Reconciling Gravity and the Geometry of 3-D Digital Geospatial Data

(Geoid modeling is rarely needed if geodetic height is used for the third dimension.)

© Earl F. Burkholder, PS, PE, F.ASCE
Global COGO, Inc., Las Cruces, NM 88003
eburk@globalcogo.com www.globalcogo.com

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Abstract

Remarkable advancements in technology have occurred since invention of the transistor in 1947. While other applications have often captured the imagination of the public, few have had more impact on modern civilization than those building on the geospatial data infrastructure. Extending the work of Euclid and others, René Descartes formalized the rules of solid geometry in "Discourse on the Method" published in 1637. Those concepts are used extensively in modern spatial data applications. However, a big picture view of spatial data must also recognize gravity and acknowledge that the Earth is not flat. Horizontal positioning has traditionally relied on a horizontal datum while elevations are referenced to a vertical datum. With the advent of global navigation satellite systems (GNSS) for positioning, an integrated three-dimensional (3-D) datum for geospatial data warrants consideration. The 3-D global spatial data model (GSDM) is based on Earth-centered Earth-fixed (ECEF) coordinates and provides a consistent environment for unifying disparate applications of 3-D digital spatial data. But the GSDM defines location sans gravity. This article attempts to reconcile the impact of gravity on location within the context of a 3-D datum that combines horizontal and vertical in a mathematically consistent computational environment.

Key Words: Gravity, geoid, Earth's center of mass, geoid modeling, geoid height, ellipsoid height, geodetic height, spatial data, geospatial data, datums

Convention

Instead of referring to a 3-D position as geodetic latitude, geodetic longitude, and ellipsoid height; this paper uses geodetic latitude, geodetic longitude, and geodetic height. Humans have referred to the third dimension in terms of elevation, altitude, orthometric height, ellipsoid height, and dynamic height – each with good reason. Going forward, this convention completes the triplet of coordinates – geodetic latitude/longitude/height. Mathematically well-defined, geodetic height is synonymous with ellipsoid height taken to be the distance along a line normal to the ellipsoid, between the ellipsoid and a point. The Geodetic Glossary (NGS 1986) and the Glossary of the Mapping Sciences (ASCE/ACSM/ASPRS 1994) each include a definition for "height, geodetic" (Meyer 2021).

Introduction

Whether under a banner of space age, digital revolution, BIG DATA, national security, or navigation; this article attempts to bring fundamental spatial data concepts (geometry) into the arena of modern practice with the idea of exploiting characteristics of 3-D digital spatial data. Traditional practice, for legitimate reasons involving gravity, has relied on separate horizontal and vertical datums. A consequence of the digital revolution is that additional benefits can be realized in many spatial data applications with adoption of an integrated 3-D global spatial data model (GSDM) that combines horizontal and vertical into one consistent mathematical framework (Burkholder 1997). One challenge to realizing those benefits (Burkholder 2016a) is that horizontal and vertical have different origins –

latitude and longitude for horizontal and the geoid (a consequence of gravity) for vertical. An integrated 3-D system for geospatial data has but one origin – Earth's center of mass (CM).

Miniaturized sensors, speedy computers, and enormous storage capacity all contribute to exponentially expanding use of spatial data. In addition, knowledge of location and concepts of spatial proximity have driven development of measurement science, development of storage and management practices for spatial data, development of geospatial analytics, and enhancement of spatially related decision-making strategies affecting the global balance of power, economic development, climate change, utilization of natural resources, patterns of transportation, land ownership, and a host of other activities.

Relativity, non-inertial reference frames, and esoteric procedures used in signal processing are not discussed in this article – that is the prerogative of scientists and agencies such as the International Earth Rotation and Reference Systems Service (IERS 2013), the National Geospatial-Intelligence Agency (NGA 2021), and the National Geodetic Survey (NGS 2021a). While gravity (the sum of gravitational attraction and centrifugal force) is a consuming interest for many in the scientific community, the scope of science includes much more than issues of geometry. Nevertheless, a consequence of science is a global geometrical network of monumented Earth-centered Earth-fixed (ECEF) coordinates (NIMA 1997, NGA 2014). Those ECEF values are the primary definition for location globally and, in the United States, horizontal location is realized in terms of the North American Datum of 1983 (NAD 83). Given advances in measurement technologies and modeling practices, the National Geodetic Survey (NGS) is currently updating the NAD 83 to be known as, depending on one's location, the North American Terrestrial Reference Frame of 2022 (NATRF2022), the Pacific Terrestrial Reference Frame of 2022 (PATRF2022), the Mariana Terrestrial Reference Frame of 2022 (MATRF2022), or the Caribbean Terrestrial Reference Frame of 2022 (CATRF2022). Information on the 2022 modernization project is well documented (NGS 2020a). Regardless of which reference frame is used – past, present, or future – the underlying ECEF geocentric X/Y/Z coordinates can provide a common basis for spatial data manipulations.

NGS also plans to replace the North American Vertical Datum of 1988 (NAVD 88) with the North American-Pacific Geopotential Datum of 2022 (NAPGD2022). Information on gravity as a critical part of that effort is available on the NGS web site (NGS 2020b).

At the risk of not giving due credit for the contributions of scientists, mathematicians, geodesists, engineers, and other professionals; the concepts promoted herein are intended to enhance activities of spatial data end users while maintaining geometrical integrity and professional credibility. For example, it has been said that location is a solved problem. That is a huge accomplishment for the many talented professionals who made it happen as it provides a solid foundation for the spatial data infrastructure. Even so, positioning professionals are still needed to address "big picture" challenges such as. . .

1. What makes a point move?
2. How is a point moving?
3. Where was the point in the past?
4. Where will the point be in the future?
5. What are the stochastic properties of the point/location?

End user questions – while answering the big picture questions with scientific rigor involves significant talent, effort, and resources, the interests of many spatial data end users boil down to. . .

1. What is the location of this point now with respect to other (nearby) points?
2. What is the location of this point now with respect to its location in the past or in the future?

3. What is the positional accuracy of the point and with respect to what?

Restating, the goal of this article is to credibly support activities of the spatial data end user. By and large, rectangular flat-Earth coordinates are the preferred computational environment for many applications – engineering and otherwise. However, it would be naïve to ignore the impact of gravity. An award-winning paper presented at an NMSU Technology Conference (Burkholder 2004), argues that Geomatics educators should embrace a larger perspective that includes 3-D. Built on scientific principles, the GSDM preserves the integrity of precisely located ECEF coordinates while simultaneously allowing the end user to work with local rectangular coordinate differences. The stochastic portion of the GSDM embodies concepts and procedures for addressing spatial data accuracy (Burkholder 1999).

