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Evolution of GIS: Learning from the Past—Looking to the Future

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Abstract

Since about 1970, Geographic Information Systems (GISs) have been implemented as a tool to organize spatial data related to locations on or near the surface of the Earth. As technology advanced, features of GISs evolved to accommodate measurement systems, data processing procedures, coordinate systems, and an expanding array of applications. Simultaneous advances involved numerous technological developments and policy decisions were made which were appropriate at the time. Given the current state of practice and visions for the future (including AI), certain practices should be reevaluated. This article draws on several (of many) resources which cover policy and practice options of the past, the present, and the future. Without being critical of how we got to where-we-are or where-we-are-going, it appears that the concept of "using a 3D model for 3D data" merits additional consideration. The convergence of abstraction, technology, policy, and practice underlies the definition of the 3-D global spatial data model (GSDM) based on the ECEF/ITRF and rules of solid geometry. The GSDM has been defined, is in place, and can beneficially serve the spatial data user community worldwide. Using 3D spatial data components obtained from observations and computing primary X/Y/Z locations in 3D space offers efficiencies and advantages over computing positions using traditional geodesy equations. Both local directions/distances and latitude/longitude/height can be computed directly from stored X/Y/Z coordinates.

Keywords

Digital Revolution, Spatial Data, 3D Space, Falsification, Geodesy, Flat-Earth, Map Projections

1. Introduction

1.1. Perspective

Given the digital revolution, this article looks at past and current spatial data practices in the context of what has come to be known as geographic information systems (GISs). Future implementations for spatial data continue to evolve as technological advancements find their way into established practices. This article examines the impact of starting with the assumption of a single origin for 3D data—Earth's center of mass (COM). Location is defined in terms of Earth-centered Earth-fixed (ECEF) coordinates—taken to be the spatial data primitive. Currently, map projections are firmly entrenched in the mindset of many GIS users and there is an enormous investment in the software tools used to process spatial data. Disruptive innovation based on the ECEF system provides a better choice for the future and leads directly to true geometrical representation of local directions and distances. The ECEF system is routinely employed by spatial data users such as SpaceX, NASA, the military, and others (things driverless). It has been said that the 7 most expensive words in the government are, "we do not do it that way." Many challenges lie ahead. It will take time, foresight, and visionary leadership for the GIS community to embrace and adopt more efficient processes.

1.2. Forward Looking

What lies ahead for (specifically end users of) geographic information systems (GISs)? The topic is huge and no attempt is made to provide a complete summary. But undeniably, progress has been truly remarkable with development of GIS concepts, technology, and end user applications during the past 50 years. Given the plethora of options constituting current spatial data workflows (from observations to final deliverable), future practice should continue to exploit benefits of the digital revolution. The goal expressed herein is to make the workflow more transparent and more efficient without sacrificing the integrity or quality of spatial data. In short, significant benefits can be achieved by using a "3D model for 3D data" which embodies rules of solid geometry common to all disciplines worldwide. Based on the ECEF system used globally, the 3D global spatial data model (GSDM) [1] fulfills those requirements and is already in place. The GSDM also provides a convenient common meeting place [2] for both generators and users of 3D digital spatial data. Simultaneously, the GSDM includes a stochastic model for handling spatial data accuracy uncertainties, whether large or small.

1.3. Additional Resources Cited in Support of the Stated Goal

- Hazelton [3], Part I, is an article describing the history and techniques of surveying practice—"The Surveying Revolution of 1550-1650: an Examination and Implications for the Current Geospatial Revolution. 11 pages.
- Hazelton [4], Part II, is an article drawing parallels between the past and current Geospatial Revolution surveying practice during the past, present, and fu-

ture—"The Surveying Revolution of 1550-1650: Implications for the Current Geospatial Revolution." 13 pages.

