Timeline Showing Evolution of True 3-D and Pseudo 3-D Geospatial Data

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3-D has been around "forever" but brought into focus more recently by the digital revolution, GPS/GNSS, computers, GIS, digital twins, high-definition maps, and artificial intelligence (AI).

The purpose of this article is to provide background and clarification by constructing a timeline showing the evolution of concepts leading to the "disruptive innovations" of true 3-D.

Geometry: Logically, a point has no dimension, a line has one dimension (distance), a surface has two dimensions, location has three dimensions, and a moving element (including translation and/or rotation) is described with four dimensions – time added to location. This article deals with static location and the geometry of 3-D digital spatial/geospatial data. Other than gravity, forces that cause movement/equilibrium and esoteric issues such as spatial reasoning, relativity, and the curvature of time and space are not discussed.

Three-dimensional (3-D) refers to geometrical relationships in the physical world. Location of a point/object/person is expressed in terms of distance relative to another point/object/person or to an origin, sometimes called a point-of-beginning (POB). Distance (spatial separation – curved or straight), not a point, is taken to be the geometrical primitive because a point is meaningless unless/until it is described in terms of distance relative to another geometrical element.

A POB is fundamental to several kinds of coordinate systems – in this case, rectangular or curvilinear. A rectangular coordinate system consists of straight lines referenced to mutually perpendicular x/y/z axes while a curvilinear system utilizes two angles to locate a point on a sphere (or ellipsoid) along with a linear distance (the third dimension) for elevation.

A model is an abstraction that establishes a connection between elements in the physical world and their representation on paper, in a computer, and/or in the human mind. The best model is the simplest one that adequately describes the observed phenomenon. An on-going challenge is the trade-off between simplicity and rigor. It often happens that a simple model fails to describe a phenomenon adequately, necessitating use of a more complex model. It goes without saying that end users prefer using "simple" models – sometimes to the detriment of integrity.
For example, rectangular flat-Earth coordinates that ignore Earth curvature have limitations.

When choosing a model for spatial/geospatial data, two separate issues are relevant – the difference between 2-D and 3-D and the difference between rectangular and curvilinear coordinate systems. The following combinations of geometrical relationships include:

1. Rectangular: Straight distances define a location with respect to an origin.

a. 2-D: Location in a plane is given by distances from a pair of mutually perpendicular axes – an x-axis (abscissa) and a y axis (ordinate) – intersecting at the origin. Taken together, x and y are a pair of co-ordinates. Plane Euclidean geometry is universal.

b. Location in 3-D space is defined by three distances from the origin, the intersection of three mutually perpendicular axes. X and y lie in a plane and z is the distance above or below that plane. Rules of solid geometry are applicable in this true 3-D environment.

2. Curvilinear: Location on a sphere (or ellipsoid) is given by two angular measures.

   a. 2-D: In the case of the Earth, the angular measures are latitude and longitude. Latitude is measured north or south from the Equator and mathematical longitude is measured eastward from the Greenwich Meridian. West longitude is also used by many in the Western Hemisphere. All meridians are perpendicular to the Equator.

   b. The 3-D location of a point is established in the curvilinear environment by adding a vertical component, distance, to the 2-D latitude/longitude position. Two options, dictated by the choice of origin for the third (vertical) component include:

      1. Pseudo 3-D: Historically, the origin for the third dimension (elevation) has defaulted to the distance above (or below) sea level – or more particularly, the geoid. The problem with this assumption is that the origin (geoid) does not share a mathematical definition with horizontal components of latitude and longitude. Thus, a latitude/longitude/elevation position is called pseudo 3-D.

      2. True 3-D: the Earth-centered, Earth-fixed (ECEF) rectangular geocentric X/Y/Z coordinate system used for satellite navigation has its origin at Earth's center of mass. The curvilinear equivalent of a geocentric X/Y/Z position is obtained by selecting a "best-fitting" mathematical ellipsoid having its origin at the same center of mass. Latitude, longitude, and ellipsoid heights computed from the ECEF geocentric X/Y/Z's suffer no loss of geometrical integrity and are true 3-D.

The difference between true 3-D and pseudo 3-D is not new. Those geometrical relationships are long-standing, and the equations are all in the public domain. True 3-D and pseudo 3-D are both embodied in the definition of the Global Spatial Data Model (GSDM) first defined in 1997 – see Figure 3, http://www.globalcogo.com/gsdmdefn.pdf. The fly-in-the-ointment is geoid height – the separation between the geoid and the ellipsoid. While the best-fitting ellipsoid enjoys concise mathematical definition, the geoid is a smooth continuous surface whose shape is irregular due to gravity and reflects the non-uniform distribution of mass within the Earth. If the value of gravity were known at all points, it would be possible to compute a reliable geoid height at a given point. Regretfully, that is not the case.

As one of the four fundamental physical forces, the impact of gravity cannot be overstated – gravity makes it possible for humans to walk erect on the Earth and gravity keeps our planet in orbit around the sun. Even so, really understanding gravity remains a challenge for everyone – the human population, including scientists and cosmologists.

1. At very small distances, gravity is not counted in the standard model for particle physics CERN. How does gravity and the very small mass of an electron affect the trajectory of a beam in an accelerator?

2. At the large extreme, the force of gravity is so strong that nothing, not even light, can escape from what is referred to by cosmologists as a "black hole."