Context

Although gravity is the weakest of the four fundamental physical forces, its range is infinite and the gravitational attraction between heavenly bodies keeps Earth in orbit about the Sun. Gravity also keeps humans standing erect on terra firma. It seems ironic that gravity is not part of the Standard Model of Particle Physics (CERN 2012) as gravity has little or no influence at the sub-atomic level. However, the impact of gravity on human experience is undeniable and concepts of gravity are studied extensively by scientists, engineers, surveyors, and others. With that said, it is convenient for spatial data users to rely on flat-Earth solid geometry relationships for many applications. But Earth is not flat and geometrical integrity can suffer if gravity is ignored. Heretofore the impact of gravity has been accommodated by using two datums – horizontal and vertical. Horizontal position is referenced to latitude and longitude while the third dimension is referenced to the geoid (approximated by mean sea level). The GSDM provides a consistent computational model for handling geospatial data in a single 3-D datum and can be implemented using policies and procedures that accommodate gravity, that preserves the geometrical integrity of 3-D geospatial data, and that fully supports subordinate 2-D flat-Earth applications**. Meaning – the impact of gravity can be accommodated by computing and applying appropriate corrections before X/Y/Z values are stored in a 3-D database. For example, various corrections (e.g., gravity, ocean loading, relativity, and tropospheric) are applied before X/Y/Z coordinates are stored as defining values for the WGS 84 Reference Frame (NGA 2014).**

Issues Implied by the End-User Questions

The following issues should be addressed before answering the “simple” end-user questions.

- What are the physical and mathematical definitions of the underlying reference?
- How stable (reliable/unchanging) is the reference?
- What are the physical or geometrical circumstances of the problems to be solved?
- What measurements, units, and/or geometry are needed or available?
- Are measurements absolute or relative? Are answers relative or absolute?
- What is the uncertainty of the measurement and/or the computed position?
- How can management of measurements and use of geospatial data be linked to . . .
  - Legacy data sets?
  - Preservation for future generations?
  - Access to a common “universal” geospatial database by all users worldwide (including civilian, military, and sovereign interests)?

Figure 1 illustrates the simple questions of interest to end users. Did the ground sink or was the mailbox post pushed out of the ground? How long has the mailbox post been in the ground or when was the "settlement" first noticed? Figure 1 has no known consequences, but details do matter in other cases.

Figure 1, Localized Movement – Which Moved, the Ground or the Post? Does it Matter?

Background and Historical Information

1. Spatial data represent the location, size, and shape of an object. Geospatial data are those spatial data referenced to the Earth. The word "data" is plural while "data set" is singular. In some cases, spatial data are taken to be a subset of geospatial data and in others, geospatial data are taken to be a subset of spatial data. Context often allows for discrimination between the two uses.

2. Many activities of the U.S. Government have been developed as a consequence of and in support of Executive Order 12906 signed by then President Clinton in 1994 which states that "*In consultation with State, local, and tribal governments and within 9 months of the date of this order, the [Federal Geographic Data Committee] FGDC shall submit a plan and schedule to [Office of Management & Budget] OBM for completing the initial implementation of a national digital geospatial data framework ("framework") by January 2000 and for establishing a process of ongoing maintenance.*" Since then, the FGDC "*and its partners have developed a strategic plan for the [National Spatial Data Infrastructure] NSDI that describes a shared national vision of the NSDI and includes a set of goals and objectives for the roles of Federal agencies in achieving this vision.*" https://www.fgdc.gov/nsdi/nsdi.html (FGDC 2021).

3. The Southeastern Wisconsin Regional Planning Commission (SEWRPC 1997) published a report, "Definition of a Three-Dimensional Spatial Data Model for Southeastern Wisconsin," which advocates combining horizontal and vertical into a single 3-D database. "Definition and Description of a Global Spatial Data Model" (Burkholder 1997) is the defining document for the GSDM. That document was registered with the U.S. Copyright Office, 14 April 1997, and referenced in the SEWRPC report - http://www.globalcogo.com/gsdmdefn.pdf.

4. The concept of a *"global geospatial data infrastructure"* is described by Coleman and McLaughlin (1998) who identify the defining components, stakeholders, and interfaces. Their ". . . paper presents a definition of global geospatial data infrastructure (GGDI) and describes its potential requirements from the respective viewpoints of the military, global science, and international maritime stakeholder communities."

5. The Coalition of Geospatial Organizations (COGO), formed in 2008, consists of 13 member organizations, https://cogo.pro/ (COGO 2019). "The general purpose of COGO shall be to provide a forum for organizations concerned with national geospatial issues. . ." COGO delegates meet twice a year to discuss issues of mutual interests. Any policy recommendation made by COGO must enjoy the unanimous support of all member organizations. Patterned after the ASCE Infrastructure Report Card COGO published a "Report Card of the U.S. National Spatial Data Infrastructure" to "help Congress, the Administration, Federal agency executives, and others understand the shortcomings of the NSDI" (COGO 2015). A follow up Report Card was released February 5, 2019 (COGO 2018). The Executive Summary in that second report concludes, "At a minimum, the Report Card suggests a compelling need for a thorough assessment of user needs and requirements for a modern data system." That assessment should document both advantages and disadvantages of using a 3-D model for 3-D data. Disruptive innovation should also be addressed (Burkholder 2015, 2020) - http://www.globalcogo.com/DisruptiveInnovation.pdf.

6. Global COGO, Inc. was incorporated in the State of Ohio in 1996. There is no known connection between Global COGO, Inc. and the Coalition of Geospatial Organizations (COGO).

7. "The 3-D Global Spatial Data Model: Foundation of the Spatial Data Infrastructure" (Burkholder 2008) is a book which describes the GSDM in detail. CRC Press also published a second edition (Burkholder 2018), "The 3-D Global Spatial Data Infrastructure: Principles and Applications." The 2nd Edition contains updated information, a new chapter describing various 3-D applications, and a new Appendix E, "Evolution of the meaning of terms Network Accuracy and Local Accuracy."

8. Appendix E (Burkholder 2016b) of the 2nd Edition contains a summary of the challenge by Soler and Smith (2010) to the integrity of the GSDM and "local accuracy." The veracity of the GSDM is subsequently validated as described in said Appendix E. However, another article by Soler and Han (2017) entitled, "Rigorous Estimation of Local Accuracy Revisited" was posted electronically by ASCE on July 27, 2017, in which the authors claim to, "revisit the subject matter and close this chapter once and for all. . ." A successful rebuttal (Burkholder 2019a) to that claim is published in a Discussion of Soler and Han (2017) posted by ASCE at . . .
https://ascelibrary.org/doi/full/10.1061/%28ASCE%29SU.1943-5428.0000274

9. A separate comprehensive example of Local Accuracy, "Concepts of Spatial Data Accuracy Need Our Attention," (Burkholder 2017) based on the GSDM was presented at the Surveying and Geomatics Educators Society (SaGES) Conference at Corvallis, Oregon, in July 2017. Specifically, that example shows computation of local accuracy between two adjacent monuments which were not connected by direct measurement. This paper also shows that the chapter on Local Accuracy is not closed as claimed by Soler and Han (2017).
http://www.globalcogo.com/EFB-SaGES-ALTA-NSPS.pdf

10. The impact of gravity figures prominently in discussion of observed geological movement of the crust of the Earth in the Great Lakes region of the United States (Argus, et.al., 2020). While the focus of the Argus article is on changes of water levels and crustal loading, the statement is made

that, “Satellite altimetry estimates of the water height of the five Great Lakes relative to Earth’s mass center (CM) confirm that the water level gauge measurements are correct.” The point is that while extensive comparisons are made using height differences, heights are referenced to the ellipsoid (via the CM), not the geoid - https://doi.org/10.1029/2020JB019739.

