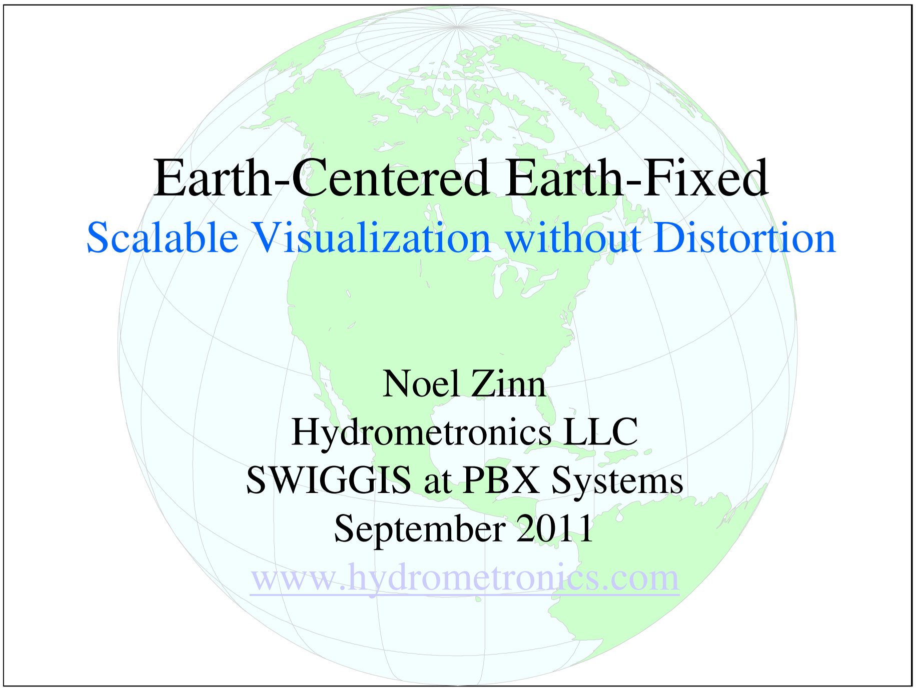
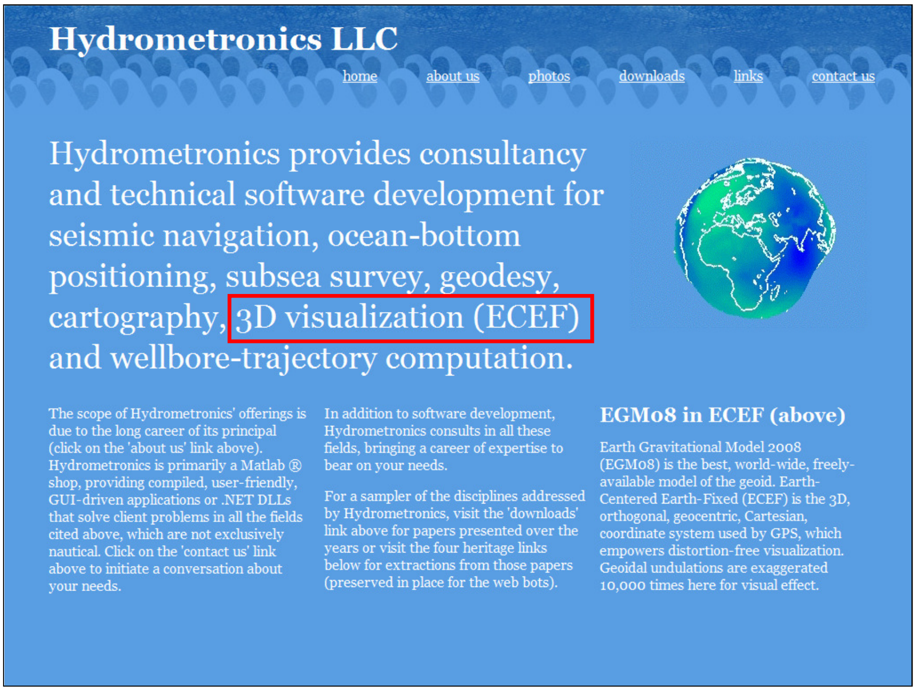