- Edited by Guo, H., Goodchild, M. F., Annoni, A. [5], *Manual of Digital Earth* is a comprehensive compilation of policies, methods, and practices related to the analog/digital revolution for spatial data. The manual is a huge resource for spatial data users in all disciplines worldwide. 846 pages.
- Goodchild, M. F. [6] is an article, "Reimagining the history of GIS" in which Goodchild summarizes the assumptions and decisions that went into development of GIS from the early days to the present. He states in the Introduction, "…this paper is intended to stimulate discussion, and to encourage others to reflect on how GIS has evolved and how it might have been different." 8 pages.
- Burkholder, E. F. [7] is an article in which the role of a geometrical model for 3D digital spatial data is highlighted in the context of various examples. Intended for peer review, this article was not accepted by three different journals. Given that those rejections did not falsify the content, the article was self-published by posting it on the Global COGO web site. 10 pages.

2. Summary of Traditional Spatial Data Models

A comprehensive discussion of traditional spatial data models would include definitions and descriptions of both raster and vector spatial data models. At the risk of not giving both models their due, this discussion acknowledges the unique advantages of both the topology of raster data and the geometry of vector data. Geometry is the focus of this thread which begins with consideration of 2 and 3-dimensional coordinate systems encountered in plane surveying and used extensively in GISs. The following features/issues are encountered in various spatial data applications.

- Local rectangular coordinates (generic $x/y/z$) are used in local flat-Earth surveying practice and provide a conceptual foundation for using 3D spatial data in a rectangular coordinate system. Survey plats show land parcels while infrastructure plans rely on plan/profile representations. A feature of a GIS is the ability to show various topics/features registered on separate map layers.
- In the bigger picture, the Earth is not flat. Location is defined with latitude/longitude for horizontal and elevation for vertical—necessitating the need for mixed units, curvilinear and length. The term "geospatial data" reflects the connection of spatial data to a curved Earth.
- Geography is a discipline which relies extensively on geographic location defined with latitude and longitude—typically on a spherical Earth. While a spherical approximation is acceptable for many applications; surveying, engineering, mapping, and other disciplines must accommodate the geometry of a flattened Earth—hence the important role of geodesy.
- Two categories of geodesy affect location differently. Geometrical geodesy references latitude and longitude to the ellipsoid while physical geodesy, concerned with gravity, describes the location of the geoid (sea level)—the refer-

ence for elevation. The result is disparate origins for the horizontal datum (Earth's center of mass) and the vertical datum (the geoid).

- Map projections are popular with spatial data users and used in many GISs because they enable latitude and longitude positions to be expressed with northing and easting plane coordinates. The disadvantage of a map projection is that a ground distance on the Earth is distorted when projected to a flat map. That disadvantage is mitigated by using a low-distortion projection (LDP). Regretfully, an LDP can cover only a limited area—necessitating multiple projections for larger areas. Additionally, map projection models are strictly 2D, while spatial data are 3D.

2.1. Hazelton's Surveying Revolution

When discussing the Surveying Revolution of 1550-1650, Hazelton [3] notes that surveying practice evolved from local practice to being global in scope. He discusses sociological and intellectual issues as part of "The European Renaissance" leading up to the Period of Enlightenment (beginning approximately with Isaac Newton, 1642-1727, and ending with the French Revolution in the 1790s). Developments related to surveying at the time include but are not limited to:

- Logarithms were invented by Burgi in 1607 and extended by Napier in 1614.
- In 1616 Rathbourne wrote a textbook "The Surveyor" in which he called for "'proper education of English surveyors…"
- Gunter's chain was invented by Edmund Gunter in 1620.
- The slide rule was developed about 1620 to perform calculations using logarithms.
- Ghetaldi developed algebraic geometry in 1630.
- Analytical geometry was developed in 1637 by Descartes and 1640 by Fermat.
- In 1665 Newton postulated that the Earth is oblate (flattened at the poles) and published his classic work on gravity, "*Principia*," in 1687.

Hazelton [4] is an interesting discussion of larger cultural and professional issues of which surveying is a part. It is not possible to capture the entire meaning of Hazelton's two articles, but he makes the following points in Part II.

- New technologies in surveying have quietly accelerated the rate of change being experienced in the Geospatial Revolution.
- But disruptive innovations are also responsible for the downfall of companies who "misread the tea leaves" as described by Christensen [8] in "The Innovator's Dilemma."
- While initial changes focused more on technology, measurement management has eclipsed those issues (author's comment—especially with the impact of AI).
- Professional practice and educational content will both benefit from an improved mindset.

Although many issues and technologies were included, it seems that more discussion of computational models would have been appropriate. Was geometry a foregone conclusion?

