Journal of Geographic Information System, 2026, 18(5), 237-247
https://www.scirp.org/journal/jgis
ISSN Online: 2151-1969
ISSN Print: 2151-1950

Reconciling the Difference between Global and Flat-Earth Perspectives for Spatial Data

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How to cite this paper: Burkholder, E.F. (2026) Reconciling the Difference between Global and Flat-Earth Perspectives for Spatial Data. *Journal of Geographic Information System*, **18**, 237-247.
https://doi.org/10.4236/jgis.2026.185013

Received: August 14, 2026
Accepted: September 15, 2026
Published: September 18, 2026

Abstract

As science matures, over-arching concepts emerge that simplify the subject. Such simplification fosters increased efficiency and practicality. Regarding spatial data, rules of solid geometry are long-standing and used in many applications. A consequence of the digital revolution is that procedures for working with flat-Earth spatial data need to be reconciled with higher-level geodetic applications of geospatial data. A simple model embodies flat-Earth assumptions while more rigorous mathematical expressions are needed to represent location with respect to the ellipsoidal Earth. The 3D global spatial data model (GSDM) is an over-arching concept which reconciles those perspectives by utilizing 3D space for computations. The GSDM is a practical solution which serves the needs of flat-Earth spatial data end users without sacrificing the rigor of geospatial data.

Keywords

Spatial/Geospatial Data, Plane Surveying, Geodetic Surveying, Electronic Distance Measurement (EDM), Conformal Mapping, Low-Distortion Projections (LDPs), Earth-Centered Earth-Fixed (ECEF), Distance Distortion, Global Spatial Data Model (GSDM)

1. Introduction

1.1. Adequate and Simple

Models are used to connect human understanding with physical reality. To the extent possible, an appropriate model for spatial data will be both adequate and simple. When selecting a model, the balance between simple criteria and rigorous criteria needs to be evaluated and justified. The global spatial data model (GSDM) described herein is an over-arching concept which incorporates the geodetic rigor of 3D digital spatial data into a local "flat-Earth" environment without sacrificing geometrical integrity. Spawned by the digital revolution; instrumentation, measurements, data storage, information processing, and spatial data applications have blossomed but updates to the underlying spatial data model have not kept pace. Although spatial data are 3D, traditional practice continues to rely on separate horizontal and vertical datums while many spatial data users routinely base their work on 3D Earth-centered, Earth-fixed (ECEF) coordinates. In time, practices based on a common "3D model for 3D data" will be more widely adopted—especially as artificial intelligence (AI) concepts are incorporated into spatial data applications. Viewed as compatible with emerging trends, this article highlights feature of the GSDM which supports practical spatial data applications.

1.2. Scope

Given the broad scope of spatial data, limits are needed to focus this discussion. First, the Earth-centered Earth-fixed (ECEF) reference frame [1] is taken to be the spatial data primitive. Abstraction describes the process of using rules of solid geometry to define the workflow from ECEF coordinates to local flat-Earth directions and distances. That process is encapsulated by the global spatial data model (GDSM) [2] which includes geometry in the functional model and spatial data uncertainty in the stochastic model. Applications worldwide include using ECEF coordinates to solve complex problems, to conduct military activities, to monitor driverless robots, and to map the physical environment. While many such operations are also covered by the GSDM, this article emphasizes a workflow that avoids conformal mapping and associated distance distortions.

2. Workflow

Efficiency and productivity are non-exclusive hallmarks of any well-run business/organization - other factors contribute as well. However, if methods and process are not regularly monitored and updated, efficiency and productivity will suffer—which can lead to an eventual breakdown of morale and prosperity.

2.1. Datums Are the Foundation

Modernization of the National Spatial Reference System (NSRS) [3] by the National Geodetic Survey (NGS) is nearing completion. The NSRS includes a rigorous definition of a 3D datum as well as separately defined horizontal and vertical datums. The GSDM can be used on the existing NAD83 datum and should perform equally well on the new modernized datum. A caveat is that when basing work on ECEF coordinates, the user should also identify the epoch for all values—being careful not to mix ECEF values from one epoch with ECEF values from another epoch. NGS has software available for moving X/Y/Z coordinate values from one epoch to another [4].