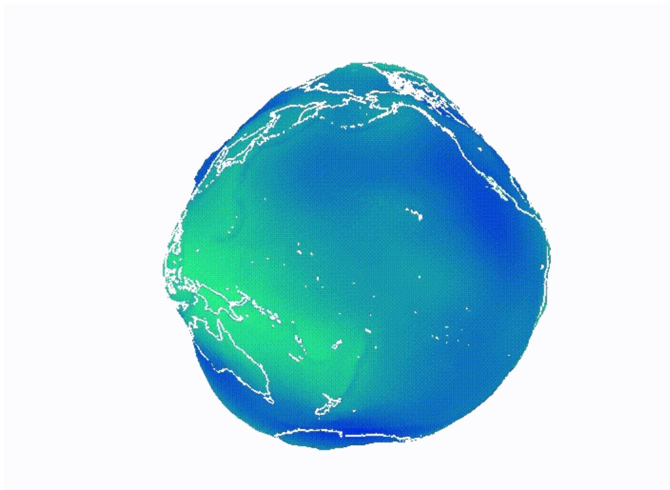

My talk today is about an Earth-Centered Earth-Fixed scheme for geodetically rigorous, 3D visualization.

Later on in the talk I'll provide a URL from which you can download this presentation.




Here's the home page of my Hydrometronics website today. Nautical positioning is not my only professional interest. Geodetically-rigorous 3D visualization in ECEF coordinates is another, and that is the topic of this talk.

# EGM2008·10,000 in ECEF



Hydrometronics LLC 3

This blue marble is an animated cartoon of the Earth Gravity Model 2008 exaggerated 10,000 times, depicted in ECEF, but its significance cannot be underestimated.

It's more than a pretty picture. First, it shows that the horizontal (the "flat" surface in which water settles) is neither flat nor even ellipsoidal. It undulates. Therefore, a 2D+1D perspective (projected coordinates with elevations attached), which assumes that the horizontal is flat, is misleading. Second, it shows that the gravity-based vertical dimension can easily be represented in ECEF. This is important for the integration of a vertical reference in ECEF.

Before one can represent the ECEF Earth in a visualization environment (VE) point elevations (the gravity-based vertical dimension) must be converted to heights (ellipsoid-based vertical dimension). EGM2008 is the best worldwide vertical model to use for this.

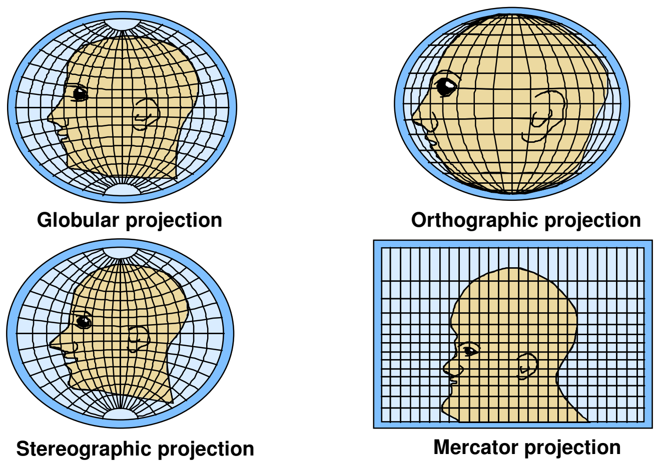
# Overview

- 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

Hydrometronics LLC 4

So, with these prefatory comments, here's our agenda for this afternoon. (Read and elaborate.)

# Cartography is distorted …




Hydrometronics LLC 5

The simple point to be made with this slide is that 2D map projections necessarily change shapes in ways that are specific to the type of projection. Here are some examples. Both the Stereographic and the Mercator projections are conformal, which means that lines intersect at the same angle on the map that they do on the surface of the Earth. Local shapes are preserved on conformal projections, but large shapes change, and change differently (as can be seen). The Orthographic projection is the view from space (i.e. from infinity) and it plays an important role in the theme of this talk. More later on the Orthographic. The Globular projection is somewhere between the Stereographic and the Orthographic. Neither the Globular nor the Orthographic are conformal.