11. In November 2020, the FGDC (2020) published the “National Spatial Data Infrastructure Strategic Plan 2021-2024” as directed by the Geospatial Data Policy Act of 2018 for the “FGDC to develop a strategic plane for the NSDI to provide strategic direction to support and leverage these advancements.” The Vision is to empower “a geo-enabled Nation and world for place-based decision making” and the Mission is to “provide a national network of geospatial resources that seamlessly integrated location-based information to serve the needs of the Nation and wider global interests.” The GSDM concepts espoused herein are viewed as being compatible with and supportive of that report – see https://www.fgdc.gov/nsdi-plan/nsdi-strategic-plan-2021-2024.pdf.

12. The November 2020 issue of Civil Engineering magazine contains an article, “Getting the Height Right: The North American Vertical Datum of 1988” (Witcher 2020). The article describes issues related to the development of the North American Vertical Datum of 1988 (NAVD 88) and, looking ahead, notes that “The new era will be defined by the Global Navigation Satellite System (GNSS) which promises to produce orthometric heights more efficiently and accurately.” NGS professionals are to be commended for developing vertical datums and addressing the challenges associated with “getting the height right.” GNSS provides geodetic heights, but geoid modeling is an additional step required to obtain the promised orthometric heights. Geodetic heights are compatible with 3-D geospatial data computations and support the Mission of the FGDC (2020) to provide seamlessly integrated location-based information. https://source.asce.org/getting-the-height-right-the-north-american-vertical-datum-of-1988/

Concepts

While the following concepts are intended to be correct within the context of most geospatial data applications, it is acknowledged that specific applications extend beyond issues discussed herein. For example, specialized professionals use geodynamic heights to compute hydraulic grade lines for the Great Lakes system. Even if/when geodetic height is adopted as policy for the third dimension as proposed herein, the science and the tools for hydraulic gradient computations remain available to those needing them. Proven long-standing methods continue to provide a foundation for established practice in many areas of science. **But the frontiers of science are being expanded in various disciplines and society stands to benefit from associated innovations – in this case, exploiting the geometry and characteristics of 3-D digital geospatial data.**

1. No attempt is made in this article to accommodate relativity or the curvature of space and time.

2. Physical constants of pi (irrational) and the speed of light, *c*, are fixed and unchangeable. While the value of pi is known to many significant digits, the speed of light is the result of precise measurements and is accepted as “exact” by the scientific community worldwide. It seems unlikely that the value adopted for the speed of light will be modified anytime soon.

3. The ECEF coordinate system is attached to the Earth and is used as an inertial reference frame for geospatial data applications. However, strictly speaking, because the Earth is rotating, the ECEF system is a non-inertial reference frame for higher-order applications – such as computing the effect of Coriolis forces.

4. With respect to geospatial data, an absolute quantity is a fixed number (with appropriate units) within a stated reference frame – a reference frame being the geometrical foundation of a reference system. Relative is taken to be the difference between two absolute values within the same system. One weakness of this explanation is the need to describe the difference between two absolute systems. That is not possible without defining another, more encompassing, absolute system. Then, yet another absolute system – continuing ad nauseam – even beyond our solar system. It is therefore essential that the system being referenced is defined without ambiguity. Question, is one standing at the station watching the train go by or is one standing on the train watching the station go by? It gets more complicated if the word "standing" is changed to "walking." In reality, everything moves with respect to something else.

5. Measurements are generally associated with relative quantities. Temperature and gravity could be exceptions. Absolute zero for temperature is defined in thermodynamics as the lowest possible energy state of a particle and occurs at -273.15° C. It could be argued that temperatures in daily human experience are relative in that thermometer readings are interpreted relative to 0° C (freezing point of water) and 100° C (the temperature at which water boils).

   Gravity does not have a physical or an absolute starting point value other than the "standard" value of 9.80665 m/sec^2 adopted by the National Institute of Science and Technology (NIST, 2020). However, values for absolute gravity are obtained from independent measurements of the acceleration of mass under carefully controlled conditions. Such precise measurements are costly to perform. It is more economical to make gravity measurements at two locations and to use the difference in readings as a relative gravity measurement. Given that any uncertainties in gravity measurements at two proximate locations are nearly identical, the difference in values (corrected for known factors) is a relative gravity measurement and such a difference can be quite precise. A gravity network is constructed by attaching numerous relative gravity measurements to an appropriate number of absolute gravity stations within the network.

6. Given the irregular shape of the Earth's crust (topography) and the non-uniform distribution of mass within the Earth, obtaining reliable gravity values is an ongoing challenge for those needing precise gravity data. Such precise gravity data are important because gravity affects the location of the geoid – conventionally taken to be the reference (starting point) for orthometric height.

7. What about time? Relative time can be measured very precisely with atomic clocks and – given an unchangeable value for the speed of light – it translates into an equally precise definition for distance. But defining a reliable starting point for absolute time is also a challenge. Should the starting point for time be midnight, January 1st, the Gregorian calendar, or the BIG BANG? Trivia item – when watching a football game on TV, the measurement for first-down shows the football and the pole at the leading end of the chain. The integrity of a first-down decision is not questioned because the audience sees the evidence. However, the integrity of the first-down decision also relies on the correct (stable) location of the "starting point" (which the TV audience never sees).

8. Most distance measurements are relative quantities but, depending on how systems are defined, geodetic height can be taken as an absolute distance; the Earth's center of mass (CM) is a well-defined starting point and the procedure for computing geodetic height is unambiguous. Differences of geodetic heights are relative. Similarly, an azimuth from north can be considered an absolute quantity while an angle is a relative quantity defined as the difference between two azimuths. What about elevation (orthometric height); is elevation absolute or relative? Differences

in elevation are relative and can be measured quite precisely. That begs the question, what is the starting point for elevation?

The geoid is taken to be the starting point for elevation and is arbitrarily defined as an equipotential surface (units of work) that most closely matches sea level on a global scale. But, due to Earth tides (caused by gravity), the distance between the geoid and the CM can vary by 20 cm or more throughout the day (Leick 2004). Typically, Earth tides are discounted when computing elevations because Earth tides affect the location of the geoid and points on the Earth's surface by similar amounts – a bench mark and the underlying geoid move up and down in unison. But earth tides are not the only component of geoid (sea level) instability. Several perplexing issues could be moot if the location of the geoid were as stable as the Earth's CM or the speed of light.

9. Before leaving absolute and relative – the center of mass of the combined Earth/moon system moves in orbit about the Sun. However, with respect to the ECEF coordinate system, Earth's CM does not move – it is the origin of the ECEF system. Points on or near the Earth's surface may move relative to the Earth's CM but, the CM does not move. What about earthquakes? Points (including large portions of the crust) move with respect to the CM during an earthquake, but the CM is fixed by definition. What about continental drift or melting of polar ice caps? Same answer. Satellites orbit the CM which, by definition, is a physical point.

