Earth-Centered Earth-Fixed

Scalable Visualization without Distortion

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SWIGGIS at PBX Systems

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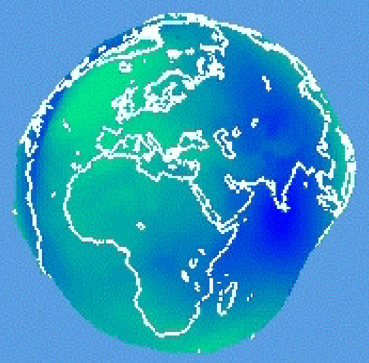
www.hydrometronics.com

Hydrometronics LLC

Hydrometronics provides consultancy and technical software development for seismic navigation, ocean-bottom positioning, subsea survey, geodesy, cartography, 3D visualization (ECEF) and wellbore-trajectory computation.



The scope of Hydrometronics' offerings is due to the long career of its principal (click on the 'about us' link above). Hydrometronics is primarily a Matlab ® shop, providing compiled, user-friendly, GUI-driven applications or .NET DLLs that solve client problems in all the fields cited above, which are not exclusively nautical. Click on the 'contact us' link above to initiate a conversation about your needs.

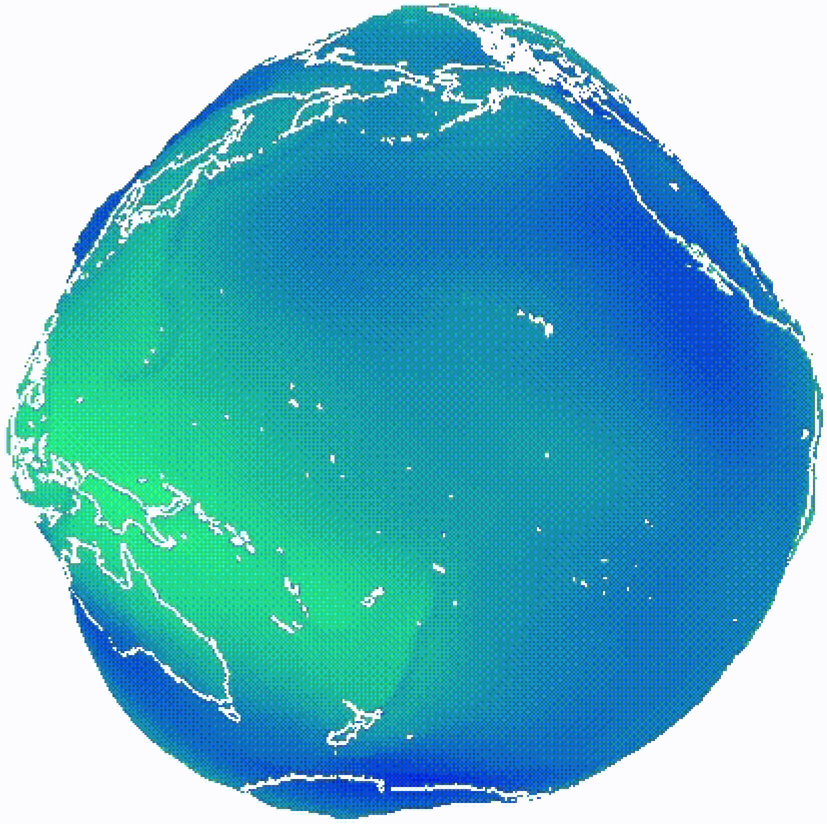
In addition to software development, Hydrometronics consults in all these fields, bringing a career of expertise to bear on your needs.

For a sampler of the disciplines addressed by Hydrometronics, visit the 'downloads' link above for papers presented over the years or visit the four heritage links below for extractions from those papers (preserved in place for the web bots).

EGM08 in ECEF (above)

Earth Gravitational Model 2008 (EGM08) is the best, world-wide, freely-available model of the geoid. Earth-Centered Earth-Fixed (ECEF) is the 3D, orthogonal, geocentric, Cartesian, coordinate system used by GPS, which empowers distortion-free visualization. Geoidal undulations are exaggerated 10,000 times here for visual effect.

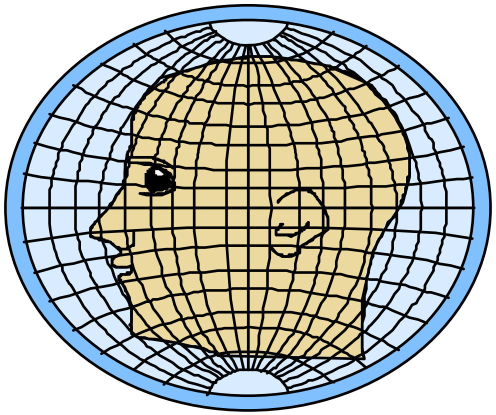
EGM2008·10,000 in ECEF



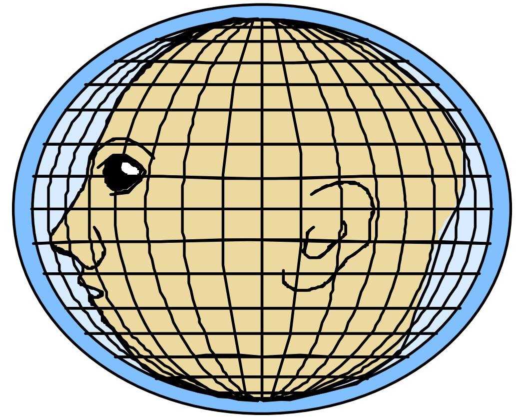
Overview

- Cartography (2D) is distorted.
- Geodesy (3D) is not, but …
- … 3D visualization environment (VE) required,
- … and geoid also required.
- Coordinate Reference System (CRS) primer
- Earth-Centered Earth-Fixed (ECEF)
- Topocentric coordinates (a “flavor” of ECEF)
- Orthographic projection (topocentric in 2D)
- This presentation => www.hydrometronics.com

