Earth Centered Earth Fixed

A Geodetic Approach to Scalable Visualization without Distortion

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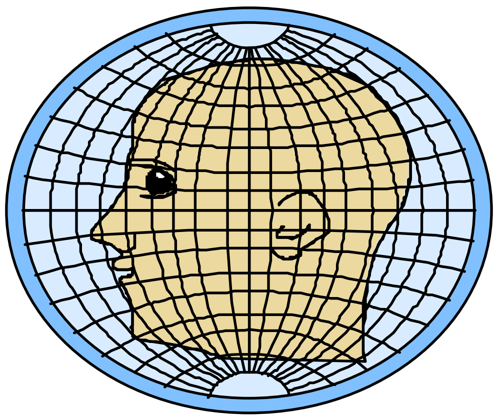
The Hydrographic Society - Houston Chapter

July 2010

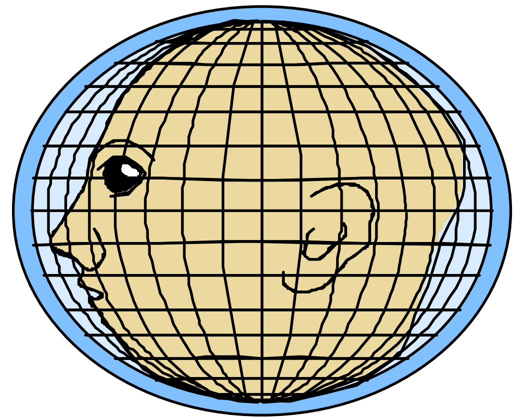
Overview and Download

- 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)
- Product announcement
- This presentation => www.hydrometronics.com