2.2. Relevant Developments Not Discussed by Hazelton

Hazelton's articles contain a lot of good information, and it would be unfair to criticize his work for not discussing coordinate systems. But, as noted in Section 2.0 above, reference systems provide context for spatial data. Reference systems used in GISs evolved from flat-Earth to geographical to 3D spatial, to geodetic, to state plane, to 3D geocentric. Although the flat-Earth view has been popular though the ages, Eratosthenes determined the size of the curved Earth within about 16% approximately 200 BCE. Since then, scientific observations and philosophical debate have contributed to a refined knowledge of Earth's size and shape. Of many sources related to the evolution of reference systems embodied in GISs, the following stand out:

- Results of two separate geodetic surveying expeditions, (one at a high latitude in Lapland, the other across the Equator in Peru), conclusively settled the debate whether the Earth is prolate (elongated at the poles) or oblate (flattened at the poles). Based on previous surveys, the Cassinis (French) insisted that the Earth is prolate while Newton (British) argued for an oblate Earth based on an analysis of forces—gravitational attraction and centrifugal force due to Earth's rotation. The Peru expedition left in 1735 and took 7 years while the Lapland expedition left in 1736 and returned in 1737. Smith [9] provides a fascinating account of the Peru expedition in his book, "From Plane to Spheroid: Determining the Figure of the Earth from 3000 BC to the 18th Century Lapland and Peruvian Survey Expeditions." He includes diagrams, figures, maps, and lists of observations. Newton was correct—the Earth is oblate.
- Fifty years later, the French embarked on another geodetic surveying expedition for the purpose of defining the meter as the standard of length, to be one ten-millionth of the distance along the meridian through Paris from the Equator to the Pole. Commencing in 1792 and collecting data for 7 years, the results of that expedition have influenced standards worldwide ever since. In writing "The Measure of All Things: The Seven-Year Odyssey and Hidden Error That Transformed the World," Adler [10] describes challenges of surveying through the countryside of France during the French Revolution. In addition to writing about the science that went into definition of the meter, Adler also describes the professional interaction of strong personalities, professional integrity, and consequences of the hidden error. With notable exceptions, the meter is currently used worldwide.
- State Plane Coordinates by Automatic Data Processing, Claire [11], provided the user community with algorithms for computing state plane coordinates on the NAD 27. This document was an early manifestation of the digital revolution for surveyors and others. State plane coordinates use map projections to bridge the gap between latitude/longitude (geodetic coordinates) and plane coordinates for local projects. Algorithms and software for computing state plane coordinates on subsequent datums are available from the National Geodetic Survey (NGS) [12].

- Since the mid-1980s, GPS and subsequently GNSS have become the workhorse for many surveyors and others using spatial data. The Earth-centered Earth-fixed (ECEF) coordinate system established by the US DoD is described in "Department of Defense World Geodetic System 1984: Its Definition and Relationships with Local Geodetic Coordinate Systems," NIMA [13]. More recently, the international scientific community observes and promulgates the International Terrestrial Reference Frame (ITRF) [14]—nearly identical with WGS84. NGS is using the ITRF in modernization of the National Spatial Reference System (NSRS) [15].
- The modernized NSRS includes 4 reference frames needed to reflect tectonic plate movements in North America. Information on the modernized state plane coordinate system (SPSC22) is available from NGS—The "Blueprint for the Modernized NSRS, Part 3: Working in the Modernized NSRS," [16].

The previous examples show a progression from flat-Earth to spherical Earth to refinement of Earth's size and shape to using spatial data in the context of the modernized NSRS. The talented dedicated professionals at NGS deserve credit for achieving this milestone. But, in the future, GIS users stand to benefit from working in 3D space, an improvement over working with 2D map projections.