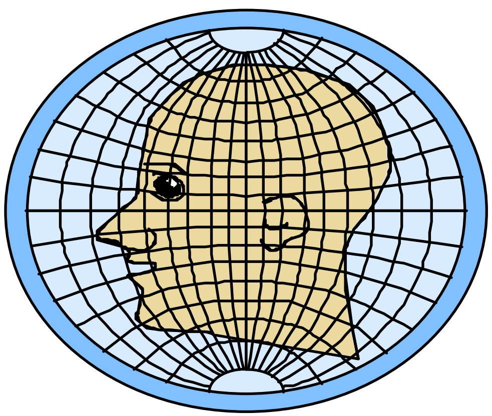
Cartography is distorted …



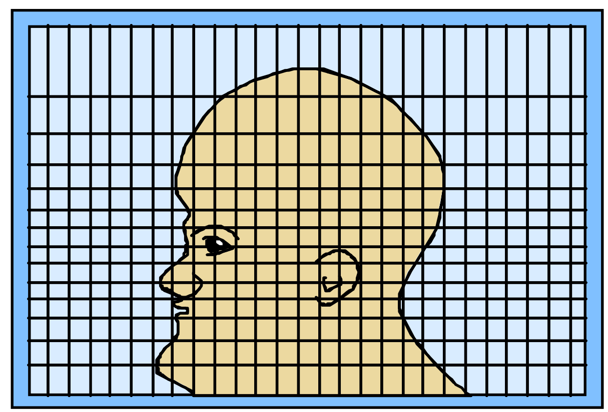
Globular projection



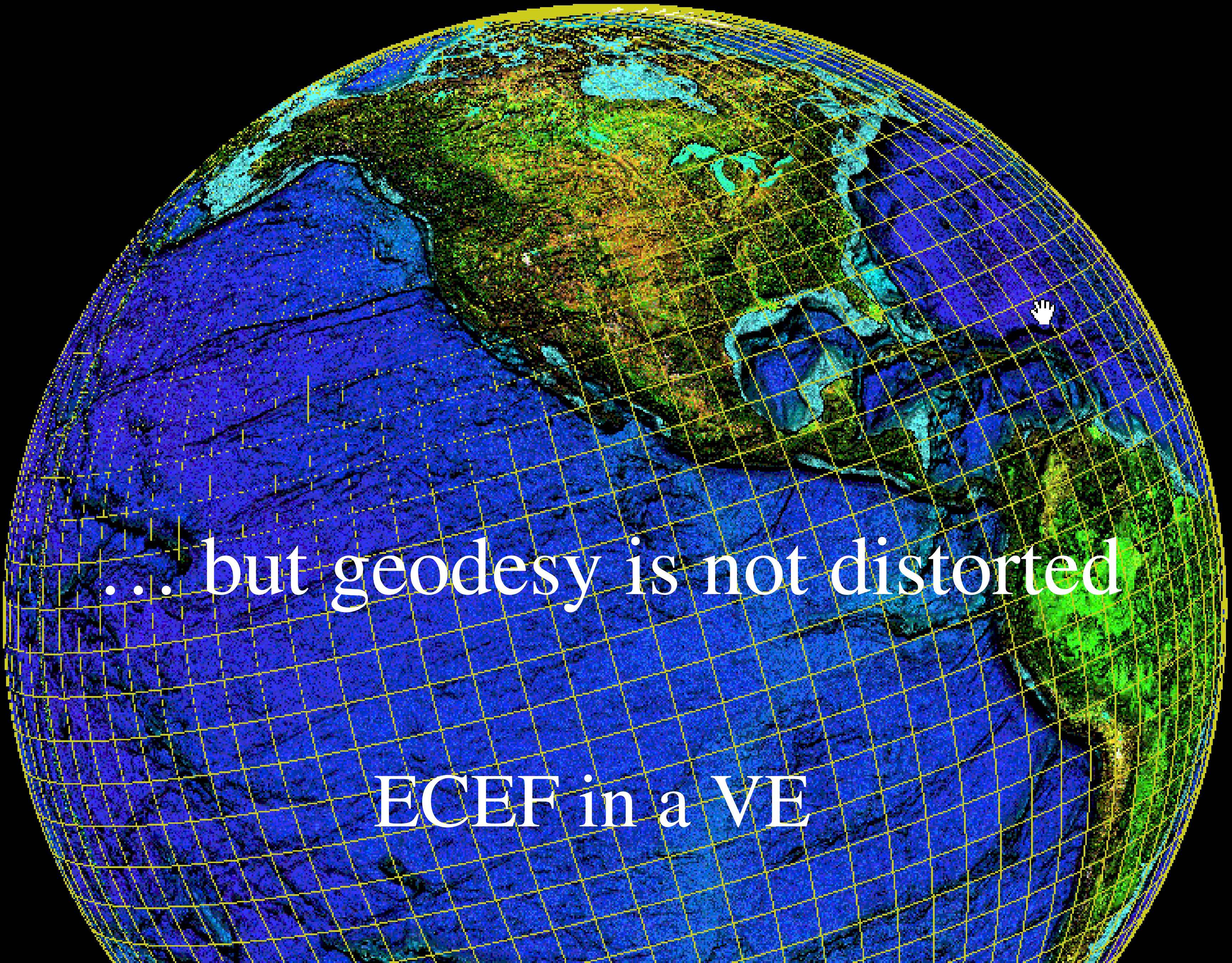
Orthographic projection



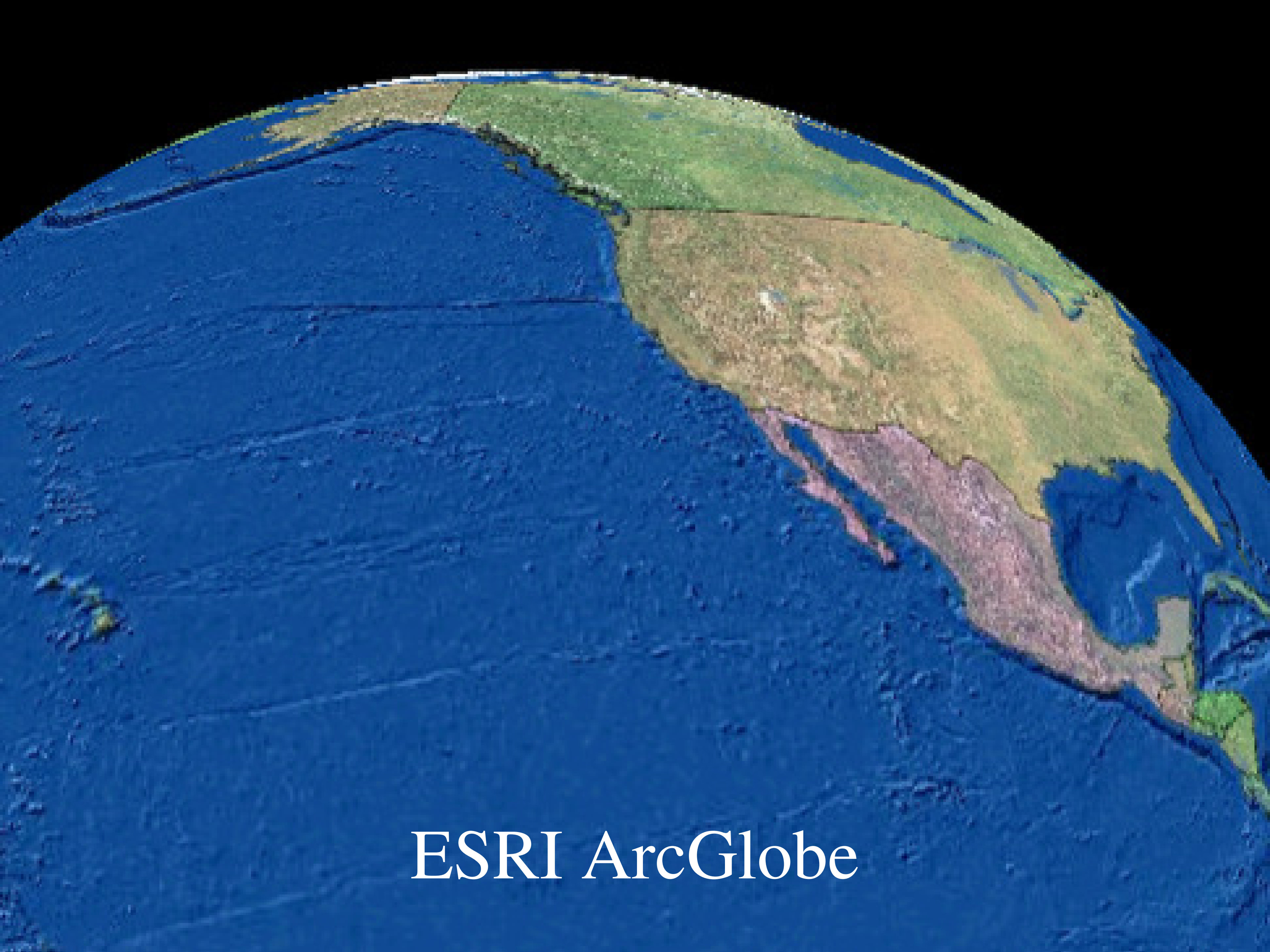
Stereographic projection



Mercator projection


… but geodesy is not distorted
ECEF in a VE

Google Earth


ESRI ArcGlobe

Issues

- Plate-to-pore scalability is desired in earth science software
- That software has heretofore used 2D projected coordinates in the horizontal and 1D depth/time in the vertical
- Projections have distortions of linear scale, area and azimuth that increase with project size
- These distortions can be quantified and managed on an appropriate map projection

Issues

- Earth science software is evolving toward visualization environments (VEs) that:
  - Operate in a 3D “cubical” CRS
  - Excel at graphical manipulation
  - Are geodetically unaware
- A pure 3D approach will:
  - Exploit the native power of VEs
  - Avoid the distortions (3D=>2D) of map projections
  - Achieve plate-to-pore scalability
  - Provide a new perspective on the data

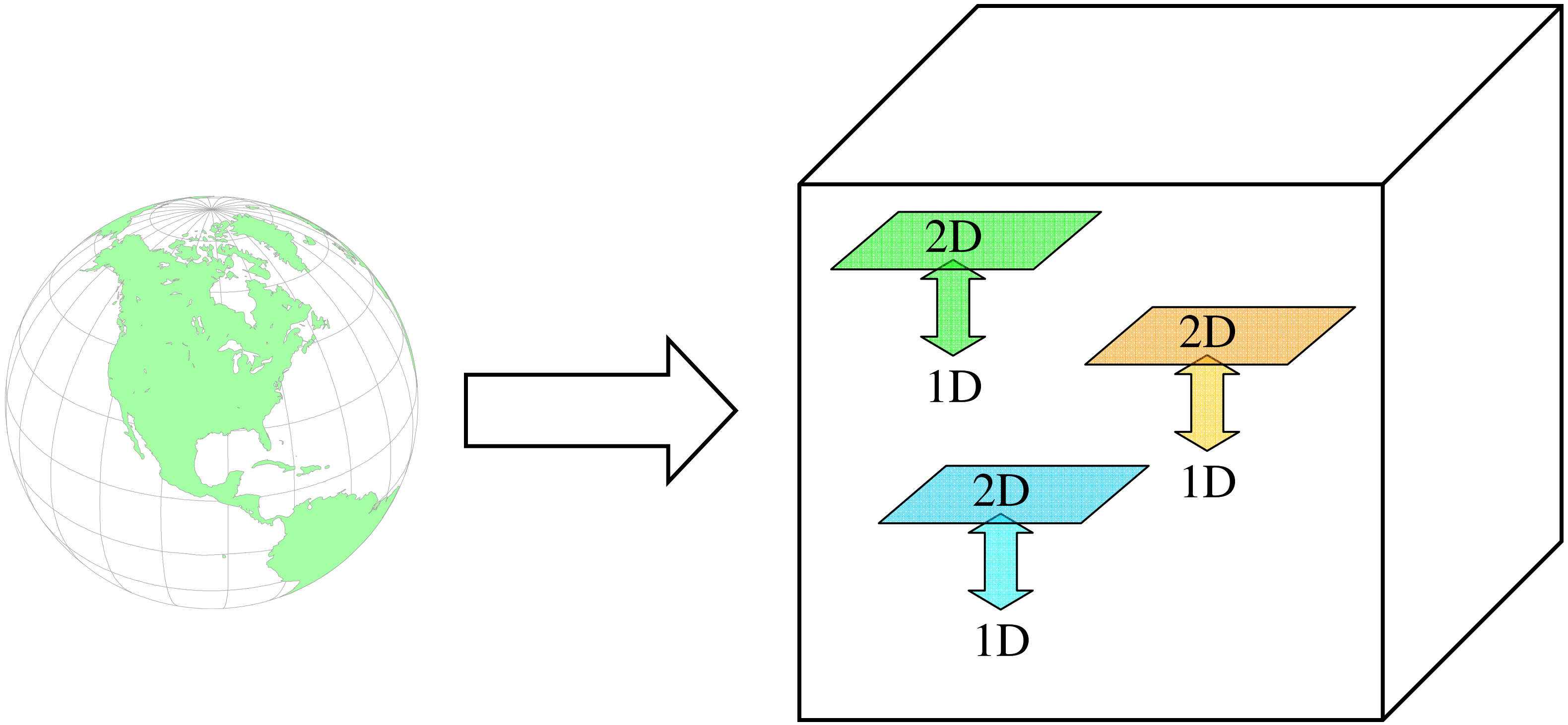
What are some VEs?