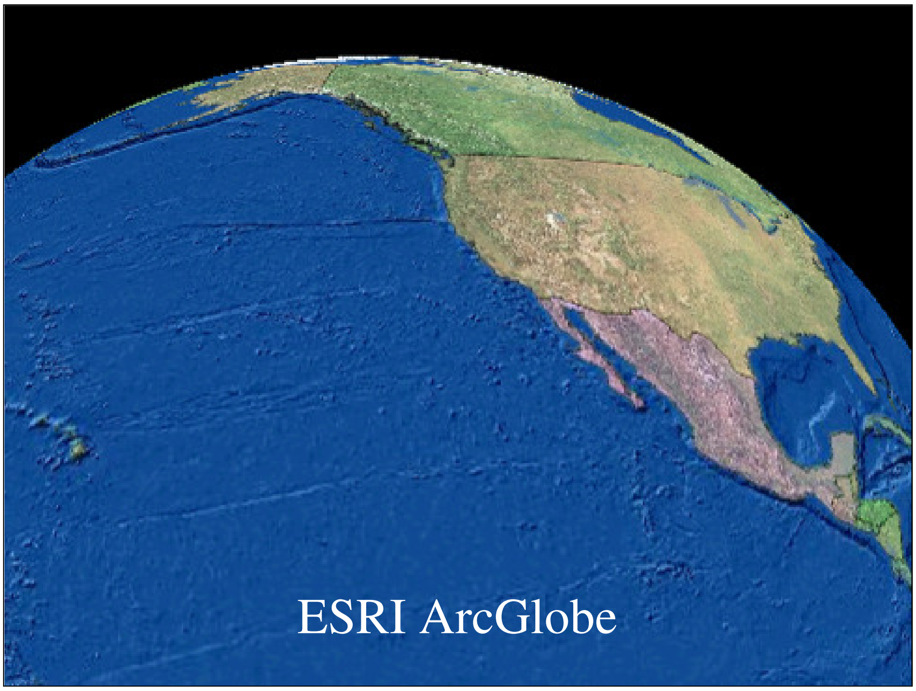
Cartography is distorted …


… but geodesy is not!

This graphic is of a latitude/longitude graticule and some low density satellite imagery in ECEF in a 3D geoscience visualization environment (VE). In ECEF the Earth is presented as an ellipsoidal that can be rotated with your cursor. Any particular area of interest can be viewed normally (that is, perpendicularly) without distortion. It's like having a globe in your hands.


A similar perspective is provided by Google Earth, but probably not in ECEF.

Google Earth's popularity has informed Earth scientists in the value of this perspective.  A feature provided by ECEF in geoscience workstations that is not provided by Google Earth is the ability to view below the surface of the Earth into our seismic projects.




Another similar perspective is provided by ArcGlobe, a companion product to ESRI's ArcGIS.

ArcGlobe works its magic with a "cubic" projection, not with ECEF.

# 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



These are the issues.

(Read and elaborate.)

# 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



(Read and elaborate.)

# 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!)

Hydrometronics LLC 11

Let's unpack the phrase "visualization environment" (VE)

The largely French Gocad Research Group of multidisciplinary researchers (supported by a Consortium of 18 companies and 121 universities) began about 20 years ago to define new approaches to build and update 3D subsurface models. Today, the Gocad software is a commercial product of Paradigm Geophysical.

Petrel was developed by Technoguide in Norway using the HueSpace 3D renderer by Headwave, also Norwegian. Today both Petrel and HueSpace are owned by Schlumberger.

The Matlab "matrix laboratory" is my 3D VE of choice, using the 'plot3' command.

ArcScene (not ArcGlobe) is the ESRI 3D offering.

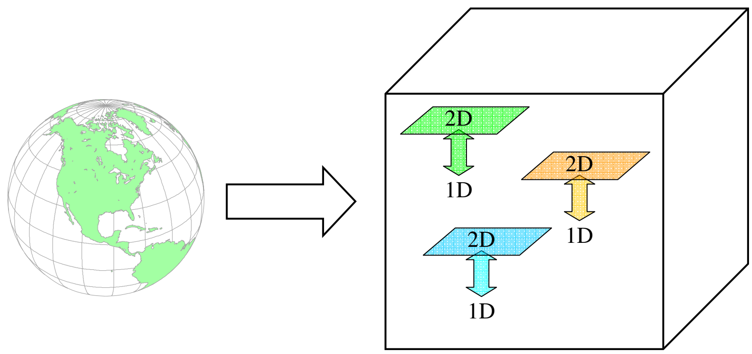
VTK is a $27M visualization environment (assessed by adding up developer hours) that you can download for free from www.vtk.org.

Mayavi is a user-friendly front end to VTK using the Python scripting language, an improvement of VTK's native Tcl/tk (tool command language/toolkit) IMO.

BMCG has some remarkable graphical capabilities in 2D, which is another significant advancement over the 1993 version I showed your earlier. Is 3D the next step?