10. A sacred concept in land surveying is that the "original undisturbed monument" controls even if it was placed in the wrong location. A parallel concept is that a land surveyor is duty-bound to collect and evaluate relevant evidence when locating or re-tracing a boundary. There are many examples of blazed trees, buried stones, pine stumps, iron pipes, brass tablets, and other objects which may be considered "absolute" in the eyes of the law. If a monument – called for in a legal description — is not found, when does the relative location of a boundary corner with respect to other corners on the same parcel become controlling? In land surveying, all known relevant evidence is to be gathered and evaluated. Finding consistency between the record (the written deed) and current physical measurements of the property boundary is a satisfying part of land surveying. Sometimes it is not so easy. If one of the corners of a parcel is missing, the relative location of the missing corner with respect to other corners of the property may be the best evidence available and resetting the corner can be a routine operation. Relative location is a friend of the land surveyor.

    Coordinates express an absolute position with respect to the defined origin and the difference between coordinates (in the same system) expresses the relative location of one point with respect to another. Are these relative values also the friend of the surveyor? Answer, it depends. Coordinate surveying is used extensively in modern practice and relative values obtained from coordinate differences can be reliable evidence of where a previously established point is to be re-located. On the other hand, it is also possible for absolute coordinate values to be misused to the detriment of "good practice" and/or harm to the public.

11. The land surveying profession is heavily invested in the discussion of coordinates versus monuments. In 2017 the Southeastern Wisconsin Regional Planning Commission (SEWRPC 2017) established a Task Force to study the issue. Their "Report on the Possibility of Substitution of Coordinates for Monuments in Control Survey Preservation" was published as Technical Report Number 59. The report promotes and honors the sanctity of the monument and is available at. . . http://www.sewrpc.org/SEWRPCFiles/Publications/TechRep/tr-059-substitution-of-coordinates-for-monuments.pdf.

12. Analyzing the impact of gravity on elevation involves both interpolation and extrapolation. Both are legitimate mathematical tools and, used properly, can be quite beneficial – especially if changes between known data points can be reliably predicted by some known function, linear or otherwise. Without a reason to do so, it may be dangerous to assume a uniform rate of change between data points. Additional data points may be needed to confirm the assumption of a uniform rate or to improve the model. Example: it has been said that GNSS can be explained as a huge interpolation device. The hypothesis is that if signals from all GNSS satellites (radial to the Earth) are observed simultaneously at “network” stations around the world, the simultaneous adjustment of the global geometrical network (treating the Earth as a deformable solid) will provide results that are stronger in the radial component than can be achieved piecemeal using only those signals from satellites visible above the horizon at a given station. Many details and obstacles need to be addressed to prove or disprove that hypothesis.

    Computing the age of the universe is viewed as an example of extreme extrapolation. Using “red shift” observations, astronomers and scientists estimate the universe to be about 13.8 billion years old (Wikipedia 2021a). Undoubtedly reputable science is involved but, to a skeptic, it seems a stretch of rigor to extrapolate existing “red shift” data over billions of years.

    Existing satellite orbits are a better example of both interpolation and extrapolation. Satellites are tracked in their orbit and their positions are computed with impressive accuracy. Given the record of where the satellite has been, the future location of a satellite in its orbit is predicted by extrapolation. The estimated orbit parameters of each satellite are uploaded to all satellites in the constellation. The predicted orbits are then transmitted back to the Earth as the broadcast ephemeris. The accuracy and integrity of the broadcast ephemeris is impressive but actual measurements of the orbits are interpolated (after the fact) to determine a better historical record of each satellite orbit. The precise ephemeris is often used to improve the quality of a GNSS position computed using the broadcast ephemeris. While the precise ephemeris is not available for real-time positioning, the GNSS industry can now deliver RTK comparable results using precise point positioning (PPP) which relies on (local/global) correctors to obtain centimeter-level answers in as few as 3 minutes.

    Interpolation and extrapolation are also associated with inertial surveying. An inertial measuring unit (IMU) monitors acceleration and orientation of the sensor and, based upon knowing its location relative to the Earth, computes differential positions. Part of the challenge has been separating movement of the sensor relative to the Earth from the movement experienced while stationery (fixed to the Earth). When inertial positioning units were first used in surveying applications, the IMU was periodically brought to rest with respect to the Earth during a data collection mission for a “zero velocity update.” Although GNSS has largely replaced inertial positioning for most surveying applications, inertial positioning (which relies heavily on gravity) is still used extensively for navigation in many environments—cars, drones, ships, submarines, airplanes, and missiles etc. Inertial positioning remains a “competitor” to GNSS positioning but, increasingly, various positioning technologies are used in concert and the end user enjoys the assurance of a reliable result – **especially if results are brought into a common compatible 3-D environment for comparison, analysis, and application**.

    More will be said later about interpolation and extrapolation as related to gravity and location, but the reader is reminded that the goal in this article is to justify continued use of flat-Earth rectangular coordinate differences (spatial data) where possible without violating the geometrical integrity of underlying ECEF coordinates and coordinate differences (geospatial data). That is done by computing and applying appropriate corrections to gravity related measurements before the X/Y/Z values of a point are stored in the 3-D spatial database. That will simplify current practice and solve many issues for the spatial data end user without detracting from scientific endeavors.

13. Although the words are sometimes used interchangeably, horizontal and level each have a specific definition. Horizontal is defined as being perpendicular to the plumb line at a point while level is defined as being perpendicular to the plumb line at all points. That difference – a consequence of gravity – is a huge justification for adopting and using two datums, horizontal and vertical.

14. Rollins and Meyer (2019) provide a simple rigorous definition of *horizontal distance at elevation* as "the length of the straightest curve (geodesic) between two points, A and B, lying on an elevated reference surface." Other definitions for horizontal have been used successfully within the context of spatial data (Burkholder 1991) but Burkholder (2019b) adds a wrinkle by noting that horizontal distance in the context of a surveying total station measurement is typically referenced to the plumb line while horizontal distance as computed from stored coordinate data is referenced to the ellipsoid normal. The small numerical difference between a plumbline-based horizontal distance compared to a normal-based horizontal distance (caused by deflection-of-the-vertical) may be of no consequence, but the conceptual difference is important, especially knowing that GNSS distances and photogrammetrically derived distances are already normal-based. Wrestling to find an appropriate definition of horizontal distance as described in Example 5, Chapter 15, Burkholder (2018) suggested that a rigorous definition of horizontal distance may not exist. As noted above, Rollins and Meyer (2019) provide a simple rigorous definition of horizontal distance.

15. Level of significance (threshold) is a concept that contributes to many decision-making processes. While this discussion is far from an "end-all," two perspectives are considered – signal-to-noise ratio and ethics/consequences. One perspective is objective – numbers based – while the other is more subjective – values based. Both perspectives need to be considered when deciding "does gravity matter?" Realistically, some things (issues) are inconsequential—too small to make a difference—and some issues are irrelevant even if a statistical difference can be documented.