- Gocad (Paradigm, proprietary)
- Petrel, HueSpace (Schlumberger, proprietary)
- Matlab (The Mathworks, proprietary)
- ArcScene (ESRI, proprietary)

- VTK (Visualization Toolkit, open source)
- Mayavi (Python GUI front end to VTK, open source)

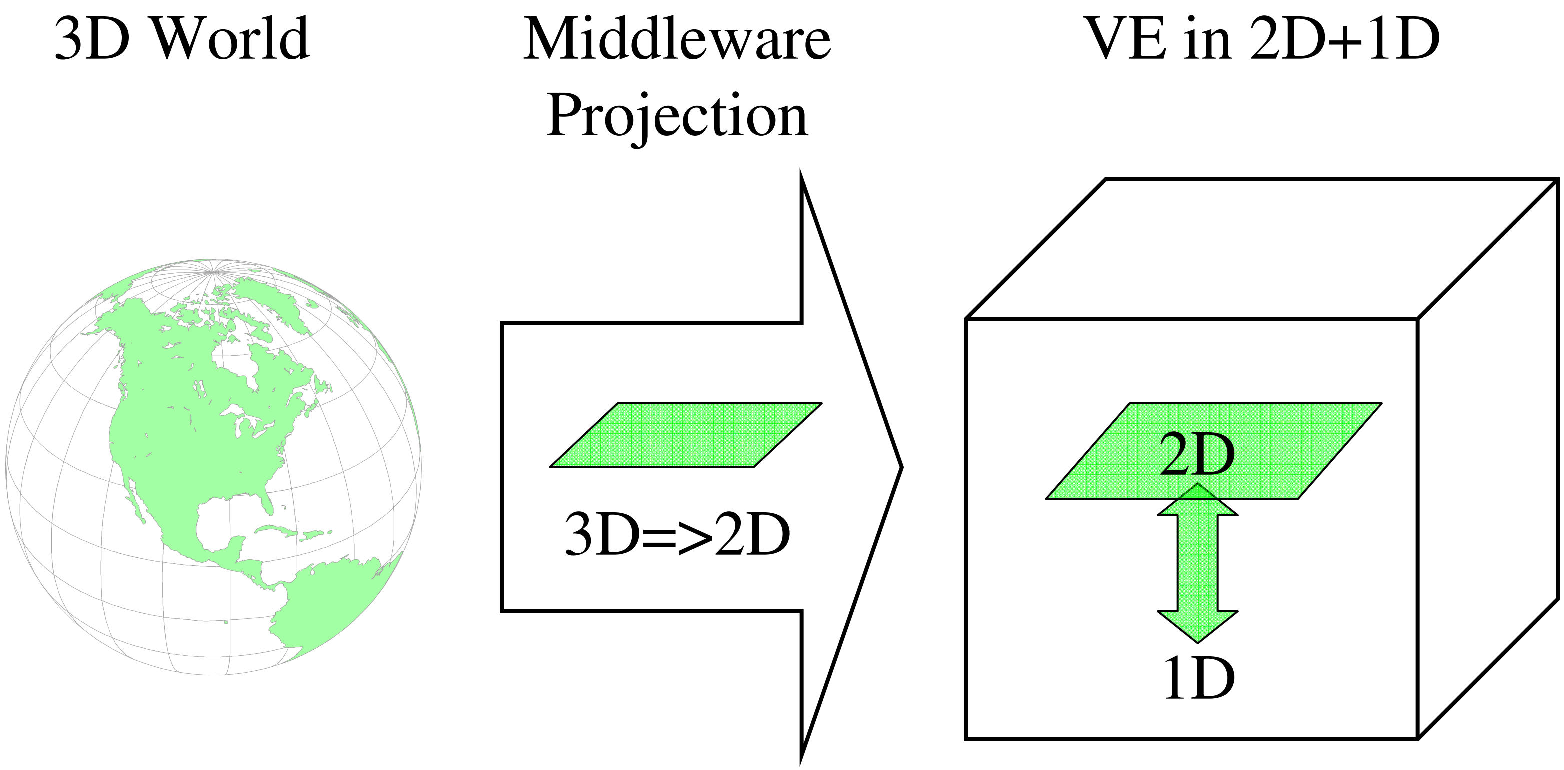
- iPod/Phone/Pad? Android? (some day, if not already!)

Heritage Applications



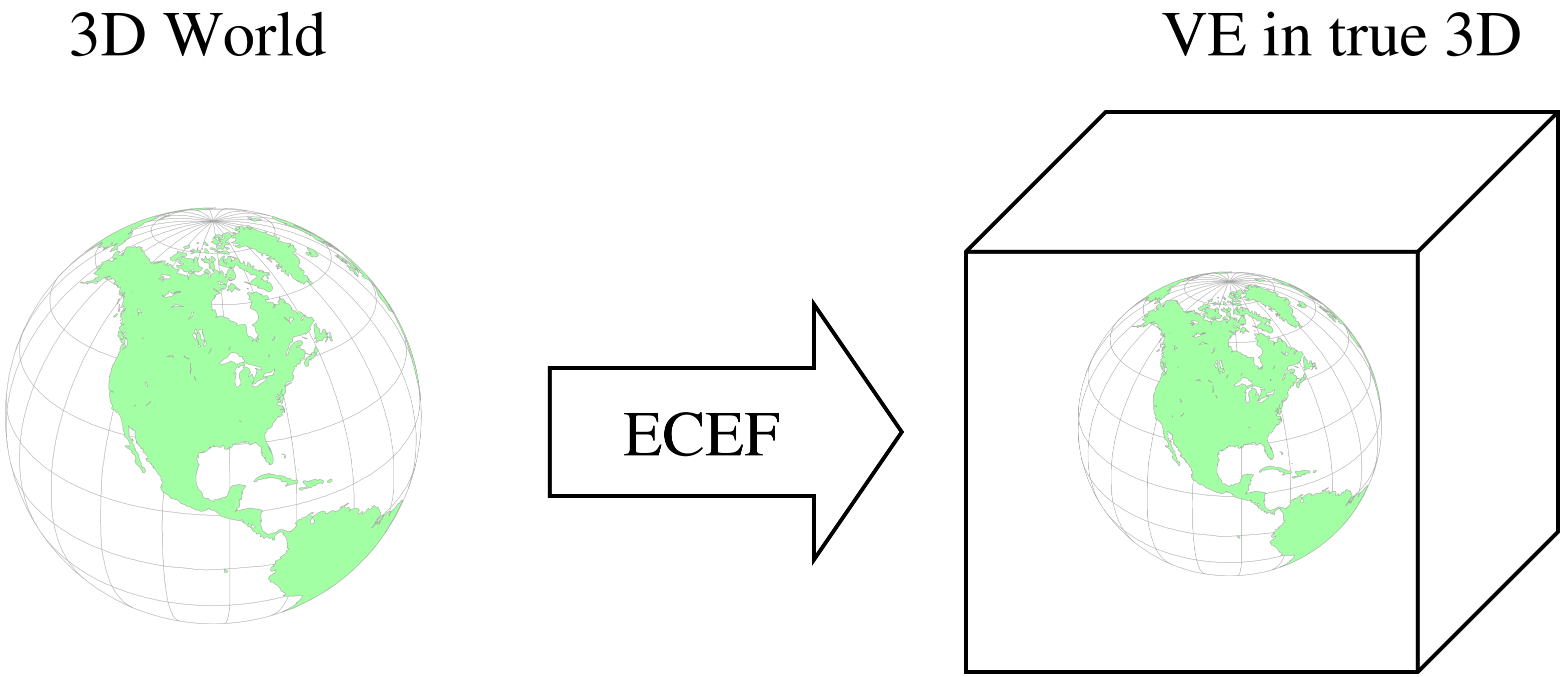
Heritage earth-science applications with internal geodesy support any projected coordinate system (2D horizontal + 1D vertical), but with the usual, well-known mapping distortions

Current Path to VE via Middleware



VEs have no internal geodesy. Coordinates are projected "outside the box" (in middleware). Only one coordinate system is allowed inside the box at a time.

Proposed Path to VE via ECEF



If ECEF coordinates are chosen in middleware, the VE "sees" the world in 3D without any mapping distortions. If ECEF coordinates in WGS84 are chosen, then projects throughout the world will fit together seamlessly.