3. Digital Earth-Present

The comprehensive Manual of Digital Earth [5] was written by more than 100 authors from 18 countries and published by the International Society for Digital Earth in 2020 to "support scientific development and societal needs." Interdisciplinary in scope, it includes overarching concepts relating to digital spatial data and in the Conclusion of Chapter 1 "…describes some of the key challenges and future needs for the development of Digital Earth over the coming years." It includes discussion of Geospatial Information (GI), Geospatial Information Infrastructure (GII), and Discrete Global Grids (DGG). Appropriate sections include GNSS and ITRF, but a word search failed to find information about the underlying geocentric ECEF global reference system or the solid geometry computational environment inherent in the ECEF system. It is stated in the Conclusion of Chapter 1, "As we look to the future, it is unlikely that a unified vision of Digital Earth will capture all perspectives of all stakeholders. A one-size-fits-all Digital Earth would not be appropriate for all nations and cultures." Without taking issue with those statements, a different conclusion might be reached if the abstraction process were to begin closer to the spatial data primitive. The 3D GSDM is based on the ECEF system used worldwide and accommodates both vector applications built on geometry/points and raster applications referenced to a DGG based on the same spatial data primitive.

Given that GISs continue to evolve, this article advocates improved policies and practices related to GIS applications. An important takeaway is that nothing found in the Manual of Digital Earth [5] falsifies the GSDM. It is left to others to discover if or how the GSDM might contribute to or support the goals set forth in that Manual.

4. Development of the 3D Global Spatial Data Model (GSDM)

4.1. Origin of 3D Concept

As with GIS, the GSDM did not have an instant birth but evolved over time. While the author was on sabbatical leave from the Oregon Institute of Technology (OIT) during 1990/91, studies at the University of Maine resulted in a paper [17] that contains the 3-D diagram illustrating the overall GSDM concept. Appendix III of that paper contains the results of a questionnaire sent to all 50 state DOTs in the late 1980s asking how they handled the grid/ground distance difference encountered due to incorporating GPS results into their workflow. Replies from 46 out of 50 state DOTs were very revealing and contributed to formulation of what became called the "3-D Global Spatial Data Model." The first version of that published paper [17] was presented (with a similar title—"Using GPS Results in a Coordinate System Designed for Transportation & Engineering Projects"), at the ASCE GPS '91 Specialty Conference, "Transportation Applications of GPS Positioning Strategy," in Sacramento, CA, in September 1991.

4.2. Formal Definition of the 3-D GSDM

In the early 1990s, the Southeastern Wisconsin Regional Planning Commission (SEWPC) wanted to find procedures by which transformations between NAD27/NAD 83 and NGVD29/NAVD88 datums might be improved. A suggestion to implement combined 3D transformations feeding into a 3D database was discussed but not pursued. Instead, two separate transformation reports (one for horizontal and one for vertical) were successfully completed. However, following publication of those two reports, SEWRPC commissioned a study to document design of a 3D transformation to be used with a 3D database. That report [18] published in 1997 contains the formal definition of the GSDM [1].

4.3. Functional Model and Stochastic Model

As defined, the GSDM includes a functional model component consisting of geometric geodesy equations that incorporate rules of solid geometry for computing geocentric ECEF coordinates. A rotation matrix is used to compute bi-directional conversions between geocentric coordinate differences ($\Delta X/\Delta Y/\Delta Z$) and local coordinate differences ($\Delta e/\Delta n/\Delta u$). The local coordinate differences are identical to "flat-Earth" differences used routinely in plane surveying. See video example [19].

The stochastic model component of the GSDM is optional and based on a covariance matrix associated with the $X/Y/Z$ coordinates of each point. If no covariance data are included, the stored $X/Y/Z$ values are used as exact. If standard deviations of observations are included and the errors propagated through subsequent computations, the standard deviations of derived values, directions, distances, area etc., are readily available. The stochastic model portion of the GSDM enables the user to manage the quality of spatial information. Applying a numeric filter to data drawn from a 3D database is efficient and adds confidence to decisions related to tolerances based solely on meta data. Additional information on the stochastic model can be found in Burkholder [20]. All equations for both functional and stochastic components of the GSDM are in the public domain.

4.4. Computations and Example Projects

In addition to numerous papers (available via web search) describing use of the GSDM, two Editions of the book, "The 3-D Global Spatial Data Model (GSDM)" [21] [22] were published by CRC Press. In particular, Chapter 15 of the 2nd Edition contains detailed descriptions of 12 different projects computed using the GSDM [23]. One of those projects is a popular 2D example showing steps for using 3D GPS data to compute a USPLSS breakdown of Section 31, T23S-R1E, NM Principal Meridian.