    Hypothesis testing is a well-developed concept (Ghilani 2006) and, given appropriate data, conclusions may be defended with statistical certainty. Example 2 in Chapter 15 of the 2nd Ed. (Burkholder 2018) provides "before" and "after" data for the position of a control point on the NMSU campus. The issue: "Was station BROMILOW replaced in its original location following its removal and replacement during reconstruction of the surrounding sidewalk?" Of course, the answer is "no." It is not physically possible to replace the tablet exactly where it was. But in a "spirited" discussion, the savvy construction manager finally asked me, "Can you prove that the monument was not replaced in its original location?" According to the data in the cited example, the monument was NOT replaced in the original location. Choosing a threshold of confidence is left to the reader but be warned that the construction manager will take issue with any suggestion that his crew did not do a good job.

    Another objective threshold example is found in the use of low-distortion projections (LDPs). When an elevated reference surface was designed by Professor Berry for the Michigan State Plane Coordinate System in 1964, it was deemed that a systematic error distance distortion up to 1:10,000 in the projection could be tolerated – that is, treated as random error. The use of theodolites and EDMI became commonplace in the 1970s and traverse misclosures of 1:20,000 or better became routine. The 1:10,000 threshold became obsolete. The solution was to compute and apply the distance distortion systematic error correction regardless of its magnitude. While the author successfully computed hundreds of miles of survey control on that system (Burkholder 1975 – page 7), the problem was that (some, not all) vendors and practitioners alike misused the system because they did not really understand the underlying geometry and design assumptions (Appendix C, Burkholder 1980). Since then, the threshold for distance distortion has continued to evolve with advances in measurement technology and computational capacity. Threshold trade-offs between random error and systematic error are discussed further in Burkholder (2020a & 2020b). The important consideration in this paper is to ask, “What are relevant threshold criteria for the impact of gravity on spatial data?”

Thresholds for reliable decision-making also involve subjective considerations such as ethics and consequences. Although many examples could be described, the following are offered to promote the view that exercising ethical professional judgement remains critical. Fundamentally the Hippocratic Oath “first do no harm” is applicable in many disciplines—not just medicine. The 2015 lead-in-the-water crisis in Flint, Michigan (Hanna-Attisha 2018), is informative due to the tragic consequences. The health of many children was compromised due to a plausible sequence of events that should not have happened. But the crisis occurred, and inevitable consequences were exacerbated by the callous reaction of bureaucrats and professionals at various levels who were more interested in “passing the buck” than solving the problem. Regretfully, even years later, the people of Flint continue to endure devastating consequences (Bosman 2020). Bosman notes that more than $87 million were spent replacing water pipes and that more than $600 million have been allocated for settling personal impact claims.

Remediation of a design flaw in the Citigroup Center building in New York City in the 1970s is another example of consequence-driven decisions. The case also involved significant objective criteria but the possible consequences of a major skyscraper collapse in midtown Manhattan drove a Herculean effort to re-enforce critical joints in the building ahead of an approaching hurricane (Vardaro 2013). In this case, disaster was adverted through the carefully coordinated response of responsible professionals and bureaucrats in various capacities. The Vardaro article does not document the overall costs of the retrofit but does note that the construction costs alone were over $8 million. The important point is that tragedy was adverted, albeit at significant costs (not paid by taxpayers). Compare that outcome with the cost to taxpayers of “passing the buck” in the Flint lead-in-the-water crisis. An internet search will lead to additional articles showing that decisions in the skyscraper example were not altogether altruistic.

Although still too early to draw legitimate comparisons, the two examples just cited pale in comparison to the devastating consequences of the current COVID-19 pandemic. Of course, many responsible persons all over the world are diligently working to mitigate pandemic consequences. Decisions at many levels are being made based on solid evidence while it appears that other decisions are driven by paranoia and fear of the unknown. Hindsight in the future will provide a better understanding of many lessons learned – some of which had to be learned the hard way.

16. Clarification – this article promotes using geodetic height for the third dimension in place of elevation. If implemented properly, the (conceptual/logistical/financial/computational) burden of geoid modeling can be mitigated by adopting the GSDM as a 3-D datum. It is hereby acknowledged that similar threshold arguments are associated with adoption of the GSDM in lieu of low-distortion projections (LDPs). Discussions of GSDM/LDP issues are included in a separate article (Burkholder 2020b). Irrespective of LDPs, both objective and subjective considerations need to be part of any decision criteria adopted to study the impact of gravity on policies, standards, specifications, and practices for geospatial data users.

> Decisions on gravity related issues need to be discussed and debated on various levels. In the meantime, benefits of adopting and using the GSDM instead of map projections can be realized independent of decisions related to geoid modeling. Modernization of the NSRS is an ambitious project by the NGS to replace the NAD 83 and NAVD 88 datums in the U.S. The target completion date of December 31, 2022 will not be met, and Smith (2020) explained some of the reasons for the delay. One of the options discussed by Smith (at time counter 0:50:00 +/-) included publishing the geometrical component of the project prior to completion of the more challenging part involving gravity – i.e., updating the vertical datum. The geometrical part of the modernization project will provide spatial data users the updated 3-D network which includes geodetic height. The vertical portion of the modernization is tied more closely to gravity and is important for scientific reasons. It seems prudent that geospatial data users be able to enjoy the geometrical update in a timely manner without being forced to wait for the "ultimate" solution.

Models

This article identifies a profound change in the way gravity data are used all over the world. The preceding paragraphs list both technical and value-based considerations (and thresholds) that should be part of any strategic decision-making process. This section considers the role of a model as a framework for decision-making. Note, selection of an appropriate model may be a prerequisite to other decisions. In that case, a traditional "feedback" loop and iteration may eventually be part of a solution.

Models have many applications and are used extensively to connect reality with an abstract representation of same. In the context of geospatial data, physical reality is the location of an object or feature, and the abstract representation of location is either plotted graphically or stored digitally in an electronic database—maybe both. Simple 3-D rectangular flat-Earth solid geometry relationships are universally understood and used worldwide. These are spatial data exclusive of gravity. Acknowledging significant intellectual investments in spatial reasoning (Egenhofer and Golledge 1998), this paper highlights a 3-D geospatial data model that accommodates the impact of gravity (Burkholder 2003). If, in the past, geospatial data have been considered a subset of spatial data, the view here—consistent with the FGDC Strategic Plan (FGDC 2020)—is that spatial data are a subset of geospatial data.

Discussions of "The Role of a Model" continue to be both informative and productive. A one-page flyer (Burkholder 2019c) includes 14 examples of how models are used in various disciplines. The summary also makes the case that the best model is simultaneously simple and adequate. Links to the flyer and separate arguments for adequate and simple include . . .

http://www.globalcogo.com/rolemodel.pdf
http://www.globalcogo.com/adequate.pdf
http://www.globalcogo.com/simple.pdf

With the advent of the digital revolution, both spatial and geospatial data are now characterized as digital and 3-D. Enormous increases in productivity have come about through development of workflows that standardize use of digital geospatial data. Regretfully adoption of an appropriate model for 3-D digital spatial data has not kept pace with other advances in technology. Resistance to "disruptive innovation" is understandable and, in the traditional view, geoid modeling is required to accommodate the impact of gravity. Although many may be reluctant to adopt an integrated 3-D spatial data model, it will eventually become a world standard – see "even temperament" in the following Example section. Although transition from the horizontal reference of latitude and longitude at station MEADES RANCH (origin for NAD 27) to the CM (origin for NAD 83) came about “naturally,” it is viewed as a far greater leap to make the transition from using sea level (the geoid) as the vertical reference to using the CM as the origin for 3-D data – i.e., “breaking the geoid modeling sound barrier.”