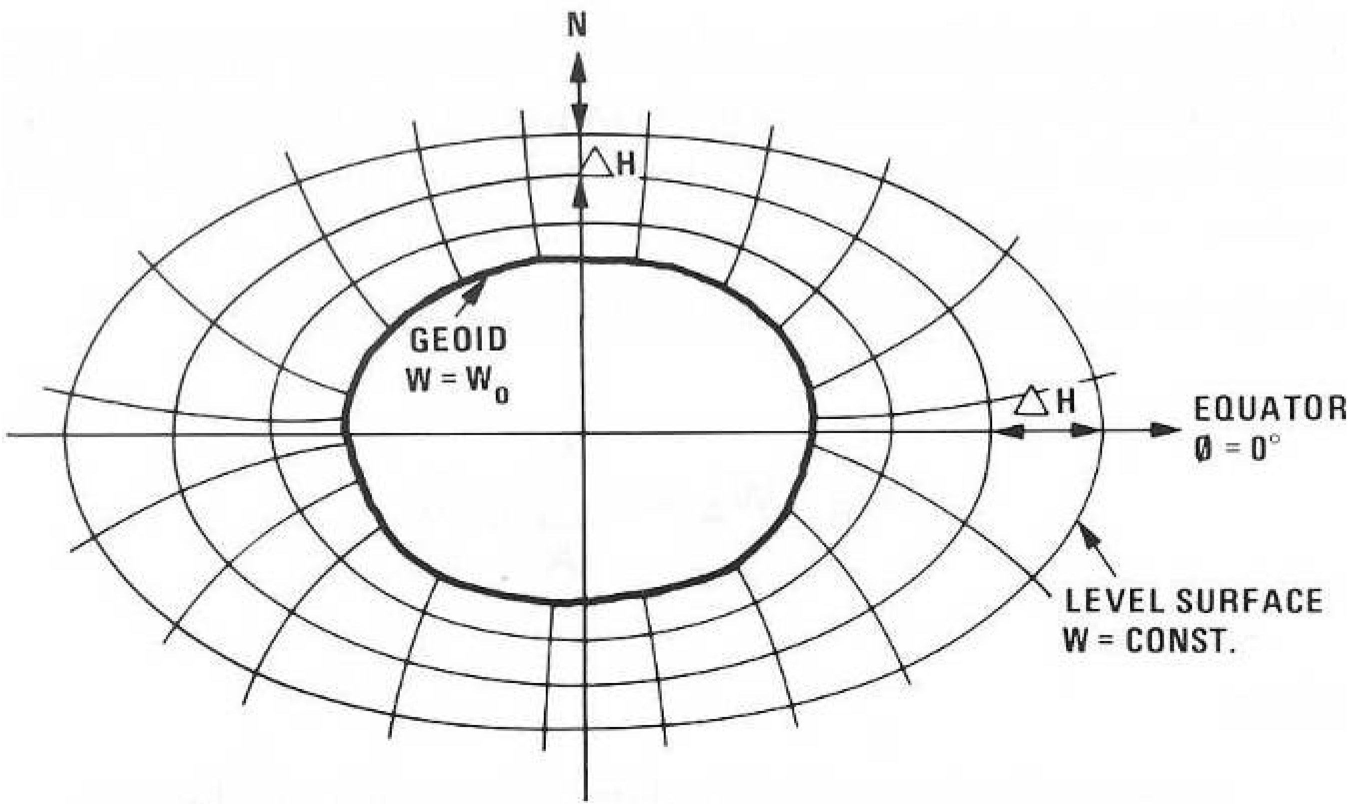
EPSG Coordinate System Primer

1. Geographical 2D (lat/lon) and Geographical 3D (lat/lon/height with respect to the ellipsoid)
2. Vertical (elevation or depth w.r.t. the geoid)
3. Projected (mapping of an ellipsoid onto a plane)
4. Engineering (local "flat earth")
5. Geocentric Cartesian (Earth-Centered Earth-Fixed)
6. Compound (combinations of the above)

Geographical CS: lat/lon/(height)

A graticule of curved parallels and curved meridians (latitudes and longitudes) intersect orthogonally on the ellipsoid. Height is measured along the normal, the straight line perpendicular to the ellipsoid surface.

Vertical CS: elevation

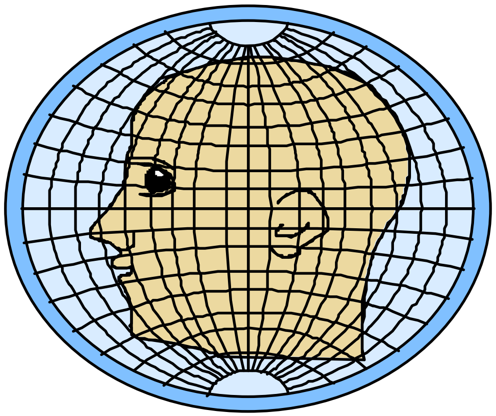


Elevation is measured along the (slightly curved) vertical, which is perpendicular to the irregularly layered geopotential surfaces of the earth. The geopotential surface at mean sea level is called the geoid. (Graphic from Hoar, 1982.)

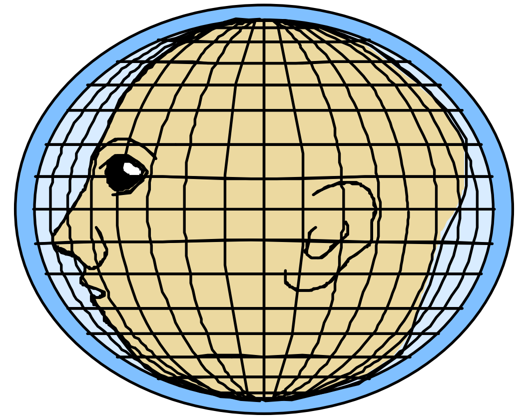
Projected CS: Northing/Easting

- Map projections of an ellipsoid onto a plane preserve some properties and distort others
  – Angle - and local shapes are shown correctly on conformal projections
  – Area - correct earth-surface area (e.g., Albers)
  – Azimuth - can be shown correctly (e.g., azimuthal)
  – Scale - can be preserved along particular lines
  – Great Circles - can be straight lines (Gnomonic)
  – Rhumb Lines - can be straight lines (Mercator)
- **Rule of thumb: map distortion $\propto$ distance^2**

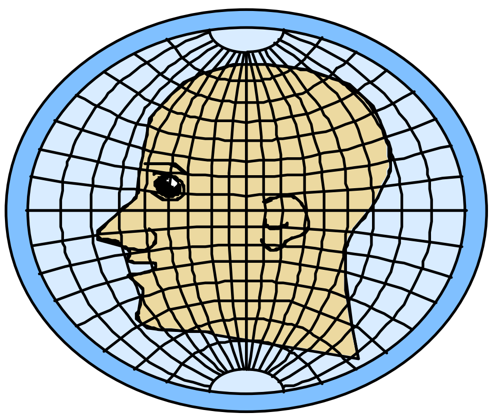
Projected CS Distorts



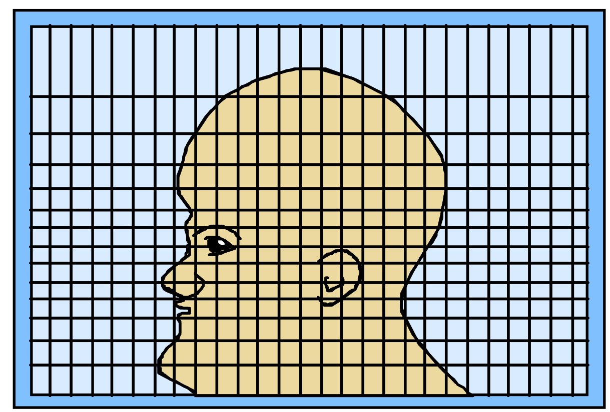
Globular projection



Orthographic projection



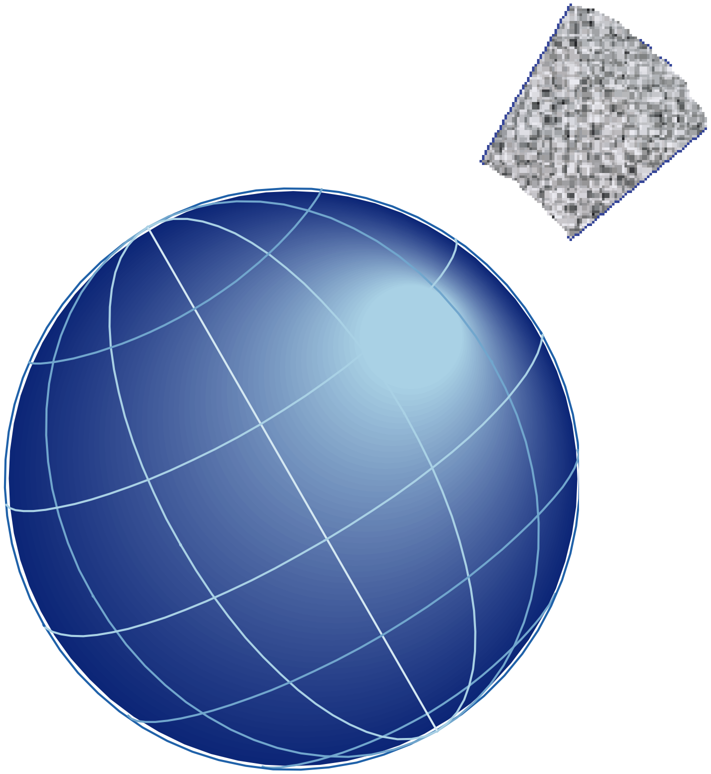
Stereographic projection



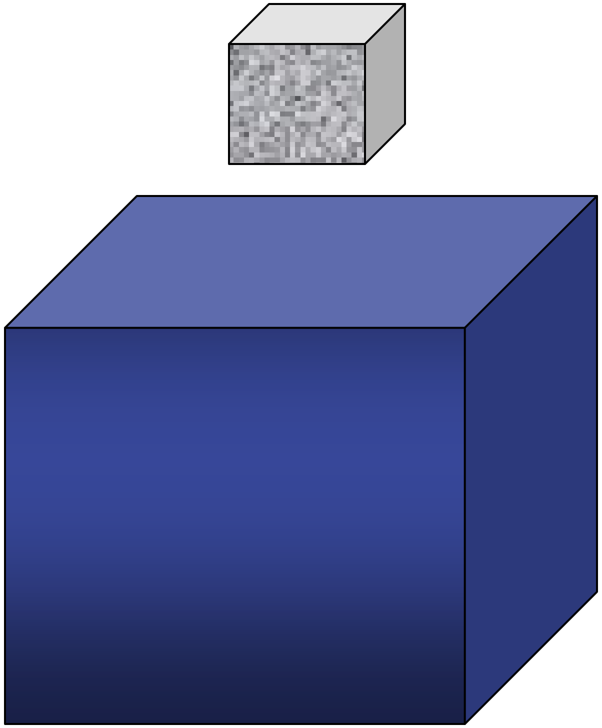
Mercator projection

Rule of thumb: map distortion $\propto$ distance^2

Engineering CRS (“Flat-Earth”)