2.2. Evolution of Networks

Historically geodetic networks were computed using geodetic equations based on latitude, longitude, and ellipsoid height. Geocentric X/Y/Z coordinates (ECEF values) were computed after the adjustment was completed. The national CORS network was readjusted in 2011 [5] to improve the NSRS and to align "the GNSS passive control with active control." A notable feature of this adjustment is that the adjustment was performed in terms of the ECEF reference frame and enjoyed the benefits of it being a linear adjustment. Testing showed that identical results were obtained from the traditional geodetic adjustments and the ECEF adjustment. The current NSRS modernization effort has benefitted from lessons learned in the 2011 adjustment.

2.3. Algorithm for Distortion Free Distances

Acknowledging parallel applications in other high-level projects utilizing ECEF reference frames [6] [7], the following workflow lists procedures for obtaining local distortion free distances in contrast to state plane coordinate distances based on conformal mapping. Vertical issues are not ignored but the focus herein is on horizontal distance and avoiding distance distortion.

- A diagram [8] of relationships between measurements and coordinate systems is helpful.
- Algorithms for use with the 3D diagram are listed in Equations (1) through (35) of [2].
- Given ECEF coordinates, differences are computed as $\Delta X = X_2 - X_1$, $\Delta Y = Y_2 - Y_1$, $\Delta Z = Z_2 - Z_1$.
- These geocentric components define a vector in 3D space anchored at the standpoint.
- A rotation matrix [9] is used to obtain the local perspective components of the same vector.
- An animation video illustrating use of a rotation matrix is provided by David Knopp [10]. Successive use of the rotation matrix yields a collection of plane surveying coordinate points in the tangent plane centered on the user-selected Point-of-Beginning (P.O.B.). As shown in the Knopp video, these spatial data are compatible with standard coordinate geometry routines used in plane surveying.
- Given any two points (A & B) selected by the user, the flat-Earth undistorted tangent plane horizontal distance between them is computed as: $HD = \sqrt{\left[\left(e_B - e_A\right)^2 + \left(n_B - n_A\right)^2\right]}$.
- If the distance distortion between points exceeds legitimate flat-Earth assumptions, other horizontal distance options can be computed at described in [11].
- The "u" component of a local vector is the perpendicular distance from the tangent plane to the forepoint. The impact of flat-Earth assumptions can be seen by comparing the "u" component with the curved earth vertical distance point-to-point computed as the difference in ellipsoid heights of the end points, $h_B - h_A$.

3. Trade-Offs

A balance between conflicting criteria involves trade-offs. Acknowledging a diversity of viewpoints within the spatial data community, the instant goal is to show how the GSDM offers significant benefits to the expanding community of spatial data users. The primary trade-off discussed herein includes combining features of the simple flat-Earth model (used in plane surveying) with more rigorous models required to express a position worldwide with geometrical clarity (geodetic surveying). The GSDM is a practical choice because plane surveying concepts are retained for local applications while the geometrical integrity of ECEF coordinates is simultaneously preserved without distorting distances. For azimuths, the GSDM allows the user to choose the point from which true azimuths are referenced or (optionally) to use the true azimuth for each line in the survey or project.

4. Precedents

If a model is not adequate, simplicity is often sacrificed to achieve a better solution. Examples:

4.1. Measurements with Steel Tapes

Steel tapes are commonly used to measure horizontal distance. Depending on the accuracy required, the observed value needs to be modified. A simple observation may be modified by applying (not so simple) taping corrections. Not stopping there, electronic distance measurements (EDM) now provide push-button simplicity to the end user while details of more rigorous underlying models (e.g., signal propagation) are left to others.