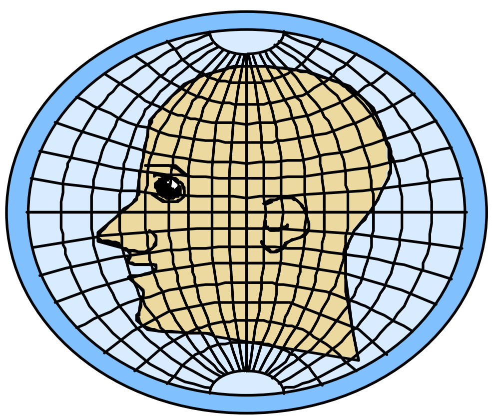
Map Projections Change Shapes



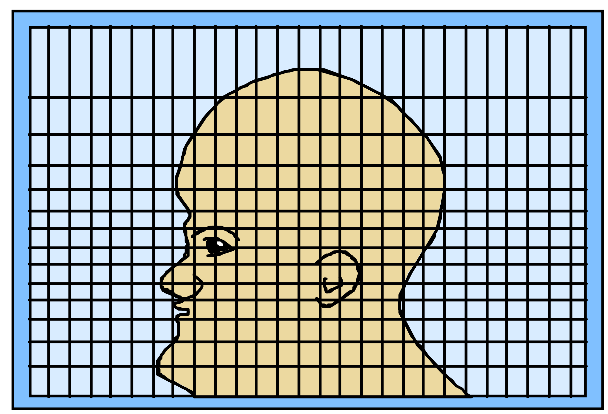
Globular projection



Orthographic projection

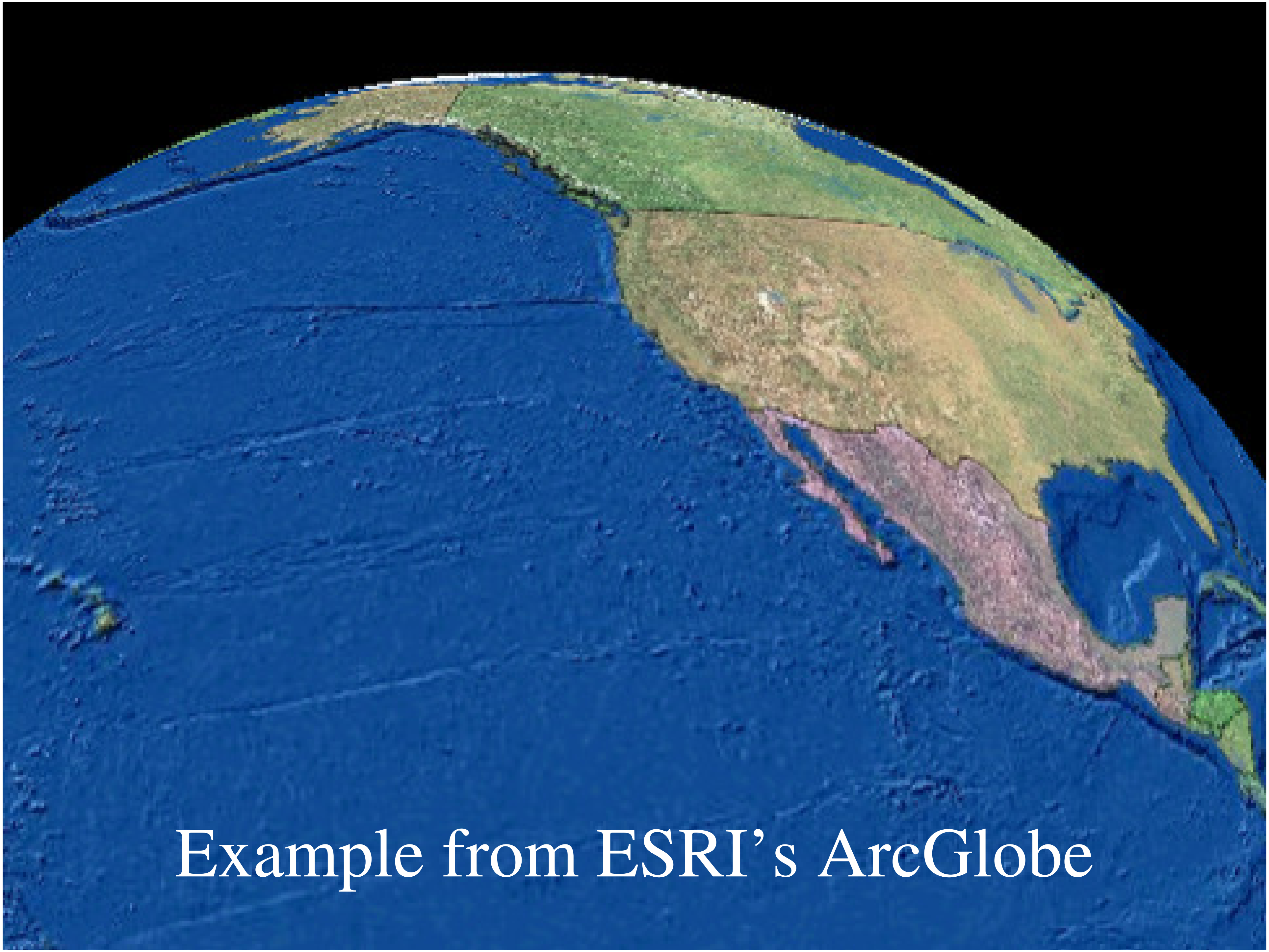


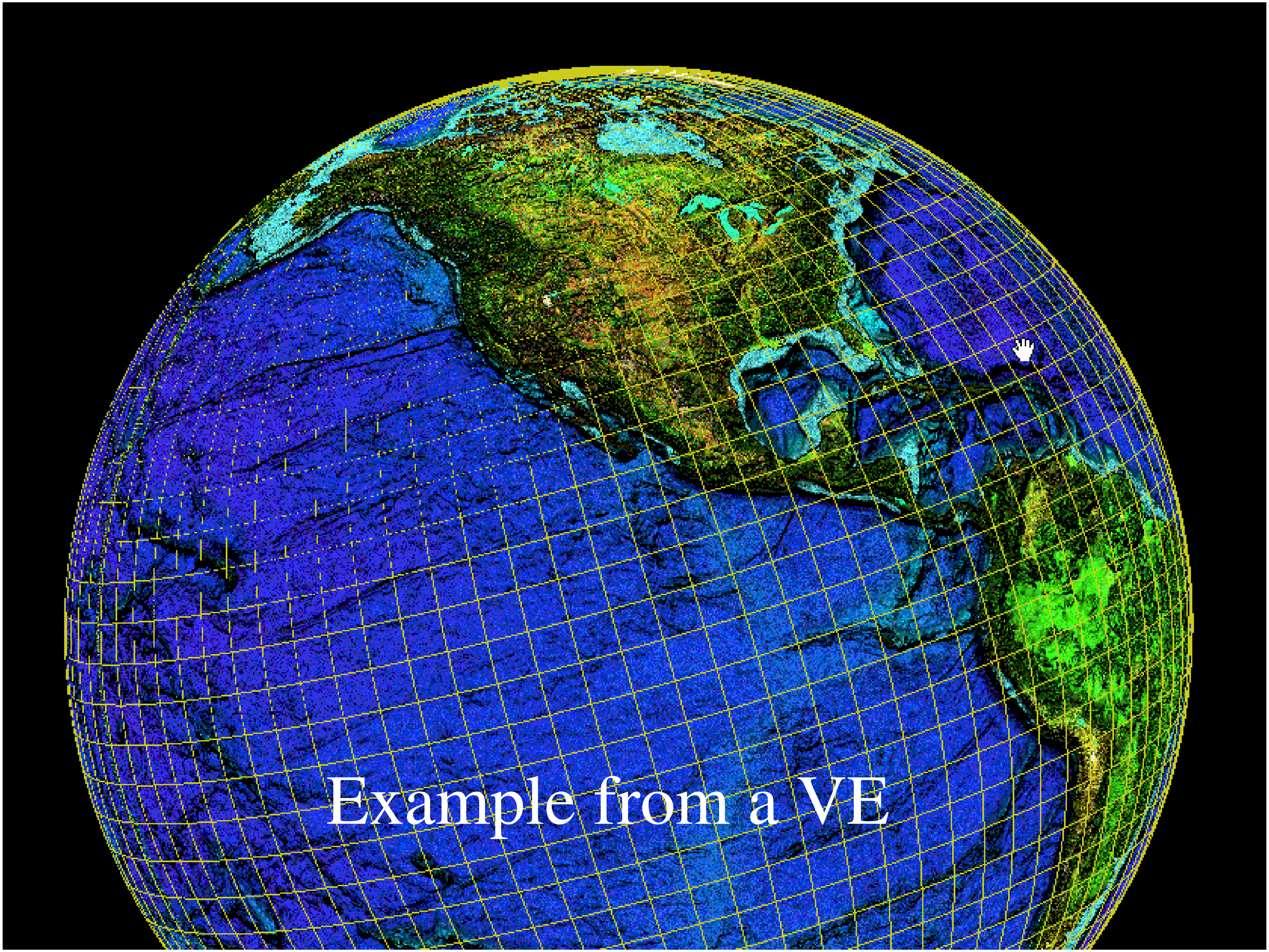
Stereographic projection



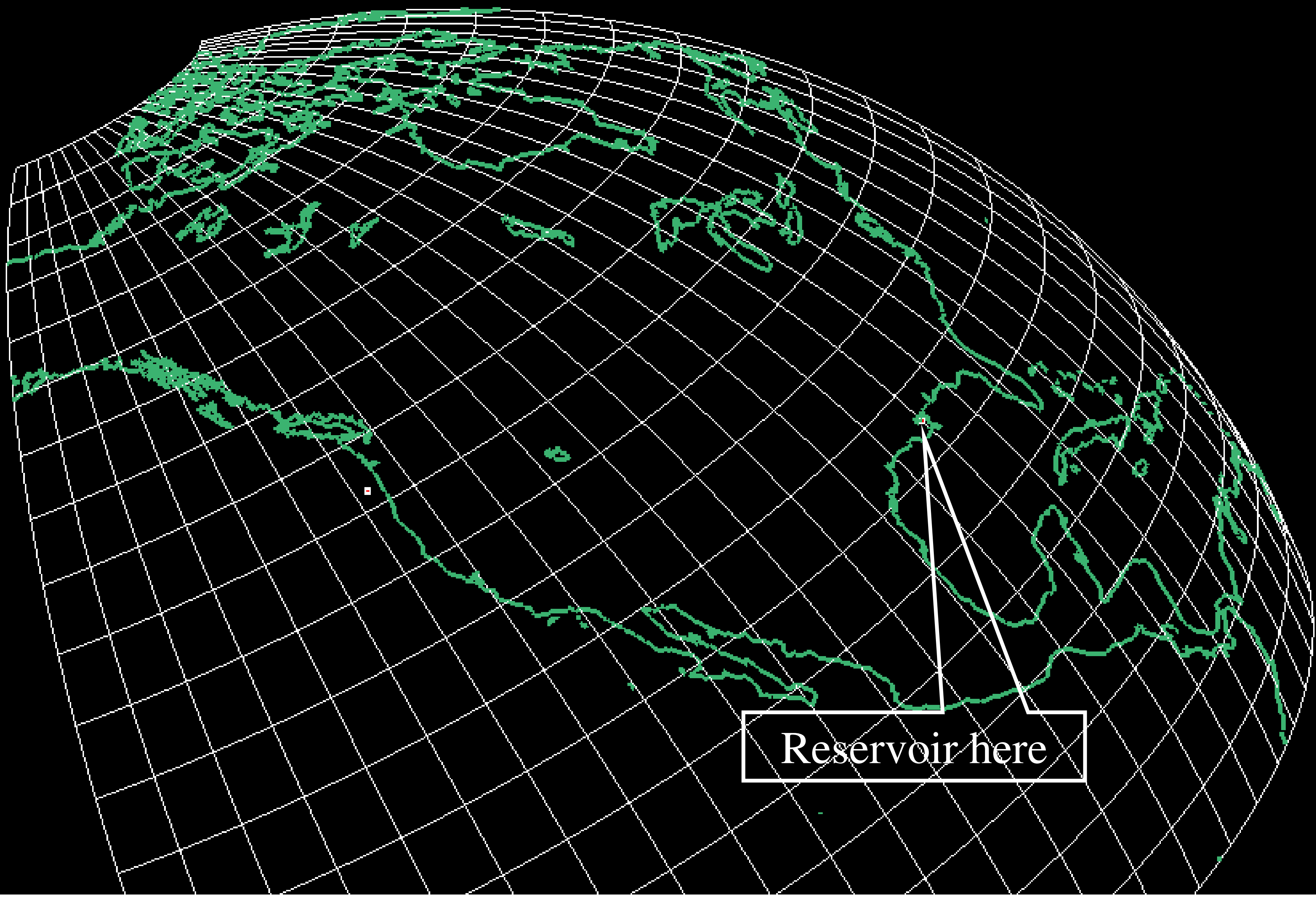
Mercator projection

Example from Google Earth

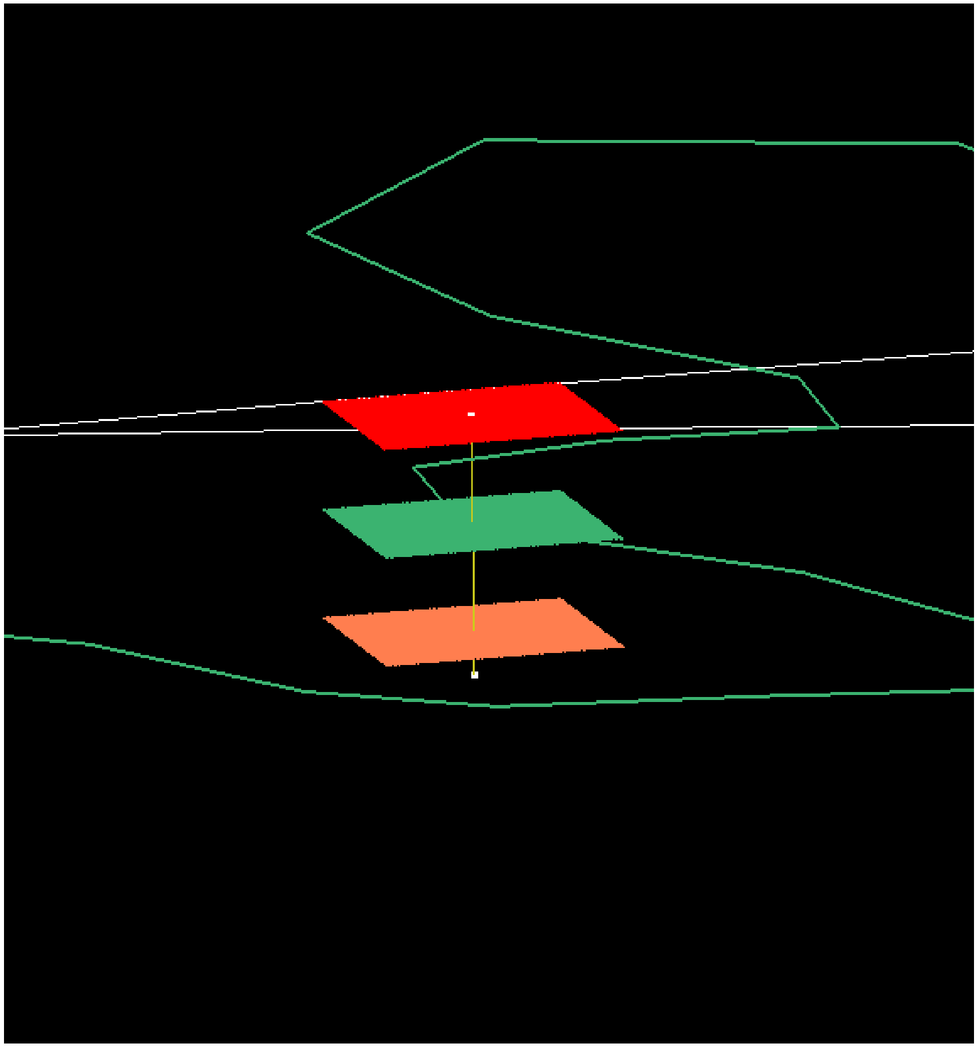

Example from ESRI's ArcGlobe


Example from a VE

Regional Cartoon in a VE



Reservoir Cartoon in a VE



This is the reservoir (a cartoon) from the previous VE slide after rotation and zooming. It is 10km by 10km horizontally with three “interpreted” horizons.