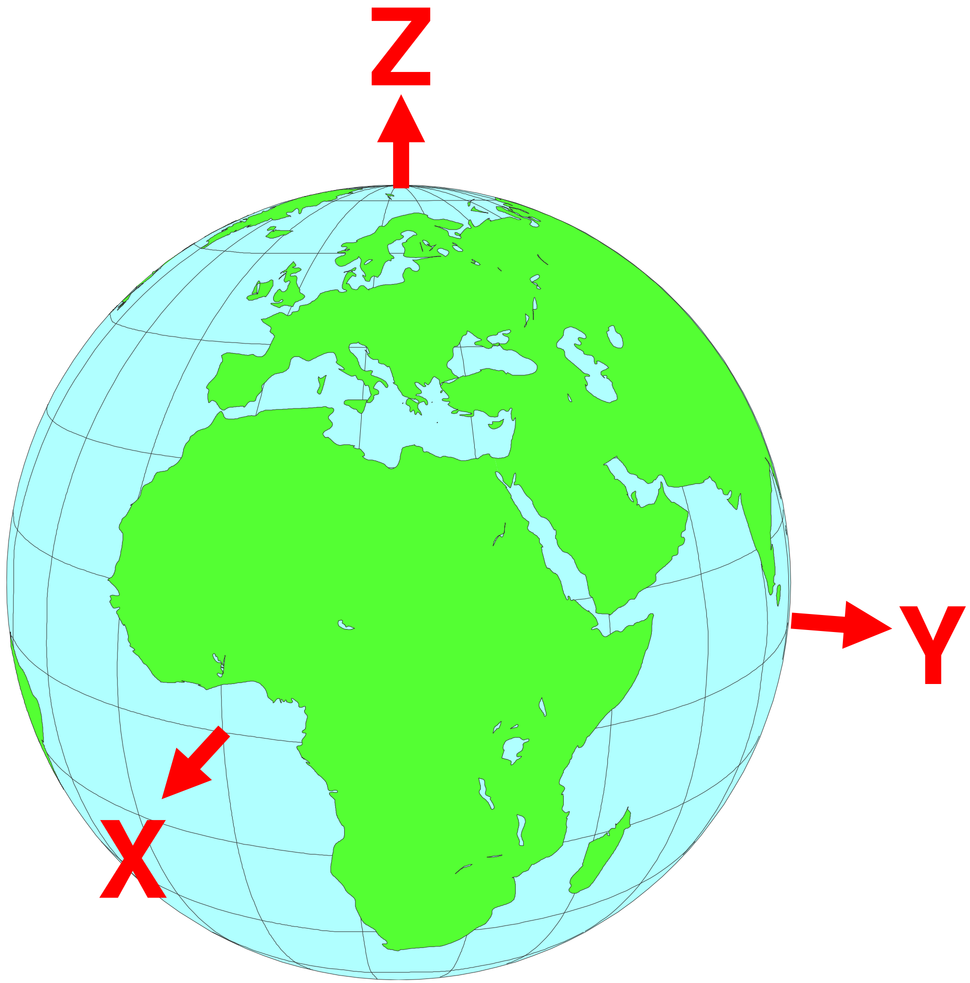


Our project extracted from an ellipsoidal earth



Our project extracted from a cubical, flat earth

Geocentric CRS (ECEF)



The Z-axis extends from the geocenter north along the spin axis to the North Pole. The X-axis extends from the geocenter to the intersection of the Equator and the Greenwich Meridian. The Y-axis extends from the geocenter to the intersection of the Equator and the 90E meridian.

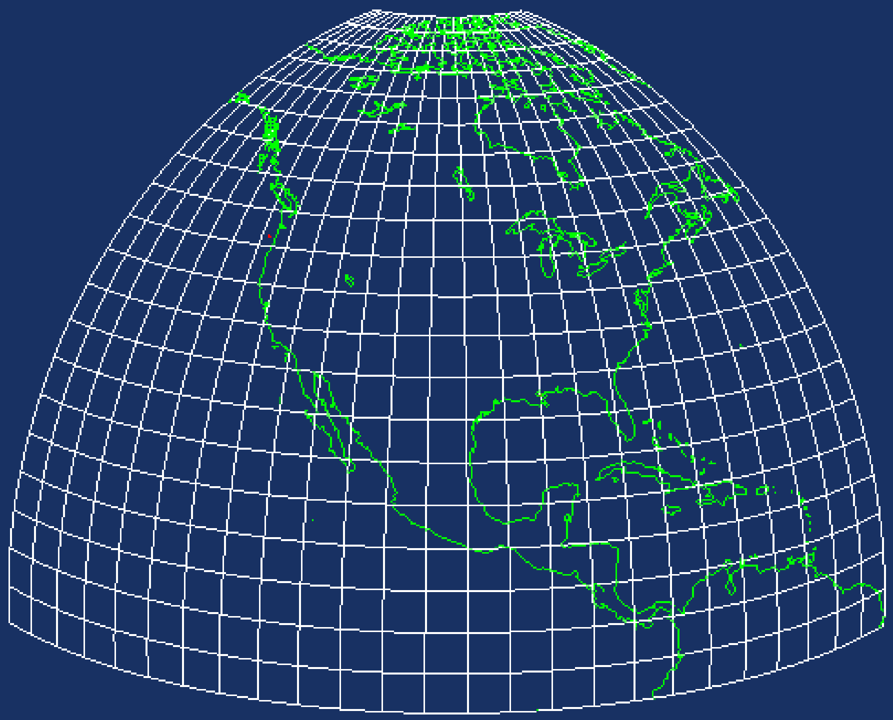
Coordinate Conversion

- The mathematics of map projections (3D=>2D) are complicated (especially TM) and generally valid over limited extents
- The mathematics of converting Geographical CS coordinates to ECEF Geocentric CS (3D=>3D) are simple and valid the world over

So, Why ECEF?

- ECEF is the geodetic CS native to a 3D VE
- ECEF in a 3D VE is a globe in your hands
- Given the proper perspective (turning the globe), ECEF coordinates have no distortion
- ECEF is scalable from plates to pores
- No geodetic “smarts” are required in the VE

North America in VTK



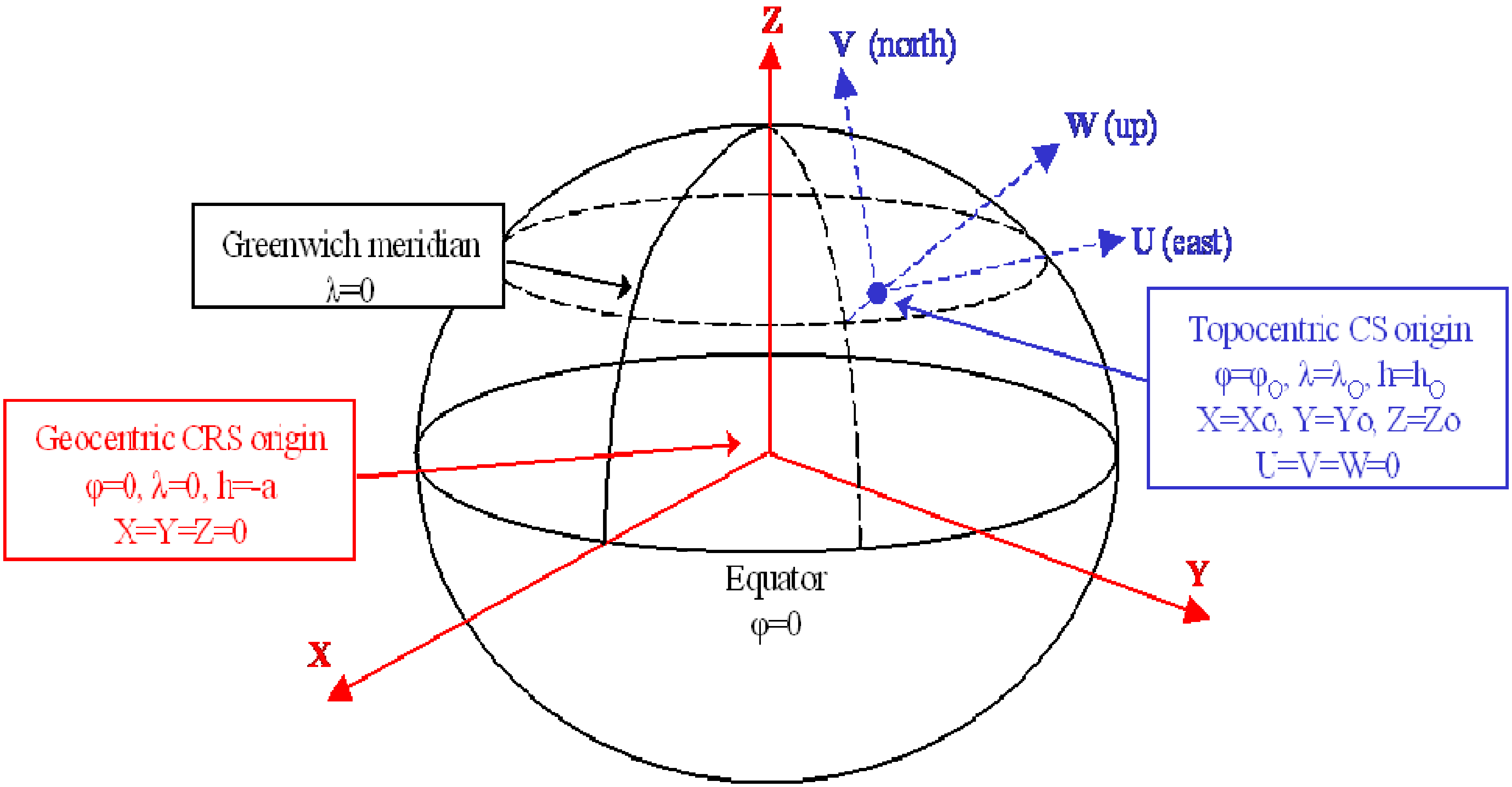
U.S.G.S. Coastline Culture Excerpts in Geographical and ECEF