4.2. Parallel Plumb Lines

Plane surveying is prefaced on the assumption that plumb lines are parallel. Without downplaying the importance of plane surveying, a consequence of the digital revolution is that digital data are 3D—placing them in the realm of geodesy and cartography. Conformal map projections have been implemented to enable plane surveyors to utilize geodetic data locally for making plane maps. Simplicity was sacrificed in favor of a more rigorous model.

Both examples (taping and plane surveying) are simple and long standing. But taping corrections and map projections are examples of using a more rigorous model to obtain an acceptable answer. Understandably, certain approximations are encountered in each case, and it is the responsibility of practicing professionals to understand possible consequences of using the wrong equation or procedure. Although the merits of professional responsibility and accountability could be discussed ad infinitum, this article strives to improve professional practice by identifying the global spatial data model (GSDM) as an over-arching concept which, among others, can replace approximations and complexity associated with the conformal mapping model.

5. Underlying Concepts

An overview of underlying concepts helps improve clarity of the "big picture."

5.1. Spatial Data and Geospatial Data

Spatial data are used to represent the relative location of points with respect to each other. Geospatial data are spatial data that are referenced to the Earth. In the mathematical sense, geospatial data are a subcategory of spatial data but from a cartographic application perspective, spatial data are a subcategory of geospatial data. Sometimes, the terms are used interchangeably. Adjudicating differing views on the spatial/geospatial hierarchy is left to the academicians.

5.2. Right-Handed Consistency

The ECEF system of rectangular X/Y/Z coordinates utilizes the right-handed system. The X and Y axes lie in the plane of the Equator while the Z axis is parallel with Earth's spin axis. When rotating a geocentric vector to the local perspective, the derived flat-Earth values are listed as east/north/up to be consistent with the right-handed convention.

5.3. Conformal Mapping Model

Even before the advent of EDM, photogrammetry, computers, GPS/GNSS, scanning, plotters, and AI (all driven by the digital revolution); users dreamed of making it possible for local plane surveying practice to enjoy benefits that could be realized by tying local surveys to the national geodetic control network of latitude/longitude positions. To that end, the state plane coordinate system (SPCS) was rolled out in 1933. Simplicity was maintained in that plane surveying procedures could still be used on local projects. Conformal mapping projections made it possible to bridge the gap between geodetic latitude/longitude positions and plane coordinates.

5.4. Limitations of Conformal Mapping

A map projection is strictly a 2D model. Spatial data are digital and 3D. Prior to the digital revolution, prudent practice included adoption of the map projection model for surveying, engineering, and mapping. To the credit of many, the SPCSs have been used extensively in the USA for nearly 100 years. What about disruptive innovation? On one hand, "If it isn't broke, don't fix it." On the other hand, an over-arching model that mitigates undesirable issues associated with the SPCS deserves careful consideration. Although the legacy value of existing map projection coordinates will continue indefinitely, issues associated with the status quo include:

- It is impossible to project a curved surface to a flat map without distortion.
- The original SPCSs were designed with a grid scale distortion limit of 1:10,000. (Presumably, land surveys could absorb that distortion without detrimental consequences.)

- The elevation of the line being projected was omitted, necessitating an "elevation factor."
- The product of the grid scale factor and the elevation factor is used as the "combined factor."
- If the distortion is not acceptable, the combined factor can be used to get a better answer.
- Because the combined factor changes slowly, a correction may unwittingly be defective.
- When using total station data, defective SPCs will result if distortion is not modeled correctly.
- Defective ground distance will result if distortion is ignored when computing from SPCS data.
- The meter is the standard length unit. Some use the international foot or the U.S. survey foot.
- Bi-directional equations for conformal mapping transformations are dictated by the Cauchy-Riemann differential equations. The geometrical integrity of all SPCS software is critical.
- SPCSs embody three projection types; Lambert, transverse Mercator, and oblique Mercator.
- Azimuths are referenced to the central meridian of a zone. Convergence can be quite large.
- The definition of horizontal distance is ambiguous unless tied to ellipsoid height. Is horizontal distance the right triangle component of a slope distance or defined by another assumption?
- False northings/eastings are chosen to avoid possible coordinate duplication.