Populations worldwide are comfortable with the psychological concept of sea level as a vertical reference and that may never change. But, as illustrated by renaming the Sea Level Datum of 1929 to the National Geodetic Vertical Datum of 1929, zero elevation does not define “mean sea level” (Berry 1976). When the vertical network was readjusted and published as the North American Vertical Datum of 1988 (NAVD 88), the origin was taken to be the elevation of station Father Point/Rimouski, Quebec, Canada. That origin and associated published elevation were chosen because that elevation propagated throughout North America represented the minimum changes needed to move elevations from the NGVD 29 datum to NAVD 88 (Zilkosky, et.al., 1992). That reference elevation is an arbitrary number assigned to an elusive physical surface (the geoid) that requires significant resources (gravity data) to locate precisely nationwide. The CM is a better (more stable and reliable) starting point for height.

Examples

The thesis stated in the subtitle of this paper is that modern practice should use geodetic heights for the third dimension instead of elevation. The view being promoted herein is that corrections should be computed and applied to physical observations to make the data compatible with an integrated 3-D geospatial database having a single origin. Of course, the corrected observations are to be subjected to the same rigorous least squares 3-D network adjustment to insure compatibility with other stored values. The stochastic properties of the computational results are a by-product of an adjustment and stored along with computed coordinates in the associated geospatial database. Those stored data are “standard,” and the same rules of use (in this case solid geometry for geospatial data) are shared by all disciplines worldwide. That recommendation is consistent with procedures previously implemented in:

- Equation of Time
- Polar Motion
- Even Temperament in Piano Tuning

Restating, relative time can be measured with impressive precision – the success of GPS depends on it. One example of absolute time – used until the adoption of time zones (1883 in Canada and the US) – might be to reference all events in the day to the instant the sun crossed one’s local meridian (Howse 1980) and (Burkholder 2002). It was well known before 1883 that 24 hours in a day measured with a mechanical timing device (clock) was more consistent than the same interval defined as the time difference between successive passages of the sun at noon (sundial). The difference between solar time and civil time was designated the as the “equation-of-time.” Synchronized railroad schedules in the U.S. were a huge benefit of inventing time zones and adopting Standard Time. Although that standardization is used (very beneficially) by the general population, the equation-of-time remains available to those persons (surveyors, navigators, and astronomers) needing mean solar time (for observation of the sun) or ephemeris time (for observations of the stars). Within society, most people are oblivious to, and have no need for, the concept of equation-of-time.

Likewise, most people understand that the North Pole is 90° north of the Equator. But, the instantaneous spin axis of the Earth is not “stable” and the scientific community, without asking the general population, quietly adopted a mathematical position for the Conventional Terrestrial Pole (CTO) based on records of polar wandering for the years 1900 - 1905 (Leick 3rd Ed. 2004). The “instantaneous pole” moves in a circular pattern rarely exceeding 10 meters with a period of about 434 days known as the Chandler period. Polar motion corrections to GPS data and other celestial observations are applied routinely by the experts such that very few end users need to worry about the fact that Polar Motion even exists. But the corrections, known as Earth Orientation Parameters, are readily available to, and used by, those needing them (Wikipedia 2021b).

Even temperament is a solution to an issue that has plagued musicians since the time of Pythagoras. It is still an issue for those persons endowed with "perfect pitch." By and large, few persons are aware that C sharp and D flat on the musical scale do not have the same frequency – yet both are represented by the same key on the piano. Very briefly, the frequency doubles on the musical scale in an octave, "do" to "do." The ratio is 2:1. Other commonly known music frequency ratios are the fourth (4:3) and the fifth (3:2). Although pleasing harmonies are built on combinations of various intervals, it is impossible to preserve those ratios on a piano tuned to 12 even intervals in an octave. The compromise is "even temperament" and few audiences can detect or hear the subtle difference (Isacoff 2001, 2003). Again, the end user (listener) is largely unaware of the compromise that was centuries in the making.

Now, compare those procedures to geoid modeling where the geodetic height enjoys a universal mathematical definition while orthometric height (elevation) is ruled by gravity. If the value of gravity were perfectly known at all points, then the geoid height (difference between geodetic height and orthometric height) could be computed with great reliability at any location. That is not the case. Instead, diligent effort is made to model (by interpolation) the behavior of the geoid to obtain the best estimate possible. Progress has been impressive but ultimate precision in geoid modeling seems rather elusive. What is the appropriate threshold level for various geoid height applications?

Geoid modeling is needed to reconcile the impacts of gravity on location defined in an integrated model of 3-D digital geospatial data. GPS has been proven capable of obtaining excellent results for both geodetic heights and geodetic height differences. Those values are part of and compatible with the mathematical definition of 3-D digital geospatial data. Somehow, possibly due to the history of how we got to where we are, many still insist that orthometric height is the "end all" for elevation. That question deserves serious discussion and evaluation of thresholds (both objective and subjective). Really, there are very few cases, except for historical practice, in which an orthometric height must be used instead of geodetic height – remember, elevation is an "arbitrary" number. At the risk of making a ridiculous comparison, the way geoid modeling is currently done is analogous to requiring every person having a 12-noon appointment (for lunch) to obtain and apply the equation of time to a reading of civil time from their watch – the purpose being to assure compliance with an obsolete mandate – so they can eat lunch as the sun crosses the meridian. Using geodetic height for the third dimension represents far more efficient use of resources, talent, and professional services. As discussed in a subsequent "Summary" section, practice in the future should build on a stable reference (Earth's CM) and employ the strongest geometrical elements (*h* from GNSS) to obtain the most reliable solution.

A review of some counter arguments (there are others) includes. . .

1. Water must flow downhill. Granted, but except in very few cases, a slope computed from geodetic height differences can provide acceptable results. For critical cases in which a demanding threshold is required, corrections (e.g., using deflection-of-the-vertical) are still available. For example, is the beam of electrons in a super-conducting super collider (steered by magnetics) referenced to a geometrical plane or to a "level" surface?

2. Another view questions stake-out of highway grades or sewer lines. Yes, two options are possible – will the grade be established with respect to a horizontal plane line or to a level surface? The difference is minimal for short distances, but consistent practice will continue to reference grades reliably to level (eventually to the ellipsoid), not a horizontal plane.

3. Separate horizontal and vertical datums are required to accommodate two physical origins. The goal of staying true to the physical measurement environment is commendable but overshadowed by the convenience of computing and applying corrections so that both total station (plumb line based) and GNSS (normal based) measurements are compatible in subsequent 3-D computations.