Geographical CS (height = 0)		Geocentric CS (ECEF)		
longitude	latitude	X	Y	Z
NaN	NaN	NaN	NaN	NaN
-50.027484	0.957509	4096874.92	-4887224.49	105871.03
-50	0.99249	4099176.47	-4885208.29	109738.48
NaN	NaN	NaN	NaN	NaN
-59.708179	8.277287	3183867.68	-5450322.48	912137.99
-59.773891	8.310143	3177350.79	-5453517.54	915733.77
-59.905313	8.462687	3163599.63	-5458662.31	932424.41
NaN	NaN	NaN	NaN	NaN
-57.060949	5.791989	3450502.62	-5325702.36	639376.55
-57.117273	5.90229	3444590.92	-5328048.22	651510.81
-57.161863	6.066569	3439416.28	-5329135.93	669578.81
-57.272164	6.26605	3427869.60	-5333753.93	691511.19
-57.391853	6.308293	3416444.41	-5340472.04	696154.65
-57.546744	6.442062	3401113.29	-5348302.30	710856.40

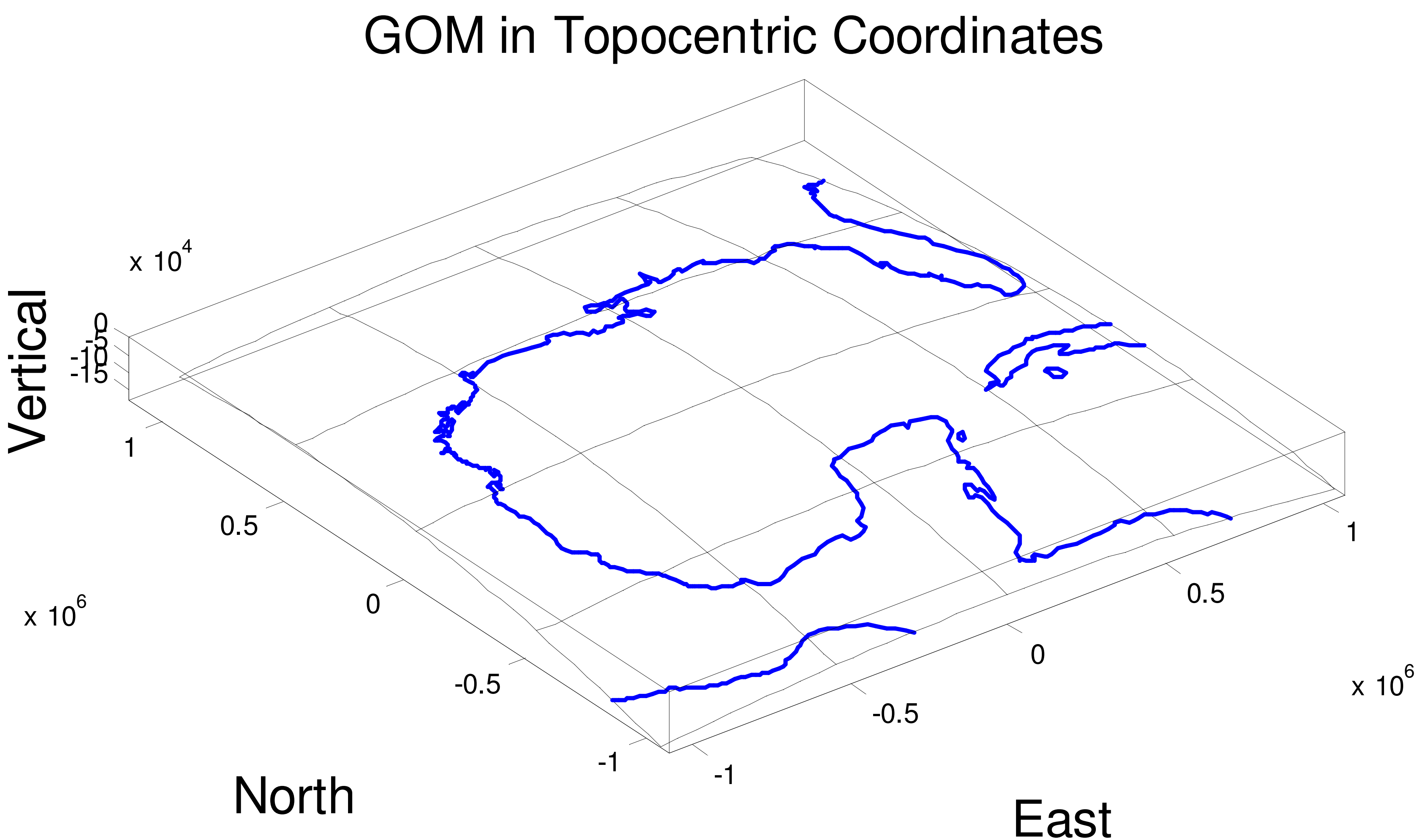
Translation & Rotation: ECEF to Topocentric

- A journey back to Projected CS because …
- … some users may prefer their data referenced to their local area of interest
- ECEF can easily be translated and rotated to a topocentric reference frame
- This conversion is conformal,
  it preserves the distortion-free curvature of the earth,
  and the computational burden is small
- VEs already do something similar to change the viewing perspective