The user can scale and rotate seamlessly from reservoir to reservoir and from reservoir to region.

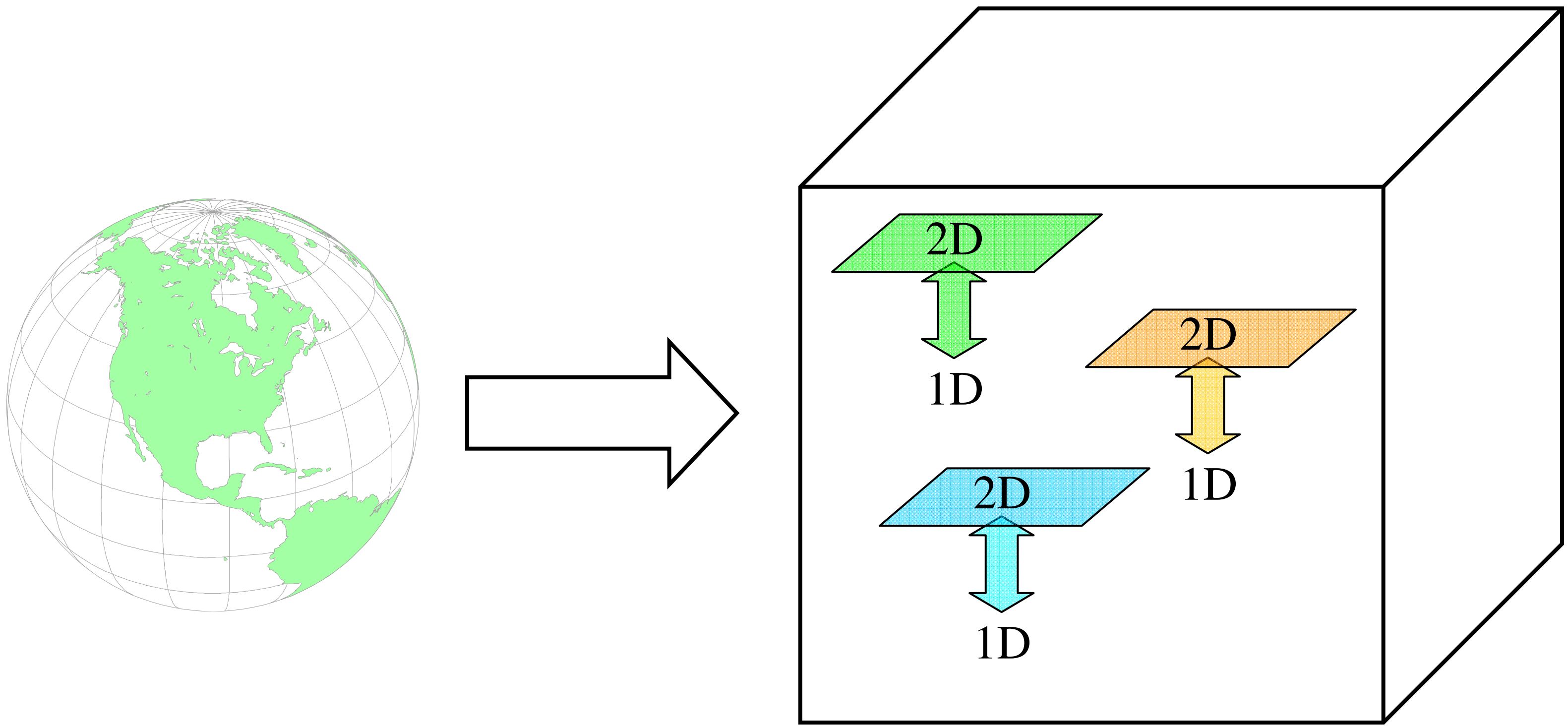
The Issue - 1

- Scalability (from tectonic plates to permeability pores) is desired in earth science software
- Software uses 2-D projected coordinates in the horizontal and 1-D 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 (if available)

The Issue - 2

- Earth science software is evolving toward visualization environments (VEs) that:
  - Operate in a 3D “cubical” CRS
  - Excel at graphical manipulation
  - Are geodetically unaware
- A different, 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

