced to sea level (more specifically, to the geoid) and will continue to be so referenced for the foreseeable future – end of discussion. However, it would be less than prudent to ignore the following.

  1. BIG PICTURE: The North American Vertical Datum 1988 (NAVD88) is planned to be replaced during Modernization of the National Spatial Reference System (NSRS).[23] Looking ahead, the numbers representing elevation will change (everywhere). Since the numbers are destined to change. . .

     a. The units for the numbers should be changed to meters rather than feet.

b. The numbers should reflect True 3-D instead of Pseudo 3-D because. . .

i.) The center of mass of the Earth is a better reference – it is more stable and easier to find than is the geoid.

ii.) Mathematical efficiency of True 3-D is superior that of Pseudo 3-D.

iii.) Modern AI/ML practice (worldwide) avoids using elevations.

2. LOCAL: Except for very precise applications (for which corrections are available), spirit level height differences can be used as ellipsoid height differences. GNSS and photogrammetric already provide ellipsoid height differences. As described in the "gravity" paper[16], local users are more concerned with local vertical distance differences than with the underlying numbers.

   a. What is the location of this point with respect to other nearby points?

   b. What is the location of this point with respect to where it was previously?

   c. In both cases a stable, easily located reference is preferred – True 3-D.

3. ECONOMIC/POLITICAL: So far, this True 3-D versus Pseudo 3-D comparison has been primarily "technical." It is hereby acknowledged that other factors are also involved. For example, the ASCE Future World Vision, describes a future that includes smart cities, digital twins, automated transportation (high-definition maps), engineering response to climate change, and other. The discussion of abstraction/technology/policy/practice will contribute to collective progress.

- National Geospatial Intelligence Agency (NGA): From this author's perspective, the military component of the U.S. Government does what it does for reasons not necessarily shared with the civilian community. The U.S. Department of Defense defined the Earth-centered Earth-fixed (ECEF) system for non-civilian purposes. But military organizations do not operate in a vacuum and benefits of using the ECEF system have been exploited by non-military users worldwide. Acknowledging that one size does not necessarily fit-all, NGA policy[24] CJCSI 3900.01D states, "In unilateral and joint operations, the U.S. military will use the WGS 84 geodetic 3-D coordinate reference system - (including Height Above Ellipsoid) unless the Commander determines that the use of other position reference systems (i.e., datum) is mission critical".

- Other federal legislation, such as the Infrastructure Investment and Jobs Act,[27] makes numerous references to applications of the spatial data infrastructure. Benefits of using an integrated 3-D spatial data model in applications worldwide seems rather obvious.

Footnotes:

1 www.globalcogo.com/true-versus-pseudo.pdf

2 www.globalcogo.com/gsdmdefn.pdf

3 www.globalcogo.com/GSDM-and-DT.pdf

4 www.globalcogo.com/sages2022.pdf

5 www.globalcogo.com/Tru3d.pdf

6 www.globalcogo.com/HD-Options.pdf

7 www.globalcogo.com/3DGPSAZ.pdf

8 www.globalcogo.com/accuracy.pdf

9 www.globalcogo.com/EFB-SaGES-ALTA-NSPS.pdf.

10 North American Vertical Datum and International Great Lakes Datum: (noaa.gov)

11 Dynamic Ht - Dynamic Height Computation (noaa.gov)

12 https://en.wikipedia.org/wiki/Bailey_Yard

13 particle fever cern - Search (bing.com)

14 https://accelconf.web.cern.ch/e06/PAPERS/TUPCH064.PDF

15 paper_beam_based_alignment.pdf (cern.ch)

16 www.globalcogo.com/ImpactOfGravity.pdf.

17 https://www.federalregister.gov/documents/2020/10/05/2020-21902/deprecation-of-the-united-states-us-survey-foot

18 https://en.wikipedia.org/wiki/High-definition_map#:~:text=A%20high-definition%20map%20%28HD%20map%29%20is%20a%20highly,maps%20can%20also%20be%20constructed%20using%20aerial%20imagery.

19 https://nap.nationalacademies.org/login.php?record_id=24938

20 Download: Evolving the Geodetic Infrastructure to Meet New Scientific Needs | The National Academies Press

21 https://www.fgdc.gov/nsdi-plan/nsdi-strategic-plan-2021-2024.pdf

22 https://www.usgs.gov/3d-elevation-program/what-3dep.

23 Earth-centered, Earth-fixed coordinate system - Wikipedia

24 CJCSI 3900.01D.pdf

25 Infrastructure Investment and Jobs Act - Wikipedia