As described in the Workflow section, the GSDM addresses those issues by defining a direct efficient workflow process starting with the ECEF values in a 3D database and computing local directions and distances needed by GIS and other users [12]. Page 3 of [13] shows a comparison of GSDM results and LDP results. The integrity of an LDP computation can be checked against the GSDM standard.

6. Abstraction Leads to the GSDM

The digital revolution drives convergence of abstraction/technology/policy/practice leading to disruptive innovation as new methods are evaluated and implemented.

6.1. Basis for Logical Process

Perhaps no component of the digital revolution has had more impact on the use of spatial data than the ECEF coordinate system developed in conjunction with the U.S. space program. Prior to the ECEF, the national geodetic control network consisted of separate horizontal and vertical datums. That made perfect sense because horizontal is referenced to latitude/longitude and vertical is referenced to the geoid (sea level)—two different origins. Although the ECEF has matured as a unified 3D datum, horizontal and vertical datums continue to be used in the United States—even with modernization of the National Spatial Reference System (NSRS) [3].

6.2. GSDM Serves Both Generators and Users

With the ECEF values taken to be the spatial data primitive and reliable local directions and distances being the goal, the GSDM serves the spatial data community by formalizing spatial data computations in 3D space and providing a better bridge between ECEF coordinates and local applications in surveying, engineering, mapping, and GIS. As such, the 3D database associated with the GSDM provides a convenient common [14] exchange point equally accessible to generators of spatial data and users of spatial data.

Although some people are competent as both generators and users of spatial data, there are many details of concern to generators of spatial data (e.g., signal processing) that may be irrelevant to users of spatial data (e.g., GIS and land surveying). The reverse is also true. Even so, the convenience and benefits of a common meeting place are to be exploited. Of course, other relevant details include whether operations are static or dynamic and whether the spatial data under consideration are associated with more than one epoch.

6.3. Resources

Details of the GSDM are included in two books by the author and published by CRC Press.

- The 3-D Global Spatial Data Mode: Foundation of the Spatial Data Infrastructure [15].
- The 3D Global Spatial Data Model: Principles and Applications, 2nd Ed. [16].

Additional material related to the GSDM can be found posted by the author at:

- Web site developed by Global COGO, Inc. as a resource for users [17].
- True 3D vs pseudo 3D (and using a 3D model for 3D data) are discussed here [18].

Recently published peer-reviewed articles by the author show how the GSDM provides an alternative to conformal mapping include:

- Burkholder, E.F., 2026, “History of GIS: Learning from the Past—Looking to the Future,” [19].
- Burkholder, E.F., 2026, “GIS Distances and Directions Directly via the GSDM,” [12].
- Burkholder, E.F., 2026, “Evolving Spatial Data Practice Reduces the Need for Conformal Mapping,” [20].

7. Applications Based on the GSDM

The following projects and applications were facilitated using the GSDM.

- A 2006 student project involved a breakdown of Section 31, T23S-R1E, NM

Principal Meridian using GPS and the GSDM [21]. That project also demonstrates how local directions and distances can be determined directly from ECEF coordinates without distortion [13]. Additional details and insight are included in three peer-reviewed articles published in 2026 [12] [19] [20].