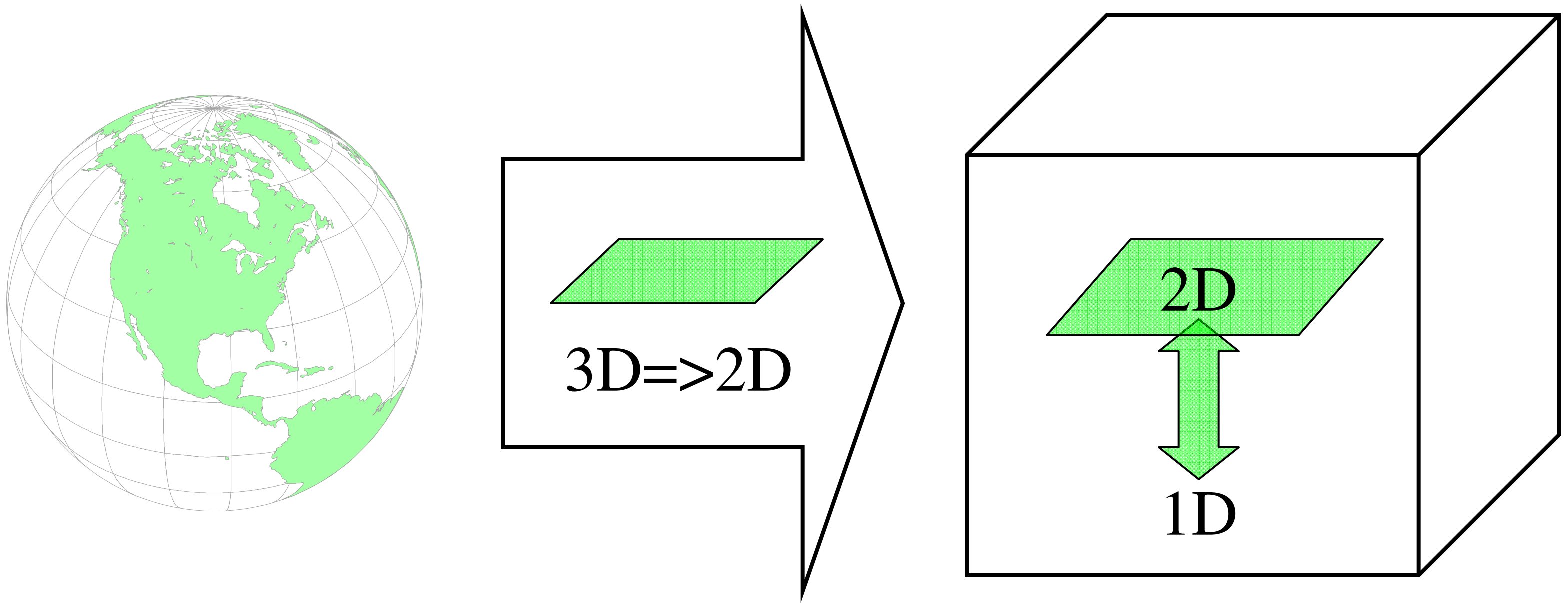
Path to Heritage Applications



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

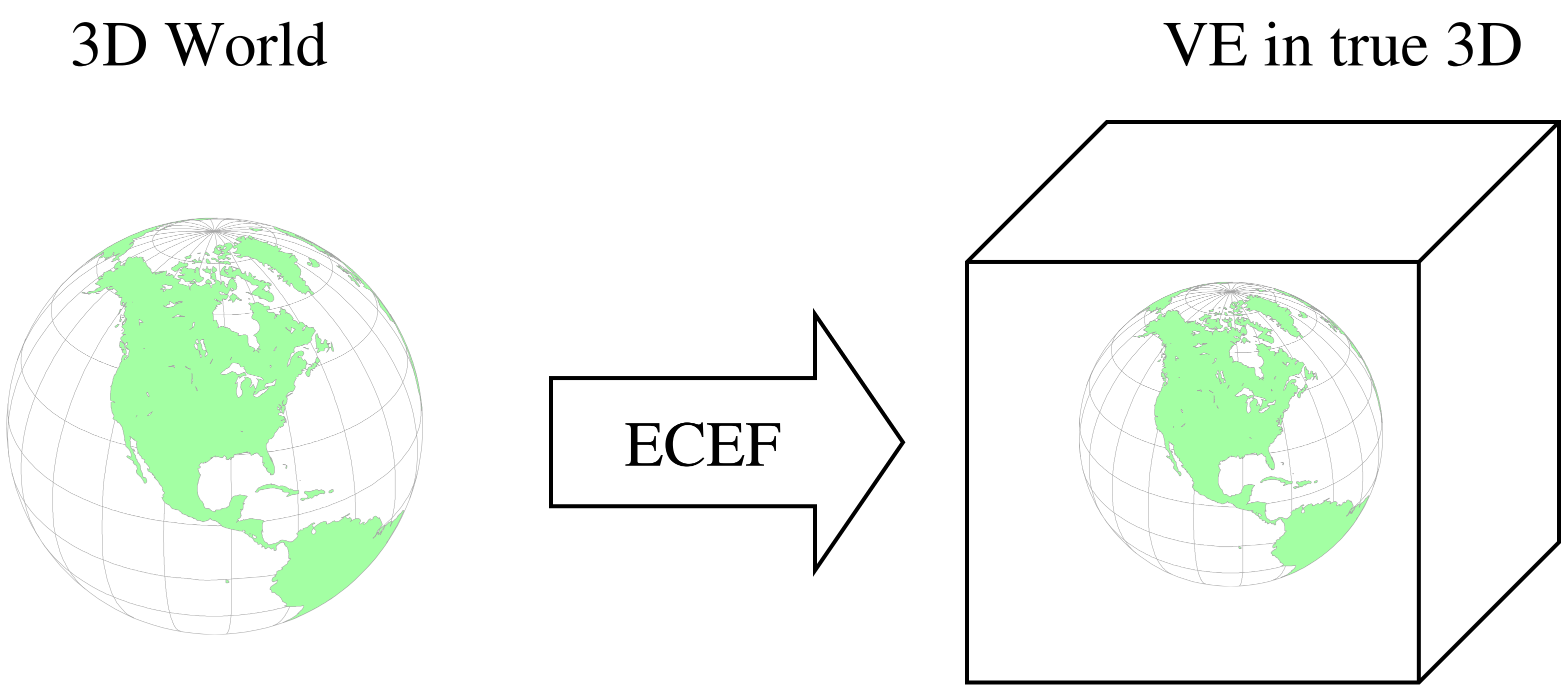
Current Path to VE via Middleware

3D World | Middleware Projection | VE in 2D+1D



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!

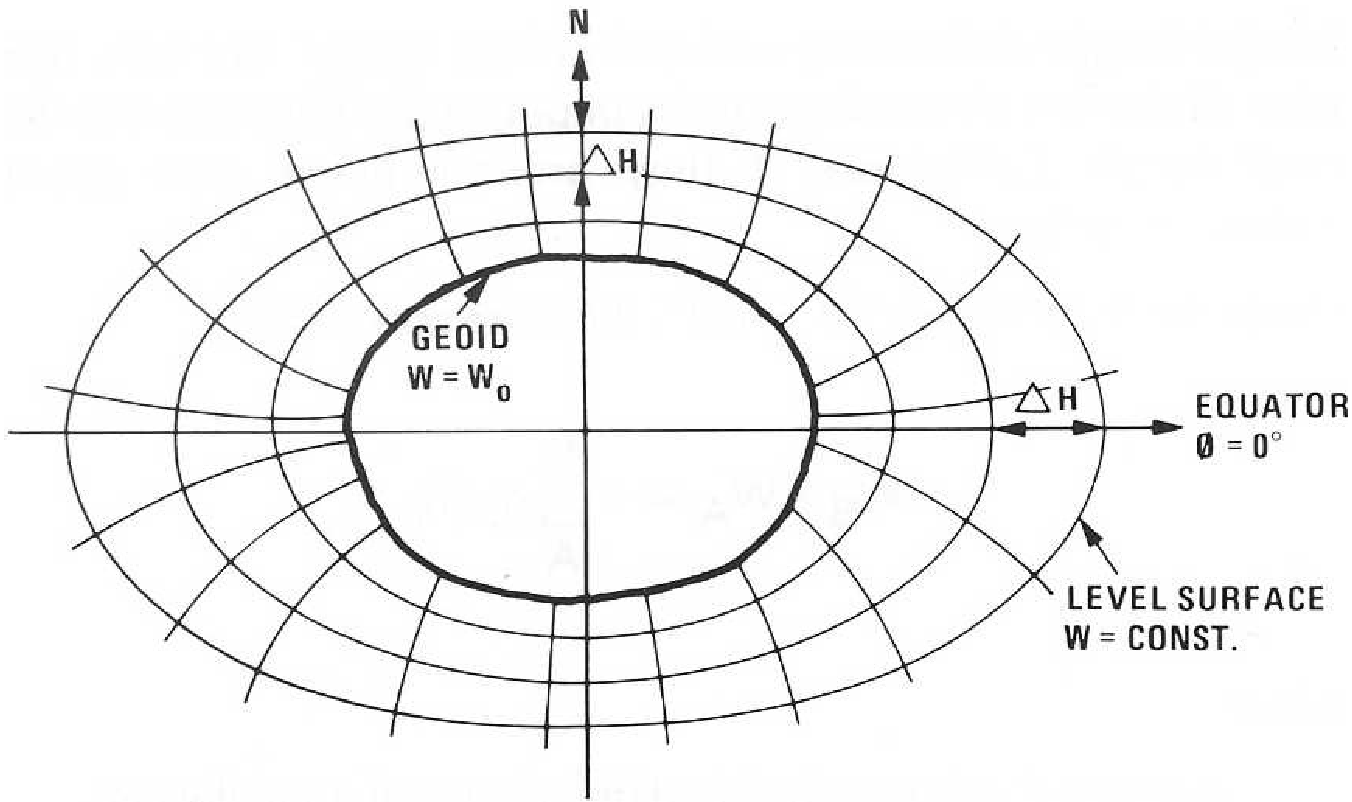
Coordinate Reference System (CRS) Primer

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

Geographical CRS: lat/lon/(height)

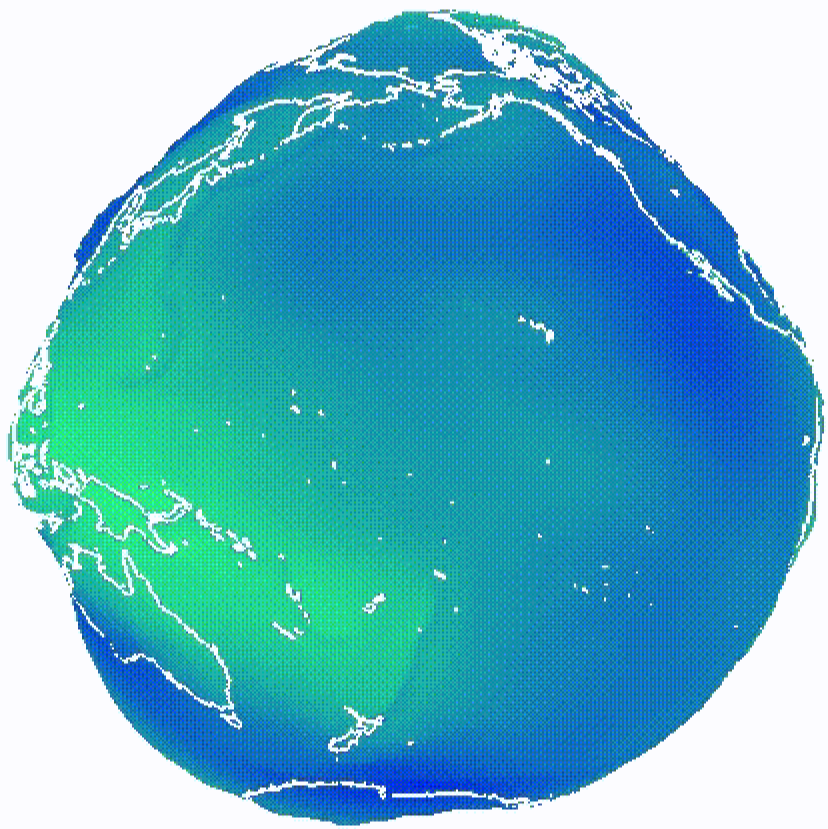
A graticule of curved parallels and curved meridians (latitudes and longitudes) intersect orthogonally on the ellipsoid. Height is measured along the normal, the straight line perpendicular to the ellipsoid surface.

Vertical CRS: 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.)