4. Orthometric height differences have already proven inadequate in demanding applications where dynamic heights are needed to insure reliable results. Dynamic heights, such as used with the Great Lakes Datum, are still readily available to those persons needing same.

5. In years past, the flying height of an airplane could be inferred from barometric pressure readings (the altimeter). An altimeter reading is an independent physical measurement made in the aircraft with relative ease – no external data or processing is required. Although it provides an altitude relative to sea level (depending on pre-flight calibration), an altimeter reading lacks the resolution of GPS which enables tighter “packing” of airspace without compromising safety. According to a retired Boeing 777 pilot, current navigation practice includes layers of redundancy and utilizes the “best” of various technologies. If/when/as needed, safety can be assured by requiring greater separation between flight paths.

6. A counter argument for the following seems elusive. The geoid lies below the ellipsoid in the contiguous United States which means that negative geodetic heights are seen along the coastline. Imagine standing near the ocean on the dock with dry feet while your GNSS unit gives you a negative height reading. Although in practice sea level is not synonymous with a zero elevation, the mind-set of the public (correlating sea level with zero elevation) is well established. Accepting negative contour lines on a topo map will be a challenging obstacle to overcome – probably more challenging than the obstacle faced by mathematicians when encountering negative values for logarithms of trigonometric functions. In the past, logarithms (still mathematically legitimate) were used extensively in surveying traverse computations and values were kept positive by adding “10” to a negative logarithmic value. The historically tabulated value of log sine 45° in surveying texts is 9.849485002-10. Adding some constant to negative geodetic heights (to satisfy the public) could be the basis of an interesting “threshold” discussion.

Another Viewpoint

A separate recommendation to use geodetic heights rather than elevations was promoted by Kumar (2005a) in an article “When Ellipsoid Height Will do the Job, Why Look Elsewhere.” His arguments are more technical in nature and quite concise. Even though Kumar’s arguments have yet to achieve critical mass, his professional stature in the international geodetic community is evidenced by his service on the “WGS 84 Committee” of the Defense Mapping Agency from 1980 to 1987 and other engagements worldwide (Kumar 2005b).

Futuristic Considerations

In this era of change and technical obsolescence, thresholds for decision-making can be rather fluid. The goal in formulating the GSDM was to start with fundamental underlying principles and identify the most direct process for obtaining reliable answers. A secondary goal (really a consequence of the first) was to find an appropriate model immune to technological obsolescence – i.e., preserving the shelf life of the model. Even though additional technical advances and refinements (for everything digital) are on the horizon, fundamental underlying solid geometry concepts and error propagation procedures remain applicable for the foreseeable future.

1. The GSDM has two main components – the functional model of geometry/equations and the stochastic model of fundamental error propagation. Both components of the GSDM have withstood critical evaluation. Unless the laws of physics, geometry, or mathematics are changed, the GSDM will continue to provide a solid foundation for the geospatial data infrastructure.

2. Ultimately, there is no "absolute" as any discussion can be derailed by questions of "with respect to what?" or three successive questions of "why?" by an inquisitive 8-year-old. "Because I said so!" as a parent is not an acceptable answer in a technical inquiry. The definition of "absolute" needs to be clarified and improved.

3. Statement of the obvious. . . there is a difference between causation and correlation. Causation fulfills the logical conditions of "if and only if" and "necessary and sufficient." Correlation is enormously important, but allowances must be made for "the contrary can be shown." Thresholds become a critical element of such discussions and the "fluidity" of a given threshold deserves careful consideration.

4. Kleppner (2006) reported years ago that a portable atomic clock with an accuracy of 10^{-18} seconds could theoretically measure the geoid within 1 cm. Is this item relative or absolute? Does it matter? A more recent article (Mehlstäubler, et., al. 2018) reports on progress made in recent decades and notes the feasibility of "chronometric levelling" once portable atomic clocks become a reality. The National Institute of Science and Technology (NIST 2018) describes performance of an existing atomic clock whose stability was measured to a level of 3.2 parts in 10^{19}. The NIST article also notes the feasibility of using such a clock in relativistic geodesy to measure the geoid within 1 cm, even on different continents.

5. When discussing interpolation, it was suggested that GPS (or GNSS) signals could be observed worldwide simultaneously and the data processed (those are radial measurements) to adjust a deformable worldwide network of ECEF monuments yielding a solution strongest in the third dimension – i.e., geodetic height. Proving that hypothesis is beyond the scope of this article and/or the resources of this author. Many physical issues must be considered to do that – similar to the challenges being addressed in precise point positioning.

6. Exciting opportunities lie ahead for those devoted to finding the elusive geoid. One conjecture is that someday gravity may be found to be an integral part of a revised Standard Model of Particle Physics. In the meantime, the admitted goal of this article is to lobby for use of geodetic heights thereby relieving many geospatial data users from unneeded geoid modeling efforts.

Observations/Opinions/Questions

1. The existence of horizontal and vertical datums is a natural outgrowth of previous practice. A 3-D datum is seen as a logical application of recent technological developments. An analogy with horizontal vertical datums is that logarithms are no longer used in traverse computations because better and more efficient methods are now available.

2. Change for the sake of change is not a good argument. Neither is the converse – not changing because "<u>this</u> is how we do it."

3. Coordinates stored in a 3-D database should be developed using the most reliable practical processes from the physical observations to the published result. Given the ease of obtaining

geodetic heights, given the challenges of finding the geoid, given that the location of the geoid is less stable than the location of the CM, and given that local geodetic height differences closely approximate orthometric height differences, geodetic heights should be used for the third dimension.

4. The speed of light is determined by physical measurements and accepted as a constant worldwide. The Earth's CM is the origin of the ECEF reference system as determined by the International Earth Rotation Service (IERS 2013) based on Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR) data. The location of the CM was described earlier as 'fixed" because it defines the origin of the ECEF system. However, once coordinates for the surface stations are computed and published, it is more convenient to monitor relative changes by holding the coordinates of the world network fixed and computing "small" changes in the relative location of the CM – see Argus (2012). It appears that threshold considerations are applicable, and that the perspective for Earth's CM was switched "from the station to the train." In that case, Earth's CM does move.

5. Rhetorical question – will the stability of the geoid ever approach that of the speed of light or the Earth's CM? The presumed answer is "no" because 1) the geoid physically moves and 2) geoid modeling efforts lack sufficient data to achieve the desired resolution. Without doubt, current research efforts have provided great strides in understanding the impact of gravity on geospatial data applications. According to the ambitious goals of NGS as outlined by Smith (2020), the impact of gravity and implementation of a new vertical datum is tied to gravity measurements. One option Smith described (video time counter 0:50:00 +/-) is to publish the geometrical result of the adjustment and to follow-up later with subsequent refinements derived from additional gravity data. That might be a preferred alternative for many spatial data users. Gravity is a complicated phenomenon and NGS is to be commended for taking the time to "get it right." But must the spatial data user community continue to wait for the "ultimate" scientific solution? Smith (2020) noted early in his presentation that the scope of the modernization project continued to evolve due to advancing technology – pushing back the deadline for completion. Using geodetic height for the third dimension avoids the inconvenience of waiting for the gravity driven solution.

