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Evolving Spatial Data Practice Reduces the Need for Conformal Mapping

Earl F Burkholder*

President – Global COGO, Inc., Las Cruces, NM 88003 USA

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***Corresponding author:** Earl F Burkholder, President – Global COGO, Inc., Las Cruces, NM 88003 USA

Abstract

A conformal map projection is used as the basis for computing plane coordinates based on latitude and longitude locations on the Earth. While it is impossible to project a curved surface to a flat map without distortion, a conformal projection preserves the value of an angle as measured on the Earth to its equivalent representation on the map. But distances are distorted. Map projection parameters are selected such that distance distortions within a map zone are controlled within some specified limit.

Driven by the digital revolution, spatial data are now digital and 3D. That said, it seems that many are now "using a 3D model for 3D data." Adopting a 3D model means that spatial data computations can be performed in 3D space, essentially replacing traditional horizontal and vertical datums with a 3D datum. Computations are less complicated in the solid geometry environment and geometrical integrity can be more easily preserved. While distance distortion cannot be avoided when using a conformal projection, local distances and directions can be computed in 3D space without distortion.

Keywords: Earth-centered Earth-fixed; Global Spatial Data Model; Geographic Information System; Mercator Map; Conformal Mapping; Distance Distortion

Abbreviations: 2D: 2-dimensional spatial/geospatial data; 3D: 3-dimensional spatial/geospatial data, AI: Artificial intelligence; ECEF: Earth-centered Earth-fixed; EDMI: Electronic distance measuring instrument; FGCS: Federal Geodetic Control Subcommittee; GIS : Geographic information system; GSDM: Global Spatial Data Model; JGIS : Journal of Geographic Information Systems; NAD1927: North American Datum of 1927; NAD1983: North American Datum of 1983; NAD2022: North American Datum of 2022; NGS: National Geodetic Survey; NSRS: National Spatial Reference System; SPCS: State plane coordinate system

Introduction

Spatial data describe the location of points and objects worldwide. The human perspective is that the world is flat and locations are described locally in terms of rectangular right-handed x/y/z (or e/n/u) coordinates. Globally, the world is nearly spherical, and location is described in terms of latitude, longitude, and elevation. Latitude and longitude are expressed in angular units of degrees, minutes, and seconds while elevation is expressed in length units. Simplicity being a goal, that mixture of units and the Earth being flattened at the poles complicates big picture (geodetic) computations.

That mixture of units also means that separate origins are needed – horizontal uses latitude and longitude, referenced to the ellipsoid while vertical is referenced to the geoid (sea level). Therefore, a horizontal datum is used for making 2D maps while a vertical datum is used to depict elevations, contours, grades and profiles. Given that spatial data are digital and 3D, modern practice is evolving to use of a 3D model for 3D data. As described herein, performing spatial data computations using rules of solid geometry in a 3D datum can be more efficient than using separate horizontal and vertical datums. More importantly, distance distortions on a map can be avoided and conformal mapping procedures are no longer needed.

Current Practice

Conceptually, models provide a connection between reality and visualization – one is real world and the other exists in the mind, is depicted on a set of plans, or is stored electronically. The best model is simultaneously adequate and simple. For example, a flat-Earth model is simple and used extensively for local spatial data applications. But the flat-Earth model lacks the rigor needed for representing the curved Earth. That is the difference between plane surveying and geodetic surveying. Geodetic equations faithfully represent locations with respect to the curved Earth, but geodesy equations are more complicated than the equations used in plane surveying. State plane coordinate systems (SPCSs) are an example of adopting a compromise model that incorporates the rigor of geodetic surveying into local plane surveying practice. "Controlled" distance distortion is part of the trade-off and SPCSs have been used successfully in the United States since 1933.

Cartography and map projections

Cartography has an illustrious history of graphical communication – map projections being a part. Of the many types of map projections, a conformal projection preserves the value of an angle on the ground to its representation on the map. But it is impossible to project a curved surface to a flat map without distorting something. A conformal map projection distorts distances. If the area covered by the map projection zone is sufficiently small, the distance distortion can be controlled within an acceptable level. The saving grace is that, if the distortion is too large, a correction can be computed and applied to account for the distance distortion.

In the 1930s, a distortion limit of 1;10,000 was selected for the original SPCS zones. For (transit/tape) surveys of nominal accuracy, it seemed that a systematic error distortion up to 1:10,000 could be absorbed without detrimental consequences. With the advent of electronic distance measuring instruments (EDMI), enhanced computing capability, and factoring in the impact of elevation, it became apparent that the 1:10,000 criterion needed to be revisited. A re-evaluation led to adoption of low-distortion projections (LDPs) in which the mapping surface is much closer to actual ground level. A further refinement of the trade-off is possible if an LDP zone is adopted that covers a smaller geographic area. Of course, that means more zones are needed to cover a given area (such as a state).

The Mercator map

Gerard Mercator (1512 to 1594) published his world map in 1569. Intended for navigation at sea, the unique spacing of parallels of latitude on his world map enabled a ship captain to sail a constant bearing port-to-port. Prior practice involved sailing across the ocean at a constant latitude. Mercator's choice of parallel spacing became known as a conformal map and is mathematically defined by the Cauchy-Riemann differential equations.