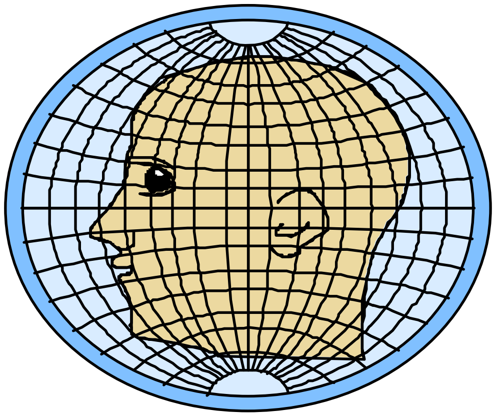
EGM2008 Geoid times 10000



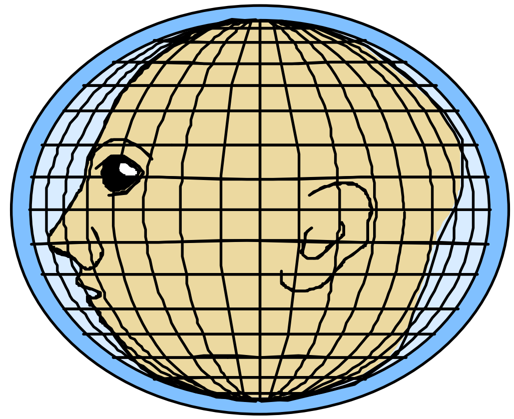
Projected CRS: Northing/Easting

- 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**

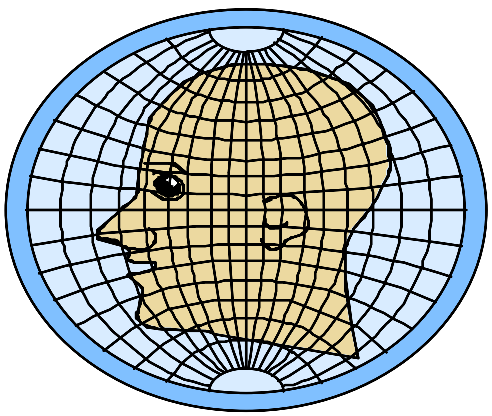
Reprojection Changes Shapes



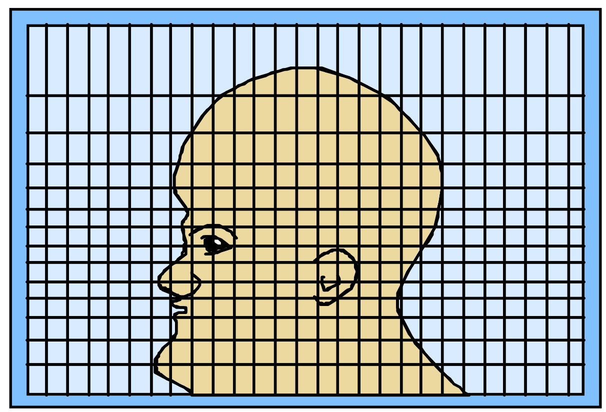
Globular projection



Orthographic projection



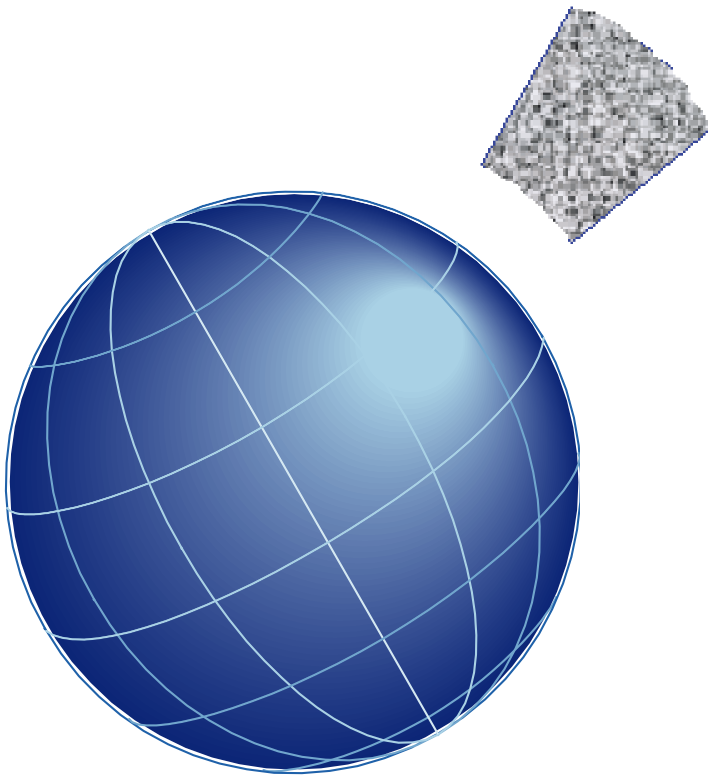
Stereographic projection



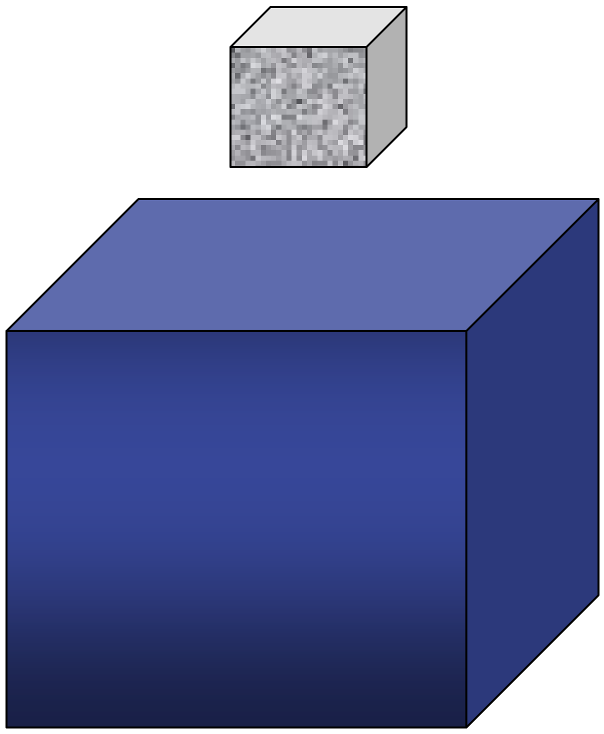
Mercator projection

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

Engineering CRS (“Flat-Earth”)

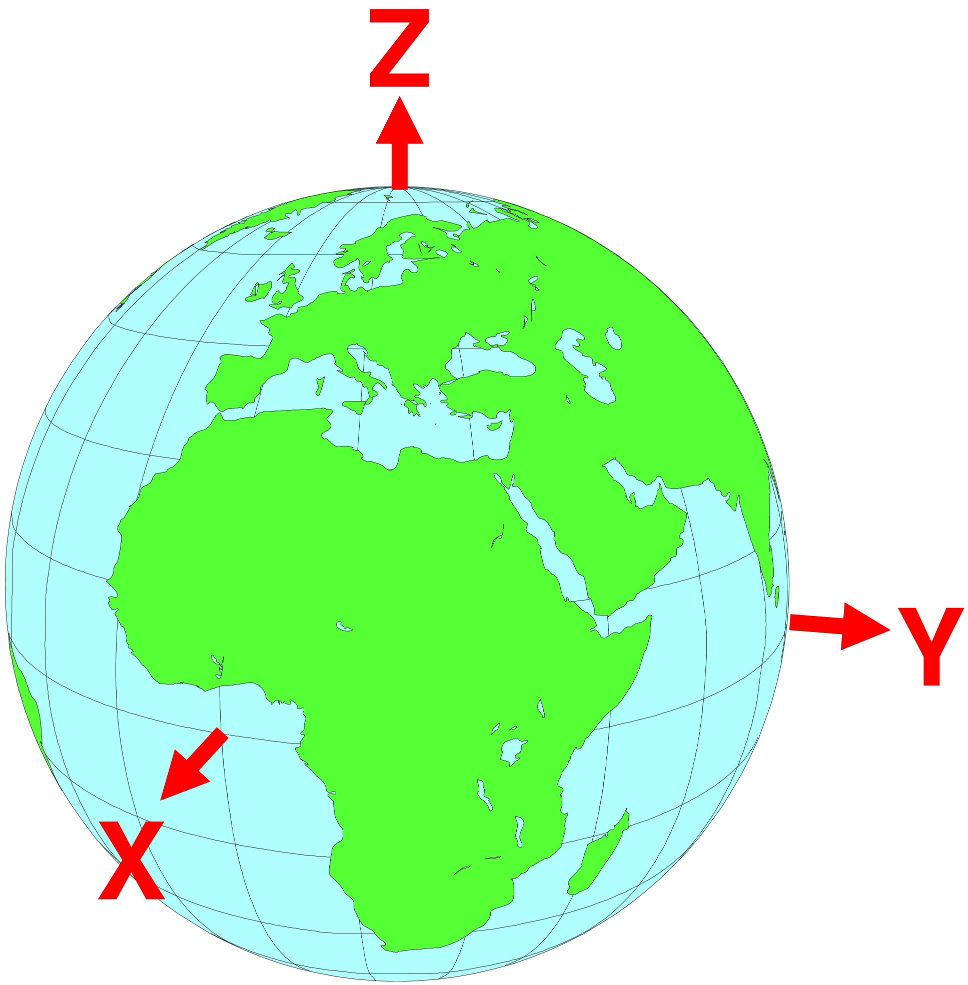


Our project extracted from an ellipsoidal earth



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 CRS coordinates to Geocentric CRS (ECEF) are simple and valid the world over
  - See the following