EPSG Graphic of Topocentric



GOM in Topocentric Coordinates

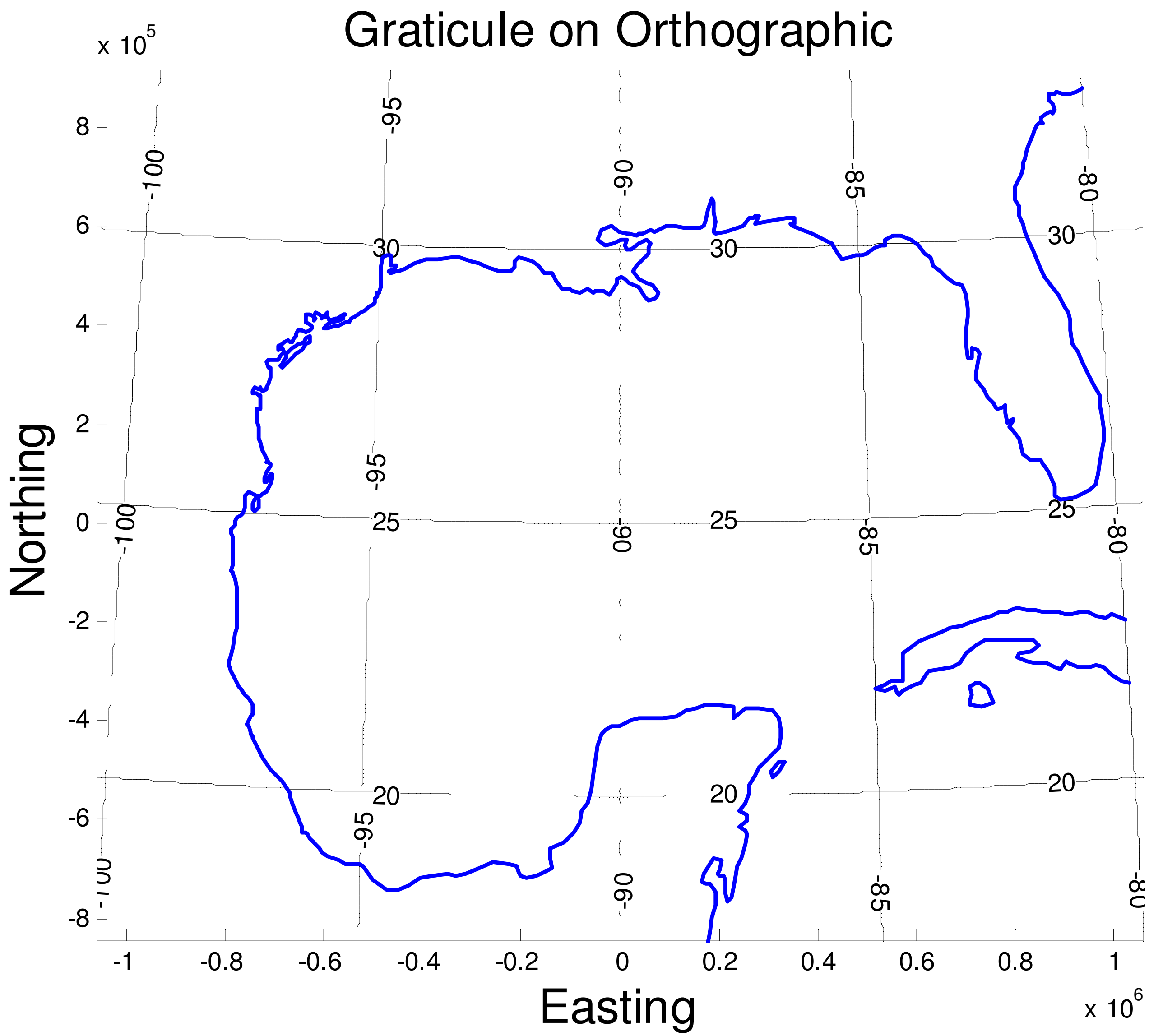


Topocentric to Orthographic

- Continuing the journey
- The orthographic projection is the view from space, e.g. our view of the moon
- Topocentric without the W vertical coordinate (3D=>2D) is the Orthographic projection
- The ellipsoidal Orthographic projection is a bona fide map projection with quantifiable distortions intermediate between our usual 2D+1D paradigm and a new topocentric / ECEF 3D paradigm

Orthographic Projection of the Moon

Orthographic Projection of GOM



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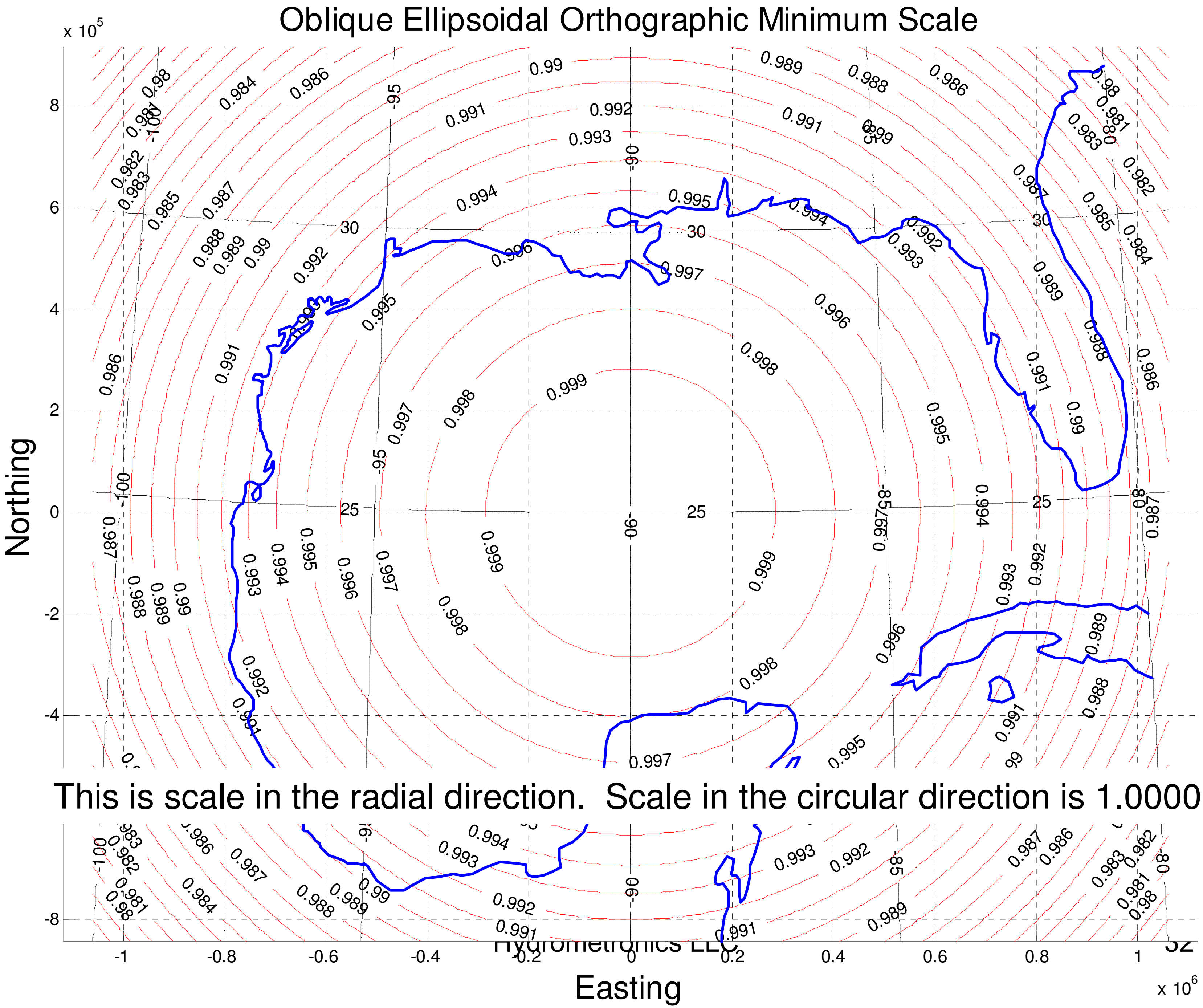
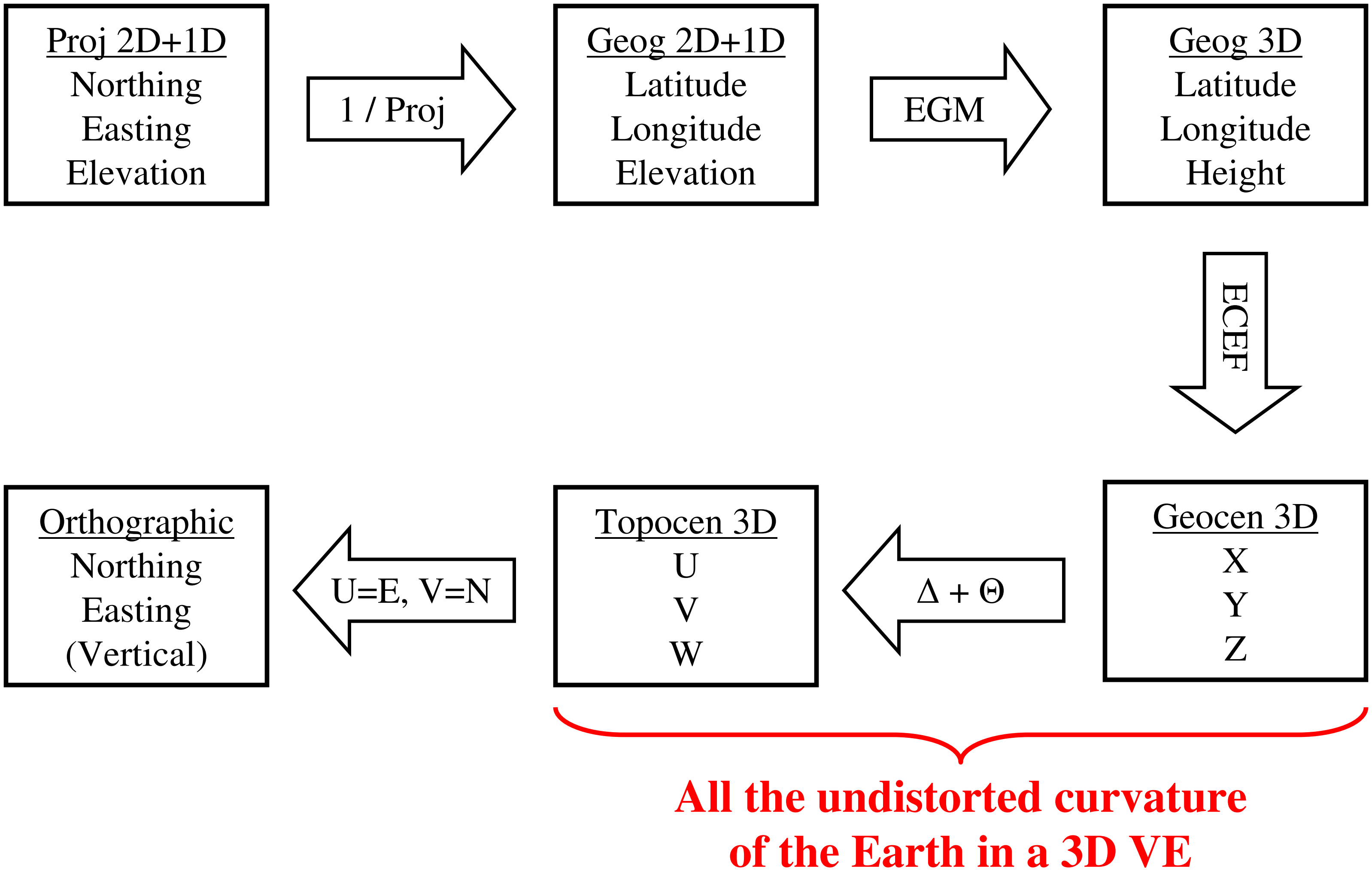
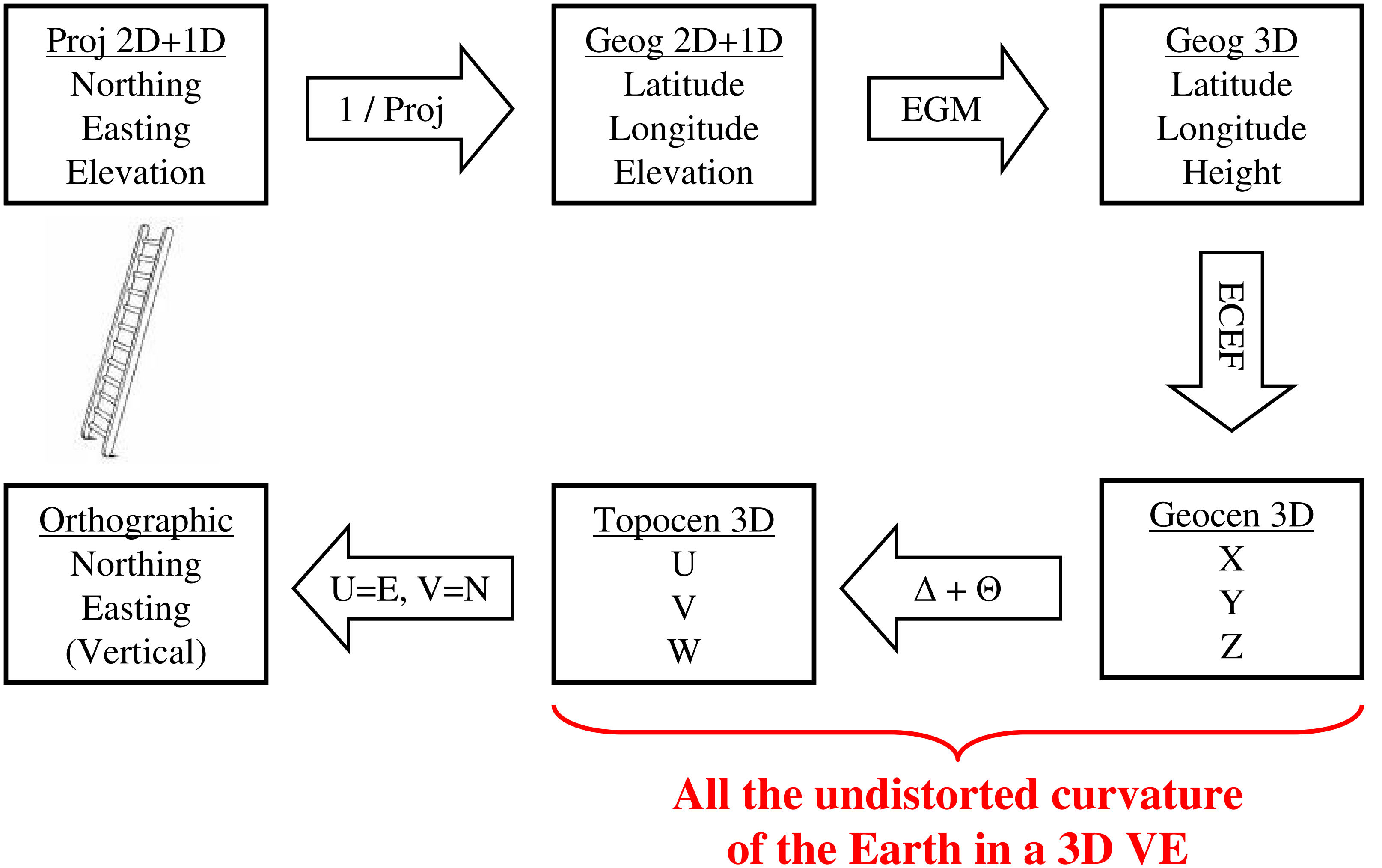