Used for sailing port-to-port, another feature of a Mercator map is that an angle on the Earth is transformed without distortion to the map. A corollary is that the scale at any point on the map is the same in all directions (but it can change from point to point). Consequently, conformal map projections have been used for the SPCSs in the United States since 1933 for the following projection types.

- Transverse Mercator projection
- Lambert conic conformal projection
- Oblique Mercator projection

Exploiting characteristics of 3D digital spatial data

The digital revolution is still driving convergence of abstraction/technology/policy/practice and is manifested in many ways, not the least of which is the explosion of AI and the construction of data centers. Although the Earth-centered Earth-fixed (ECEF) reference system was implemented many years ago by the U.S. government, it is now used internationally by spatial data disciplines worldwide and is the geometrical basis for 3D digital spatial data applications. A paper [1] "Using GPS Results in True 3D Coordinate System" was presented at an ASCE Specialty Conference in Sacramento, California in 1991. The definition of the 3D global spatial data model (GSDM) grew out of that 1991 paper [2].

The GSDM features a functional model which includes the geometrical elements of spatial data worldwide and describes mathematical relationships in terms of solid geometry and rectangular right-handed coordinates. The global view uses X/Y/Z in the geocentric ECEF reference frame while the local view is described in familiar terms of east/north/up (e/n/u). Data can be moved back and forth between the geocentric and local perspectives using a bi-directional rotation matrix [3].

The GSDM also includes a stochastic model which includes error propagation tools for establishing, tracking, displaying, storing, and using uncertainty (standard deviations) as a measure of data quality. Meta data are still important but numerical filters imposed on data extracted from a 3D data base provide unparalleled efficiency in the decision-making process – especially in applications using AI.

Although the GSDDM label is not attached, users in various disciplines routinely perform computations in 3D space. For example, the U.S. military employs ECEF coordinates for positioning, navigation, targeting, and collision avoidance. Other high level applications include aviation, transportation, and landing a rocket booster on the launch pad. Additionally, there are many robotic applications (driverless vehicles) being applied in various disciplines. And it should come as no surprise that NGS successfully compared ECEF computational results to traditional geodesy results in the 2011 adjustment, a precursor to the modernization of the National Spatial Reference System (NSRS) [4 pages 69 and 70].

The GSDM - an alternative to conformal mapping

The dramatic growth of GIS benefits many spatial data users. Data collection sensors, "unlimited" storage capacity, computer graphics, and an endless variety of "apps," all contribute to satisfying the insatiable demand of the public for location information. Not only are data presented in 2D on a display, but 3D images can also be accessed, viewed from any chosen perspective, and rotated at the whim of the user. Such capability is often taken

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for granted and the integrity of location may not be an issue.

However, geometrical integrity becomes critical in other applications such as engineering, design, monitoring, mapping, construction, and property boundaries. That being the case, the entire workflow process (observation to consumption) deserves careful examination. The stochastic model portion of the GSDM includes rigorous error propagation tools supporting such an evaluation – for example, see theory [5] or application [6], or both. But functional model issues (and integrity) are the focus of this article.

Continued use of traditional horizontal and vertical datums may be a legitimate carryover from the past but using a 3D datum for 3D data appears to be more efficient for modern computational practice. Others have noted, [7] [Section 10.c], that "as science matures there are over-arching concepts that greatly simplify the subject." The GSDM is viewed as part of the maturation process. Existing 2D practices are integral to the SPCS and the impact of distance distortion has been studied extensively. Even so, the fact remains that performing computations in 3D space obviates the need for most conformal mapping.

Two articles addressing the practice of performing spatial data computations in 3D space were published recently in the Journal of Geographic Information Systems (JGIS). Links to those two articles are included in a summary item [8] which highlights the overall abstraction process. A follow up article is being written which includes additional computational details for using the GSDM in practical applications.

An item [9] more germane to the conformal mapping issue was prepared for consideration by the New Mexico Board of Licensure for Professional Engineers and Professional Surveyors. That item compares GSDM results for Section 31 as reported in the JGIS article [10] with results from two separate conformal projections – one being the NM Dona LDP, the other being the standard SPCS2022 values for NM Central Zone. In summary. . . .

i. The GSDM determined values represent the actual ground level horizontal distances as computed from three different choices for location of the P.O.B. An additional geodetic inverse is included. All four computational cases come up with the same undistorted local distances.

ii. Separately, the same distances surrounding Section 31 were computed using parameters published by the NGS for the NM Dona LDP and using the NGS "standard" Central Zone SPCS2022 parameters. The results, shown in a Table at the end of the article, show that the NM Dona LDP value match the GSDM values within 0.002 mm while the SPCS2022 values show distortions approaching 0.060 meters in 805 meters (1/2 mile) giving a distortion of 1:13,000.

Conclusion

Of various points that could be made, the most important ones are that the GSDM. . .

- is already defined, in place, and uses one set of public domain equations worldwide.
- provides a direct connection between ECEF coordinate values and local distances/directions.
- (in many cases) eliminates the need for conformal mapping and associated zones.
- can be used to check the geometrical distortions of SPCS computations.

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