The role of gravity between the "large/small" extremes significantly impacts most human activities – the way we walk, run, fly, or swim; the way we transport people/materials; the way civil infrastructure and cities are constructed; and others. In particular, gravity is the reason for the difference between true 3-D and pseudo 3-D. Not surprisingly, gravity is the target of on-going research as it affects overall human existence. Among others, gravity waves command significant research attention and physicists at the NIST have demonstrated a connection between time and equipotential surfaces (the geoid). A skeptical observation is that spatial data users need to be patient until the scientists and geodesists define the geoid with sufficient refinement that it can serve as a reliable stable reference for orthometric heights (elevation).

Not to be critical of past use of separate horizontal and vertical datums, decisions for defining and using those datums were good decisions made for the right reasons. But the evolution of applications driven by the convergence of abstraction/technology/policy/practice gives rise to "disruptive innovation" encountered by professionals in various disciplines. Undoubtedly planning that identified the need for "modernization of the National Spatial Reference System (NSRS)" included commendable foresight. However, the time frame needed to accomplish those modernization goals is sufficiently long that the (now apparent) consequences of the digital revolution need to be considered as part of "doing the right thing," not just "doing things right." An over-simplified statement is "a 3-D model should be used for 3-D data."

As noted in the proposal submitted in January 2023 to the Director of the National Institute of Standards and Technology (NIST), (see "NIST" item at http://www.tru3d.xyz/), two significant areas of practice rely on the pseudo 3-D model and the true 3-D model.

Rational for studying the evolution to true 3-D and the GSDM is included in the NIST proposal.

A brief statement of the "best" way forward is to adopt an integrated 3-D datum (true 3-D), i.e., the GSDM for spatial/geospatial data applications. Corrections are readily available for those very few applications for which the actual slope of the geoid is critical. Reluctance to discuss disruptions caused by the digital revolution is referred to as ignoring the elephant-in-the-room. Economic and policy considerations will have an impact on the transition timeline.

An incomplete Timeline for evolution and use of true 3-D digital spatial data includes:

300 BCE	Euclid – geometry, theorems, and logic.
276 – 195 BCE	Pythagoras – hypothenuse and sides of a right triangle.
1512 – 1594	Mercator – conformal map projection of the world
1596 – 1650	Descartes – rectangular coordinate systems.
1688	Love – Geodesia or the Art of Surveying and Measuring Land Made Easy.
1735 – 1741	Meridian arc surveys proved that the Earth is flattened at poles.
1790 – 1800	Meter is defined as 1/10,000,000 of arc distance Equator to North Pole.
1807	Ferdinand Hassler named first Director of U.S. Survey of the Coast.
1816-1817	Hassler began observations following acquisition of equipment and delays.
1856-1857	Precise levels run to study tides and currents in New York Bay and Hudson River.
1866	Meter defined as legal standard for length in the United States
1877	First geodesic leveling benchmark set in Hagerstown, Md.
1878	Global 3-D polyhedron network proposed by H. Burns.
1879	First national horizontal datum established in the United States
1884	Greenwich Meridian designated as Prime Meridian of the World
1927	NAD 1927 served as horizontal datum in the U.S. for nearly 60 years.
1929	NGVD 1929 served as vertical datum in the U.S. for more than 60 years.
1933	State Plane Coordinates enable plane surveyors to use geodetic control.
1950s	Photogrammetric mapping blossoms as tool for Interstate Highway System.
1986	Publication of NAD 83 – published as a 2-D horizontal datum.
1986 – 1997	HARNs observed state by state, first truly three-dimensional HARN - 1997.
1993	**Figure 6 of ASCE paper on true 3-D http://www.globalcogo.com/Tru3d.pdf**
1994	ASCE/ASPRS/ACSM Glossary of the Mapping Sciences, no ECEF and no GPS.
1994	Silicon Graphics markets algorithm for displaying 3-D graphics.
1994	TerraVision and ART+COM developed cascading resolution for images. (Cascading algorithm utilizes mobile POB (Fig 6 above) from 1991 paper.)
1994	Google developed Google Earth and distributes gratis to users worldwide.
Note:	*(No mention is found where Silicon Graphics, TerraVision, ART+COM, or Google distinguish difference between true 3-D and pseudo 3-D. Current Google Earth displays give the user a choice of ground distance or map distance – implying the displayed results are pseudo 3-D.)*
Now:	***View Netflix documentary, Billion Dollar Code (it is fictionalized a bit).***
1997	Definition of GSDM based on 1993 paper is filed in U.S. Copyright Office.
1997	SEWRPC 3-D Report – proposes use of integrated 3-D datum, the GSDM.
2008 (3-D book)	The 3-D Global Spatial Data Model describes true 3-D/pseudo 3-D in detail.
2014	NGS modernization of NSRS promotes continued use of separate datums.
2015	Eye in the Sky – "science fiction" documentary showing military use of 3-D.
2017 (2nd ed. Book)	No new "geometry" but adds updates and material on accuracy/projects.
2020	Webpage www.tru3d.xyz contains various items promoting use of tru3-D.
2022	Digital twins arrive. See http://www.globalcogo.com/GSDM-and-DT.pdf
2022	ASCE "Future World Vision," – proposal to discuss "elephant-in-the-room."
2022	High-definition maps needed for autonomous navigation – use GSDM?
2023	Proposal to NIST to study GSDM – www.globalcogo.com/NIST-memo.pdf.
2023	AI and ChatGPT hit the stage – www.globalcogo.com/ChatGPT.html.