6. Smith (2020) did not address the following, but it goes to the heart of using geodetic heights for the third dimension. It appears that X/Y/Z coordinates for a given adjustment and the associated geoid model can provide excellent results. But inconsistencies arise when holding those X/Y/Z values and using a subsequent geoid model version to compute an orthometric height. The inconsistencies are illustrated in an example of determining the orthometric height of station REILLY on the NMSU campus from two First-Order bench marks, GPS vectors, and various geoid models. The orthometric heights of the two bench marks in the NGS database are unchanged from 2005 to 2020. The GPS vectors (used in all cases) included in the least squares adjustment of the small network were very consistent. NAD 83 (1992) X/Y/Z coordinates of station REILLY were used along with geoid models 03, 09, 12A, and 18. Separately, the NAD 83 (2011) X/Y/Z coordinates of station REILLY were used with the same geoid models. The computed orthometric height of station REILLY based on NAD 83 (1992) and Geoid03 provided an elevation of 1,190.498 m while the REILLY NAD 83 (2011) coordinates paired with Geoid12A provided an elevation of 1,190.497 m. The agreement of 0.001 m is quite impressive but the computed orthometric heights using the other geoid models (everything else being the same) varied from a low of 1,190.489 m to 1,190.500 m. The difference of 0.011 m would be more reasonable if the orthometric heights had been computed using only the modeled geoid height at station REILLY. However, the geoid height differences (supposedly more precise) were used in all cases. So, here is the question. . .once modernized NSRS values are published, does that mean the location of the geoid is fixed? If not,

the geospatial data user is better served using geodetic heights for the third dimension. The example cited above is documented at www.globalcogo.com/VariousGeoids.pdf. Admittedly, updated geoid models give different answers, but it remains to be shown that newer answers are "better."

Summary

Among others, the elements of equations 1, 2, and 3 are of primary importance to the geospatial data end user. Previously, elevation was arguably the most important of those three elements. However, with the measurement capability of digital technology coupled with computational and data storage procedures, geospatial data users in various disciplines worldwide can realize the benefits of working with geodetic heights in a single seamless system both locally and globally – hence, geodetic heights become primary.

Although the three equations express the same relationship, gravity is a driving force in the transition from using "elevation" to using "geodetic height." An overall description of the impact of the digital revolution on traditional practice could be called "disruptive innovation" (Burkholder 2015, 2020).

$$h = H + N \tag{1}$$
$$H = h - N \tag{2}$$
$$N = h - H \tag{3}$$

where h = geodetic height
H = orthometric height (elevation)
N = geoid height

Elements on the left side of each equation are determined (depending on the circumstance) by measurement or by computation. It is possible to "directly" measure:

- Geodetic height by GNSS or photogrammetry.
- Elevation by differential leveling from existing bench marks.
- Geoid height by satellite altimetry (over the oceans).

Or values on the left side of equations 1, 2, and 3 can be computed:

- Geodetic height is computed from elevation and geoid height.
- Elevation is computed from geodetic height and geoid height.
- Geoid height is computed from geodetic height and elevation.

Equations 1, 2, and 3 apply specifically to the geometrical geoid as determined from tide gage readings and extensive differential leveling. The equations also apply to the gravimetric geoid which is determined from gravity measurements. Theoretically, there is "one" geoid but there are two methods for locating the geoid. The geoid can be determined:

1. By direct computation using equation 3 at stations whose geodetic height and elevation are both known. The "GPS on Bench Marks" campaign is a concerted effort by NGS (2021b) to increase the number of known reliable geoid heights. https://www.ngs.noaa.gov/GPSonBM/index.shtml.

2. From gravity measurements using Stokes Integral (Eq. 2-163b – Heiskanen and Moritz 1967). The challenge is obtaining sufficient high-quality gravity data. NGS is using the GRAV-D program (NGS

2020b) to collect extensive gravity data to be used in developing the geoid model for the North American-Pacific Geopotential Datum of 2022 (NAPGD2022). https://geodesy.noaa.gov/GRAV-D/index.shtml.

Slope validation surveys have been conducted to document consistency between the two methods (NGS 2020c) - https://geodesy.noaa.gov/GEOID/GSVS/. The results show that airborne gravity data can be used to improve geoid heights as determined from existing bench mark elevations and GNSS data.

Challenges associated with developing a comprehensive geoid model for use on the 2022 datum are also described by Vonderohe (2019) in a summary document written for the Wisconsin Spatial Reference System Task Force. Written in a conversational mode, the document is both interesting and informative. https://www.sco.wisc.edu/wp-content/uploads/2019/05/new-2022-datums-short-book.pdf

Issues of logistics, spatial data accuracy, and (evolving) thresholds become important. If orthometric height continues to be used for elevations and if GNSS data are part of the observations, then geoid modeling will be an essential part of competent practice. Two important considerations are:

1. The location and stability of the geoid as a reference starting point.
2. The quality of geoid modeling.

Insomuch as values for the equation of time and polar motion are important for circumstances requiring their input, geoid heights remain essential in limited applications. A succession of geoid models in the United States includes Geoid90, Geoid93, Geoid96, Geoid99, Geoid03, Geoid09, Geoid12, Geoid12A, and Geoid18. But going forward, geospatial data users will be better served by geodetic heights because the geometry is “cleaner” and because Earth’s CM is more stable and more easily accessed than is the geoid.

Conclusions

1. The benefits of using a 3-D model for 3-D digital geospatial data warrant careful evaluation.

2. The impacts of gravity are important for geospatial data users and can be accommodated by computing and applying appropriate corrections. Procedures which preserve scientific principles and accommodate the impacts of gravity are applied to all X/Y/Z values prior to being stored in the geospatial database.

3. Geospatial data users all over the world can benefit from using the same database, the same solid geometry equations, and the same error propagation procedures to solve spatial data problems.

4. The use of geodetic height in place of elevation is demonstratively more efficient as being compatible with 3-D geospatial data computations worldwide.

5. There is a huge investment in established methods, processes, practices, and uses of orthometric height worldwide. The drawback is that the geoid is difficult to find and lacks desired stability. A carefully planned transition to use of geodetic heights in place of orthometric heights will allow current benefits to be realized without destroying backward compatibility to legacy data.

6. Scientific research into the nature and impact of gravity is very important and should be continued, if for no other reason than to investigate a possible role for gravity in the Standard Model of Particle Physics.

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This article is intended to be read, digested, and discussed by high-level professionals worldwide. Admittedly, the article was written from the perspective of the end user and attempts to show how geospatial data can be used more efficiently. As such, the article was formally submitted for review and possible publication. Yes, the article has been peer-reviewed but it was not accepted for publication because the focus of the article does not meet publication goals and objectives. I am deeply indebted to those involved in the editorial and review process and have improved the article based upon their feedback. The elected alternative is to post the article on the Global COGO, Inc. website and to file the article with the U.S. Copyright Office in Washington, D.C.

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