This is scale in the radial direction. Scale in the circular direction is 1.0000

Our Journey Schematically



Our Journey Schematically



Summarizing

- Cartography (2D) is distorted; geodesy (3D) is not
- Not all 3D presentations are ECEF (geodesy)
- Geodetically "unaware" visualization environments (VE) present an opportunity
- Coordinate Reference System (CRS) primer
- **Earth-Centered Earth-Fixed (ECEF)**
- **Topocentric coordinates (a "flavor" of ECEF)**
- **Orthographic coordinates (2D topocentric)**

Conclusion

- The real world is 3D
- New visualization environments are 3D
- Why incur the distortions of a 2D map projection entering real-world data into a VE?
- ECEF, topocentric and orthographic coordinates are a paradigm shift in the way we view our data, a perspective that may extract new information
- It’s time for ECEF!

More Information

- This presentation can be downloaded at www.hydrometronics.com
- There is a ECEF Group on LinkedIn
- Guidance Note 7-2 at www.epsg.org
- Wikipedia (search ECEF)
- World coastlines are available at www.ngdc.noaa.gov/mgg/shorelines/shorelines.html

Extra Slides

Mini Bio of Noel Zinn

- Noel Zinn began Hydrometronics LLC in 2010 as a technical software consultancy
- Geodesist for ExxonMobil in the Naughties
- Navigation Scientist for Western Geophysical in the Nineties
- Surveyor for NCS International in the Eighties
- Navigator for Delta Exploration (Singapore) in the Seventies
- Peace Corps Volunteer in India in the Sixties
- Studied at the University of California (Berkeley) and the University of Houston

Geographical to ECEF Coordinates

Given the ellipsoid semi-major axis (a) and flattening (f), and latitude (ϕ), longitude (λ), and height (h)

$$b = a - a \cdot f \qquad e^2 = (a^2 - b^2)/a^2 \qquad \nu = \frac{a}{(1 - e^2 \sin^2 \phi)^{1/2}}$$

$$X = (\nu + h)\cos\phi\cos\lambda$$

$$Y = (\nu + h)\cos\phi\sin\lambda$$

$$Z = (\nu(1 - e^2) + h)\sin\phi$$

ECEF to Geographical Coordinates

Given ellipsoid *a* and *f*, and X, Y and Z Cartesians

$$b = a - a \cdot f \qquad e^2 = (a^2 - b^2)/a^2 \qquad e'^2 = (a^2 - b^2)/b^2$$

$$\nu = \frac{a}{(1 - e^2 \sin^2 \phi)^{1/2}} \qquad p = (X^2 + Y^2)^{1/2} \qquad \theta = \tan^{-1}(\frac{Z \cdot a}{p \cdot b})$$

$$\phi = \tan^{-1} \frac{Z + e'^2 b \sin^3 \theta}{p - e^2 a \cos^3 \theta}$$

$$\lambda = \tan^{-1}(\frac{Y}{X})$$

$$h = (p/\cos\phi) - \upsilon$$

U.S.G.S. Coastline Culture Excerpts in ECEF and Topocentric

Geocentric CRS (ECEF)			Topocentric		
X	Y	Z	U-East	V-North	W-Up
NaN	NaN	NaN	NaN	NaN	NaN
4096874.92	-4887224.49	105871.03	4883291.81	-2534277.49	-3159278.92
4099176.47	-4885208.29	109738.48	4885208.29	-2529781.65	-3158620.16
NaN	NaN	NaN	NaN	NaN	NaN
3183867.68	-5450322.48	912137.99	4081936.14	-2375003.57	-2094765.47
3177350.79	-5453517.54	915733.77	4076073.08	-2374998.99	-2089176.88
3163599.63	-5458662.31	932424.41	4063424.20	-2367004.86	-2072737.89
NaN	NaN	NaN	NaN	NaN	NaN
3450502.62	-5325702.36	639376.55	4322880.24	-2475302.15	-2399575.74
3444590.92	-5328048.22	651510.81	4317465.71	-2468151.60	-2389219.87
3439416.28	-5329135.93	669578.81	4312558.56	-2455576.85	-2376097.067
3427869.60	-5333753.93	691511.19	4301989.21	-2442987.79	-2356979.39
3416444.41	-5340472.04	696154.65	4291904.18	-2444958.68	-2347406.64
3401113.29	-5348302.30	710856.40	4278165.68	-2440364.45	-2330009.96

U.S.G.S. Coastline Culture Excerpts in Topocentric and Orthographic

Topocentric			Orthographic	
U-East	V-North	W-Up	Easting	Northing
NaN	NaN	NaN	NaN	NaN
4883291.81	-2534277.49	-3159278.92	4883291.81	-2534277.49
4885208.29	-2529781.65	-3158620.16	4885208.29	-2529781.65
NaN	NaN	NaN	NaN	NaN
4081936.14	-2375003.57	-2094765.47	4081936.14	-2375003.57
4076073.08	-2374998.99	-2089176.88	4076073.08	-2374998.99
4063424.20	-2367004.86	-2072737.89	4063424.20	-2367004.86
NaN	NaN	NaN	NaN	NaN
4322880.24	-2475302.15	-2399575.74	4322880.24	-2475302.15
4317465.71	-2468151.60	-2389219.87	4317465.71	-2468151.60
4312558.56	-2455576.85	-2376097.067	4312558.56	-2455576.85
4301989.21	-2442987.79	-2356979.39	4301989.21	-2442987.79
4291904.18	-2444958.68	-2347406.64	4291904.18	-2444958.68
4278165.68	-2440364.45	-2330009.96	4278165.68	-2440364.45