Another computational project [24], presented at the Surveying and Geomatics Educators Society (SaGES) conference in Corvallis, Oregon in 2017 (but not included in the 2nd Edition) includes the algorithm and detailed computations for network and local accuracies. That project dramatically illustrates the impact of correlations when computing the standard deviation of an inverse distance between two points which were not connected via direct observation.

5. Historical Perspective

Considering spatial data, valuable lessons can be learned from past experiences. Goodchild [5] writes from the perspective of a professional leader having a front row seat to the evolution of practices fostered by the digital revolution. Interestingly, Hazelton [3] [4] also writes about the impact of the digital revolution, but from a somewhat different perspective. While Goodchild writes from a geographical perspective (raster mantra) and promotes use of the DGG, Hazelton writes about the impact of the digital revolution from a surveying perspective (vector mantra). Those two perspectives are not mutually exclusive as both can be traced to a common spatial data primitive.

Perhaps more telling, Goodchild notes that GIS policies were developed on the assumption of "truth" being derived from a map with a focus on building "layers" of information. Another alternative promoted by Goodchild would be to rely on the globe as the basis of "truth." Some attributes and uses of digital spatial data can be "harvested" more readily under the globe assumption. It is an oversimplification to categorize those differences as "vector" versus "raster," but Goodchild devotes an entire section of [5] on "Maps and Globes" and articulates a balanced overview of the two.

6. Looking Ahead

Goodchild's article [5] ends with speculation that current GIS practices could have been "very different." His concluding paragraph states:

It does indeed seem that GIS practice today is to some degree limited by the legacy of the past; and that interesting and viable alternatives exist to some aspects of GIS practice. Instead of a single, authoritative source of data that we could treat *as the truth, we would be motivated to find ways of accommodating the many sources of the same geographic facts that are now available, and integrating them in ways that reflect their various properties and uncertainties. If we were to wipe the slate clean and reinvent GIS today with today's computing power and visualization capabilities, the result might have been very different.*

Given that the evolution is on-going, this article highlights a third option in addition to "maps" and "globes,"—performing computations in 3D space and basing "truth" on ECEF values stored in a 3D database. ECEF coordinates are closer to the spatial data primitive and support multiple applications in spatial data disciplines worldwide. The 3D GSDM [1] describes the foundation of the global spatial data infrastructure and can be implemented by GIS users. However, using the GSDM is not limited to GIS, but will find application in other areas as well Burkholder [7]. It is left to others to identify beneficial uses and to take advantage of the efficiencies afforded by using the GSDM.

7. Circumstances

Helpful clarifications include:

- The ECEF system was developed as part of the space program and is maintained as the WGS84 by the U. S. DoD. The international community [13] subsequently developed an independent system for observing satellite signals. The computed result is known as the ITRF and is used by spatial data disciplines worldwide.
- The 3D GSDM [1] was defined in 1997 in a paper filed with the U. S. Copyright Office. All equations and procedures listed as a part of the GSDM are in the public domain. Other than acknowledging the definition, there are no restrictions on use of the term "GSDM."
- The GSDM is integral with the ECEF system but not unique to GIS. The ECEF system is routinely used in many other spatial data applications—examples include (but not limited to):
  - The U. S. military for navigation, targeting, collision avoidance etc.
  - Commercial navigation for aircraft, missiles, drones, and driverless vehicles.
  - Returning a rocket booster to the launch pad, e.g. SpaceX.
  - Documenting Sea Level Rise and Land Subsidence etc.
  - Other engineering applications.
- Unique coordinates are important to GIS users. The underlying X/Y/Z coordinates used by the GSDM are unique worldwide and are the basis for mapping and computation of local geometrical elements—distances, directions, area, volume etc.
- The P. O. B. Datum option of the GSDM allows the user to select a local origin and supports plane surveying activities of all points related to the chosen P. O. B. This allows for convenient computation of local horizontal distances without distortion.
- Goodchild [5] emphasizes the importance of spatial data uncertainty. The sto-

chastic component of the GSDM handles spatial data uncertainty with aplomb—see Burkholder [20].

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Conflicts of Interest

Subject to intellectual property issues, the author declares no conflicts of interest regarding the publication of this paper.

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