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

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

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

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

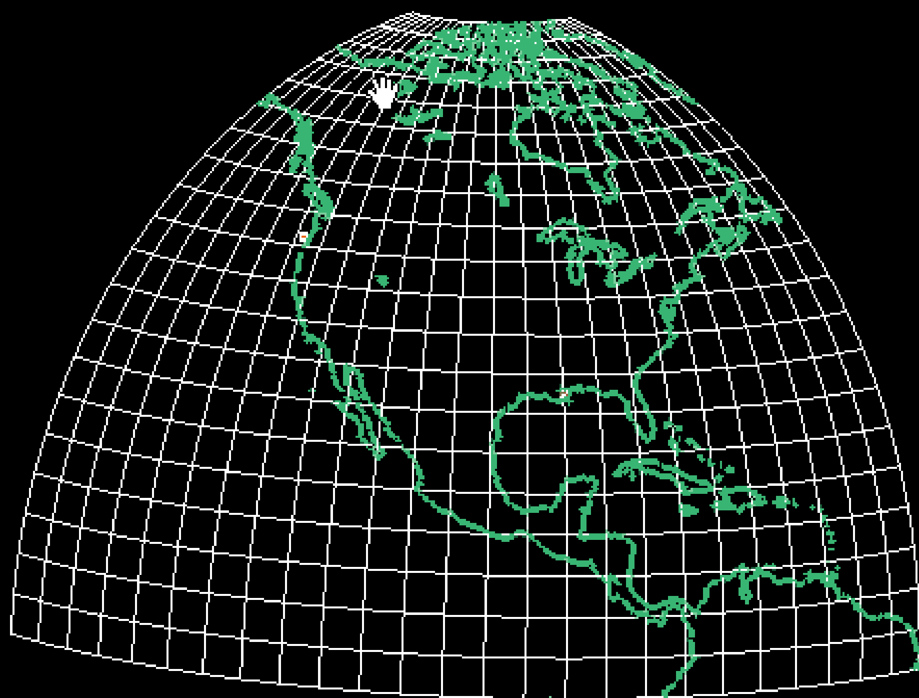
$$\lambda = \tan^{-1}(\frac{Y}{X})$$

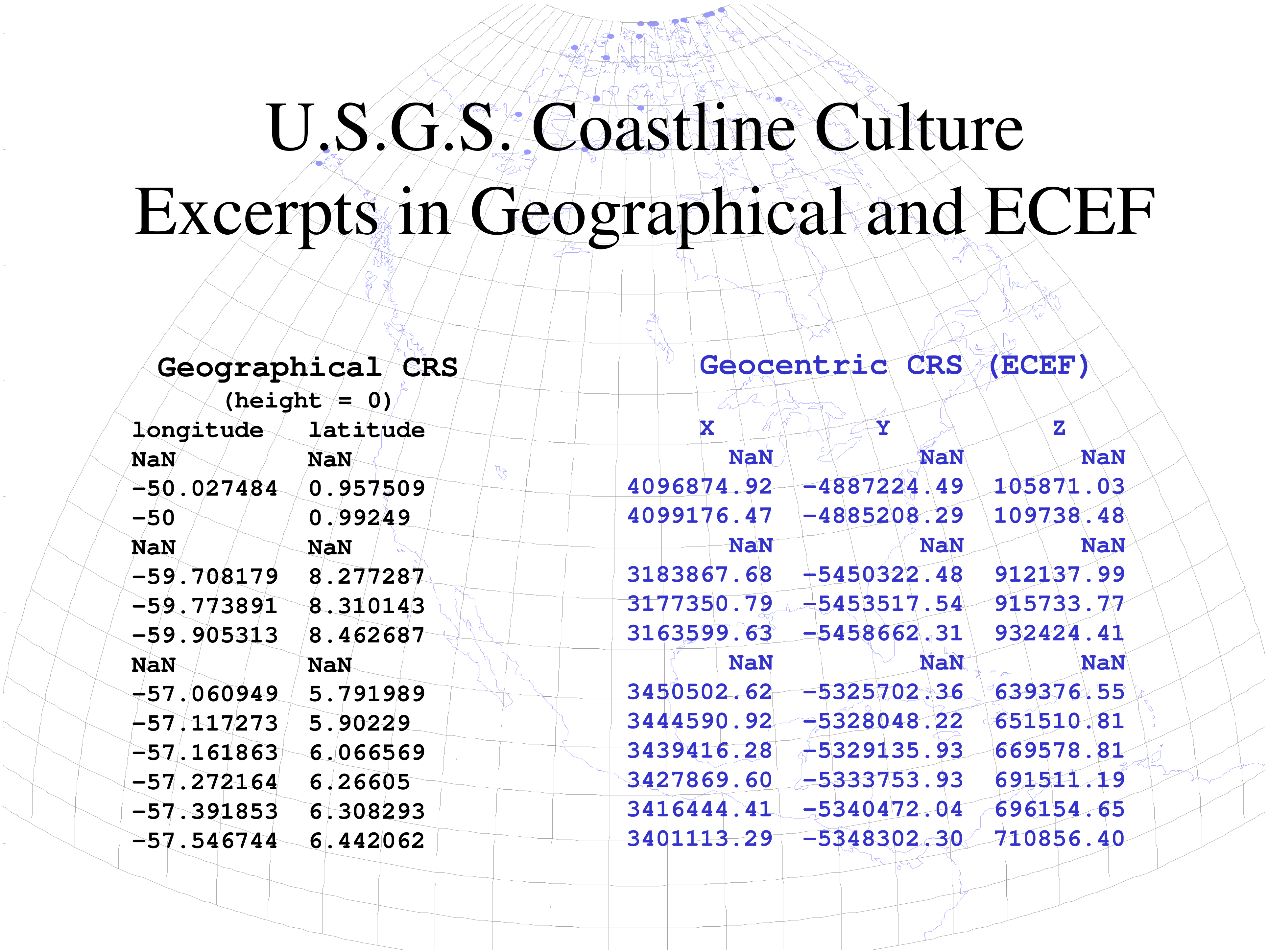
$$h = (p/\cos\phi) - \upsilon$$

Why ECEF?

- ECEF (Geocentric CRS) is the 3D CRS most similar to the coordinate reference systems already implemented in the new 3D VEs
- Coupled with the power of a VE, ECEF is like having 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

Demo of North America in VE





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

Geographical CRS
(height = 0)

longitude	latitude
NaN	NaN
-50.027484	0.957509
-50	0.99249
NaN	NaN
-59.708179	8.277287
-59.773891	8.310143
-59.905313	8.462687
NaN	NaN
-57.060949	5.791989
-57.117273	5.90229
-57.161863	6.066569
-57.272164	6.26605
-57.391853	6.308293
-57.546744	6.442062

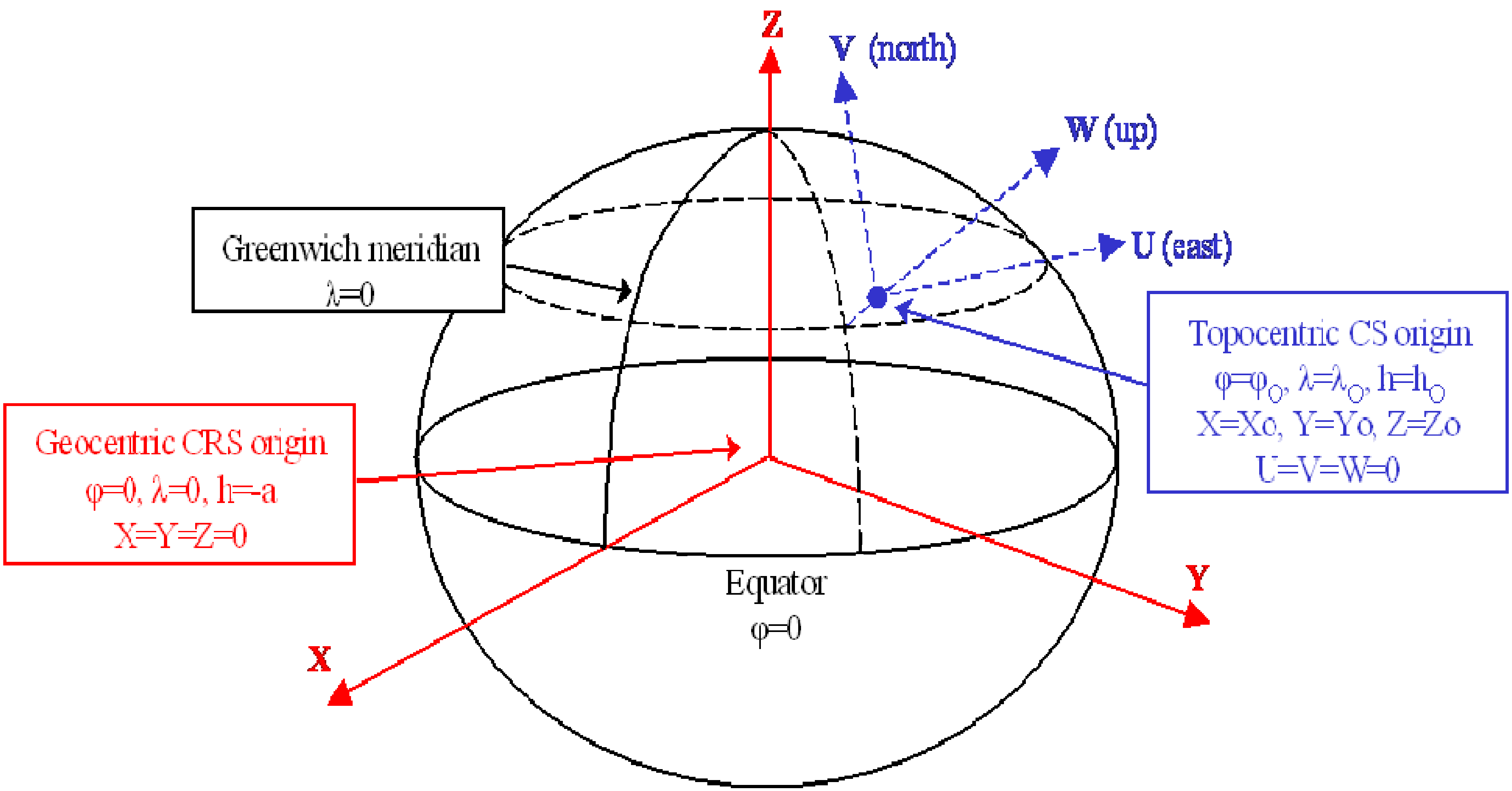
Geocentric CRS (ECEF)