- This item was another class project to survey a portion of the NM Principal Meridian between the NM Initial Point and the SW Corner of Section 31, T23S-R1E, NMPM. Two issues are highlighted: 1) the different definitions for horizontal distance that could be selected and 2) that the GSDM can be used to compute coordinates at "user selected" ellipsoid heights, for example—for computing a chord distance on the ellipsoid [22].
- Using the GSDM is not restricted to GNSS data. This project involved using horizontal and vertical angles to position a remote target (the finial of Skeen Hall on the NMSU campus) from known ECEF control points in the area [23]. A traditional solution is more challenging.
- Based upon side-shot observations, this computational exercise involves comparing three methods of determining a location on the top of the Associate Engineering Dean's desk at NMSU. The GSDM is preferred as the most "direct" method [24].
- It is "easy" to traverse on paper using the GSDM. This example shows establishing local coordinates on a true parallel of latitude (pertinent in the US Public Land Survey System) [25].
- State plane, and other map projection systems can do an excellent job of horizontal location near the surface. But underground positioning involves exaggerated vertical locations—not suitable for a 2D model. This article explores options for 3D underground positioning [26].
- Astronomers at an observatory in Arizona were concerned that a planned radar facility for weather forecasting might "pollute" the atmosphere with radiation. The imperative was that the radar facility should be in the shadow of an intermediate mountain. Based upon a GPS network of control points in the region and observations at the observatory, on the top of an intervening mountain, and data collected on-site, it was possible to compute the height of the shadow (on location) as cast by the intervening mountain. An account of the project was written up for the Professional Surveyor magazine by the

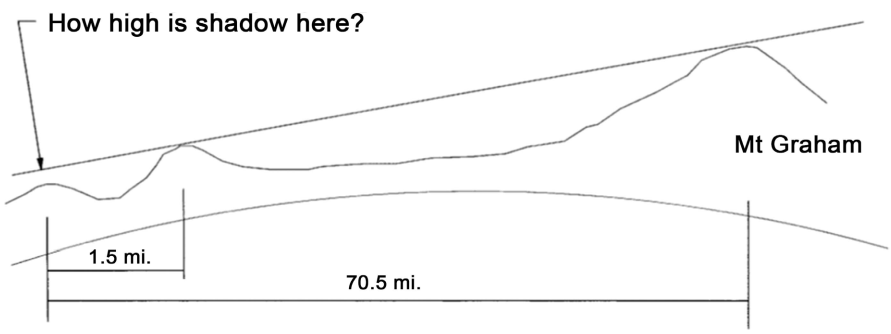

Figure 1. How high is the shadow cast at the NEXRAD site by the intermediate mountain?

collaborators on the project [27]. As explained in the article, the shadow height was computed as the perpendicular off set from the line originating at the observatory and touching the top of the intervening mountain. That answer was confirmed by a line-line intersection of the normal from the proposed site and the line from the observatory to the intervening mountain (**Figure 1**).

- Part of the boundary between New Mexico and Texas is defined by the Rio Grande River. Disagreement of the boundary location between New Mexico and Texas was settled by a survey performed in 1929 under the jurisdiction of the U.S. Supreme Court—monumented and published in 1930. GPS observations in 2005 were the basis of comparison of current physical monument locations and the record locations defined by the Supreme Court [28].
- Station REILLY on the NMSU Campus is a HARN station with precise ECEF coordinate values. Prior to this project, there was no "precise" leveling to the station. The NAVD88 elevation on the station was determined with a carefully observed GPS survey and documented in the associated article [29].
- This item shows that spherical excess is easily computed using features of the GSDM [30].
- A rotation matrix makes it easy to compute a geodetic line azimuth from any point to any other point. It could be particularly helpful for computing the azimuth to Mecca [31].

8. Conclusions

Of the many possible conclusions that could be drawn from this article, the following stand out.

- The GSDM provides an over-arching model that serves a wide range of applications.
- 3D spatial data computations avoid distance distortions found in conformal mapping.
- GSDM equations are in the public domain and less complicated than geodetic equations.
- Spatial data users in various disciplines already utilize working in the ECEF environment.
- Evolution of practice will converge on using a common exchange 3D database for spatial data generators and spatial data users.

Acknowledgements

The suggestions from anonymous reviewers are acknowledged and greatly appreciated.

Data and Materials Availability

All relevant data needed for analysis are embedded in the main text or in the references.

Conflicts of Interest

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

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