X	Y	Z
NaN	NaN	NaN
4096874.92	-4887224.49	105871.03
4099176.47	-4885208.29	109738.48
NaN	NaN	NaN
3183867.68	-5450322.48	912137.99
3177350.79	-5453517.54	915733.77
3163599.63	-5458662.31	932424.41
NaN	NaN	NaN
3450502.62	-5325702.36	639376.55
3444590.92	-5328048.22	651510.81
3439416.28	-5329135.93	669578.81
3427869.60	-5333753.93	691511.19
3416444.41	-5340472.04	696154.65
3401113.29	-5348302.30	710856.40

Rotation to Topocentric

- Some VE 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

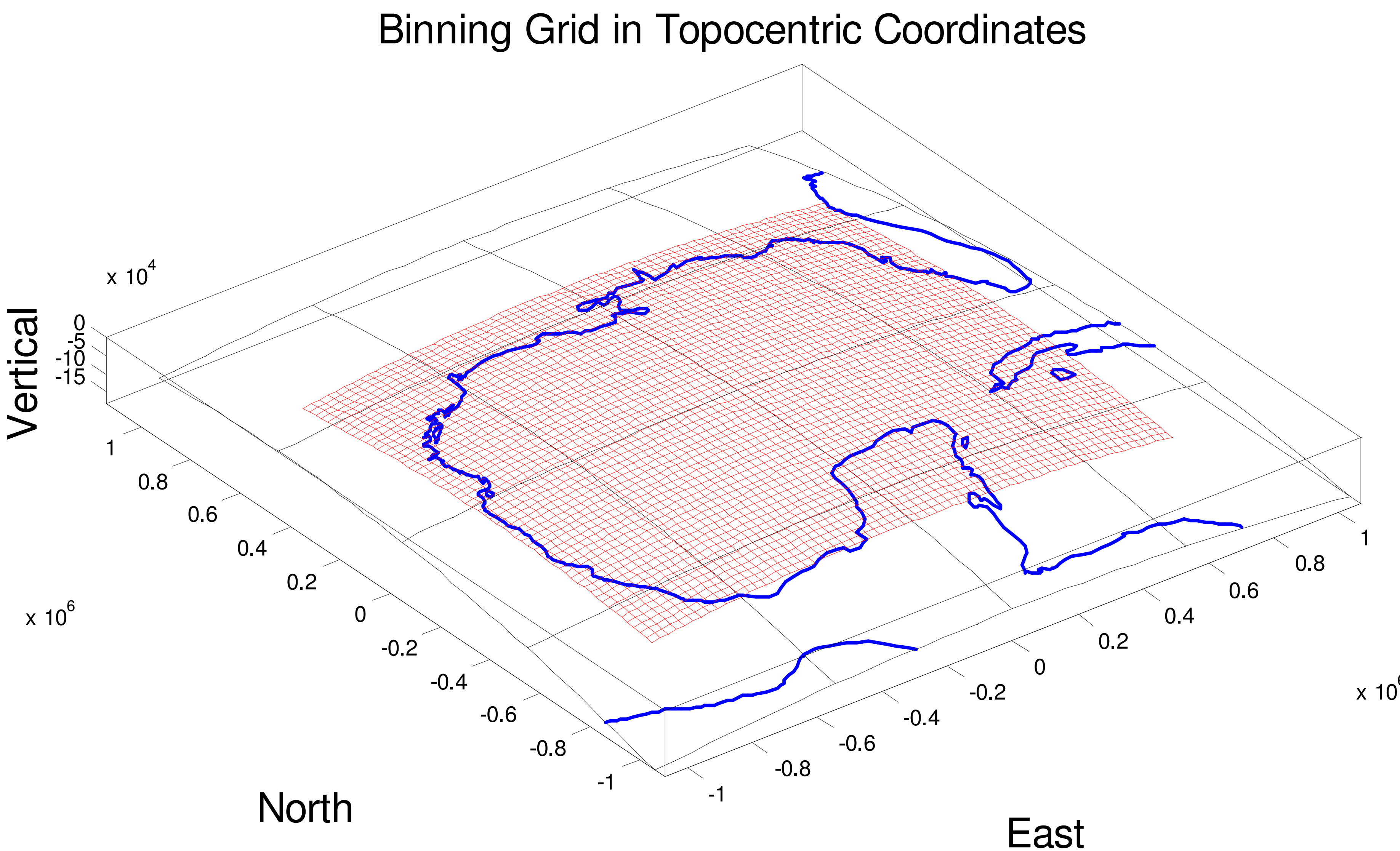


U.S.G.S. Coastline Culture Excerpts in ECEF and Topocentric

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

GOM Binning Grid in Topocentric

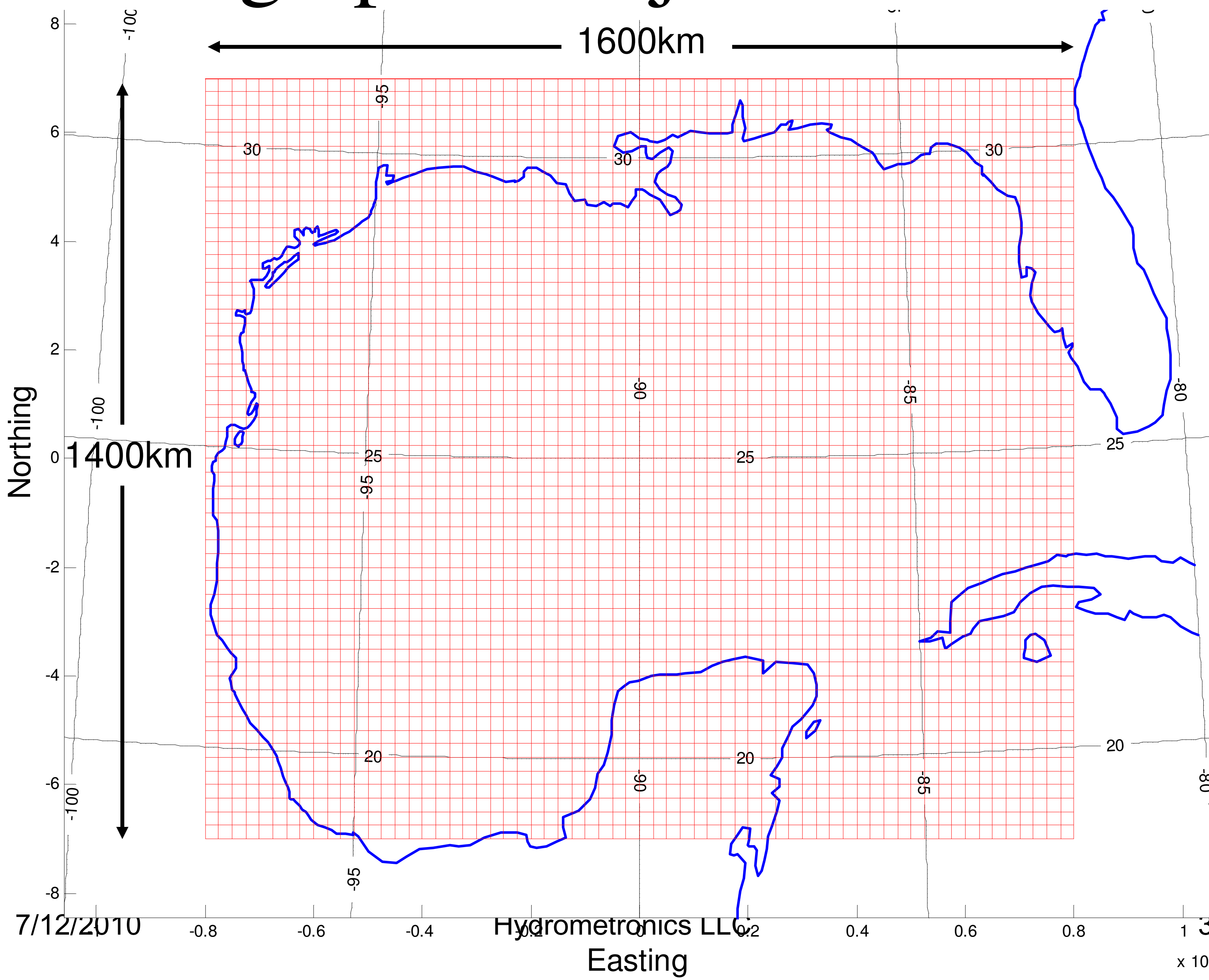


Topocentric and the Orthographic Projection

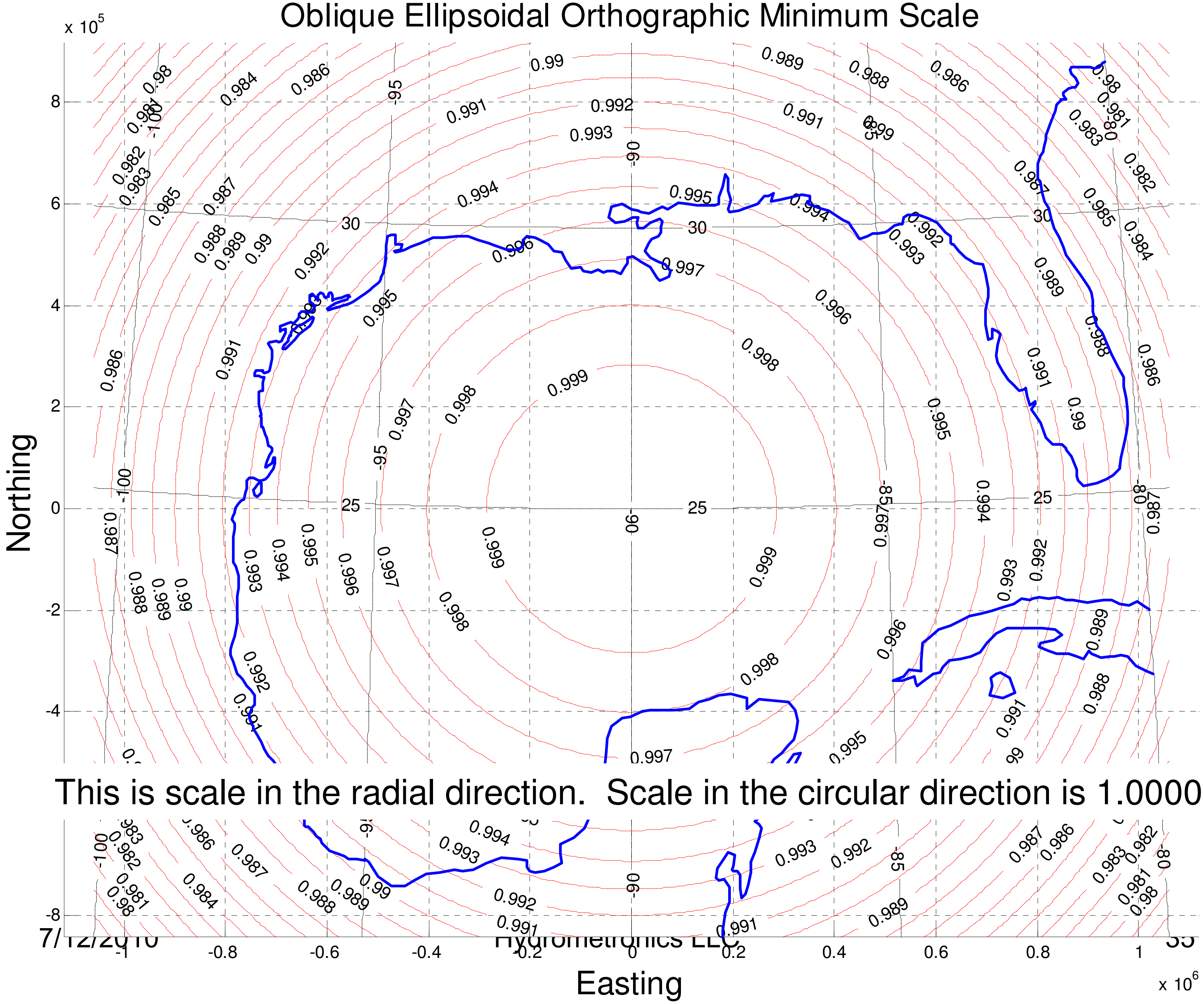
- The orthographic projection is the view from space, e.g. our view of the moon
- Topocentric without the W vertical coordinate (3D=>2D) <u>is</u> the Orthographic projection
- The ellipsoidal Orthographic projection is a bona fide map projection with quantifiable distortions intermediate between our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

Orthographic Projection of the Moon

Orthographic Projection of GOM



Oblique Ellipsoidal Orthographic Minimum Scale



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

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

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- **Orthographic coordinates (2D topocentric)**
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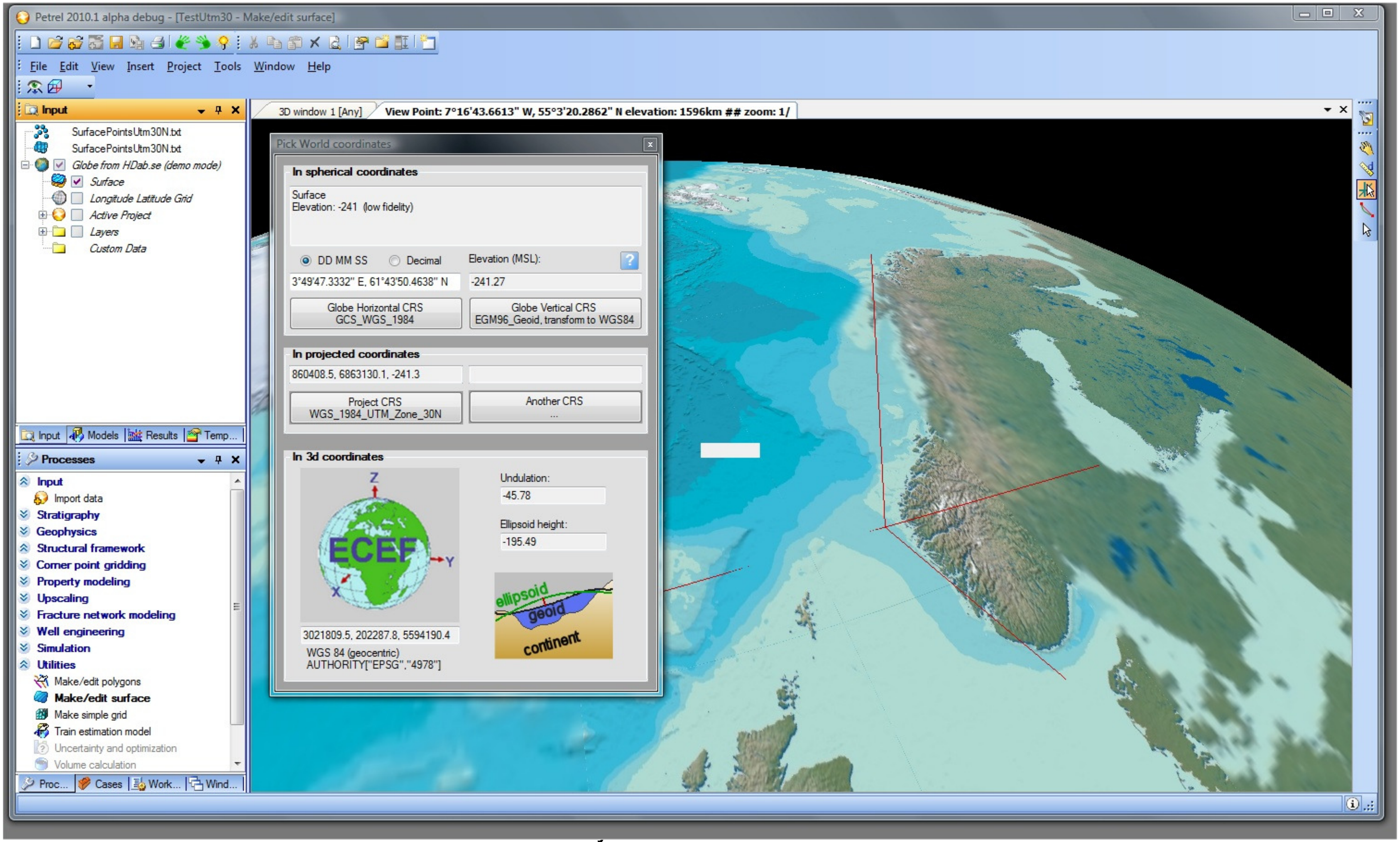
TheGlobe for Petrel



Conclusion

- The real world is 3D
- Our 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, perhaps a valuable perspective that will extract new information
- The time is ripe for ECEF

More Information

- This presentation can be downloaded at www.hydrometronics.com
- 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
- TheGlobe for Petrel at www.hdab.se

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.

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