I recently purchased an iPod touch because it has an inertial measurement unit (IMU) onboard. Some of the iPod apps certainly look 3D to me. How about ECEF in an iPod?

# Heritage Applications

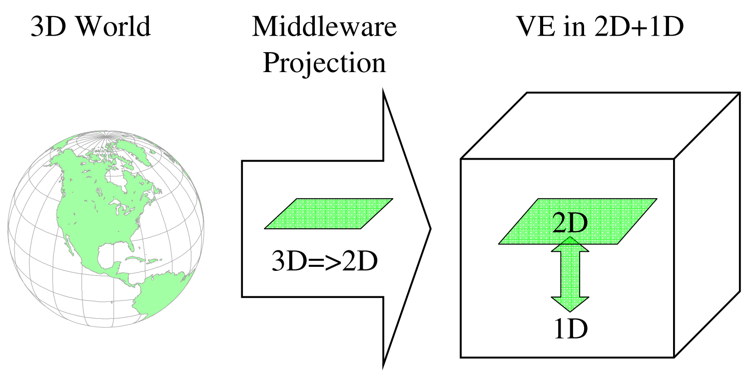



Heritage earth-science applications with internal geodesy support any projected coordinate system (2D horizontal + 1D vertical), but with the usual, well-known mapping distortions



Examples of heritage, geodetically-aware geophysical applications are Schlumberger's GeoFrame and Landmark's OpenWorks (which has BMGC as its geodetic engine). Multiple 2D projections and multiple datums coexist side by side in these applications. Projects can be transformed from datum to datum or converted from projection to projection as data management requirements dictate. Projection distortions can be managed in such as system, but distortion is always there nevertheless. The horizontal dimension is presumed to be flat with the vertical dimension perpendicular to the horizontal.

# 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.

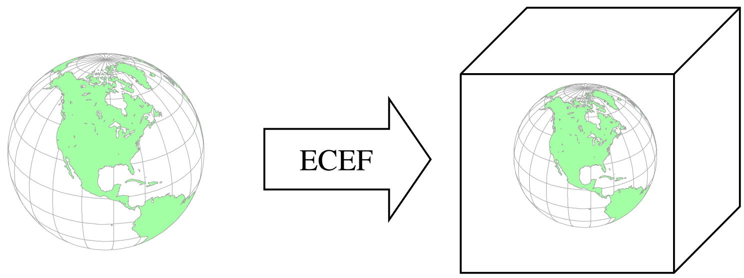


Examples of geoscience visualization environments (VE) are Petrel and GoCAD. Only one datum and projection lives inside a VE at any one time. Projection distortions cannot be managed in a VE, which is best suited to reservoir-sized prospects (minimal distortion). Regional studies have large projection distortions.

Update: Petrel projects can be flushed from the VE and reloaded in a different projection or datum as data management requirements dictate.

An example of middleware is TIBCO OpenSpirit.

# 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.



This slide depicts the (perhaps) revolutionary step proposed in this presentation. That is, use the ECEF coordinate system (described later) to move a 3D Earth into a 3D visualization environment (VE). Geodetic rigor is maintained. There is no projection distortion. Each prospect can be worked locally. All projects fit together globally. A VE in ECEF is suitable for both local and regional projects.

# 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)

Hydrometronics LLC 15

These are the coordinate reference systems (CRS) described by the Geomatics committee of the International Association of Oil and Gas Producers (OGP), formerly the EPSG.

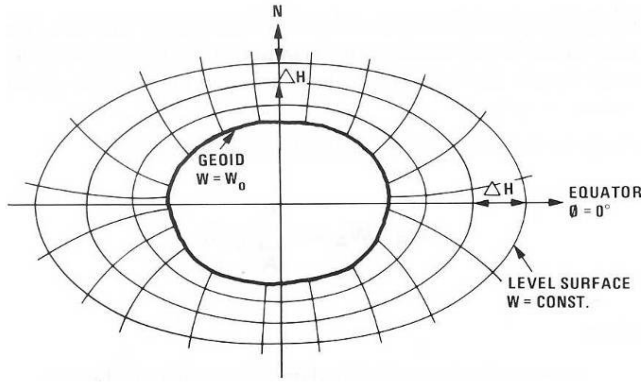
# Geographical CS: lat/lon/(height)

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.



No notes.

# 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.)



No notes.

# 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$^2$**



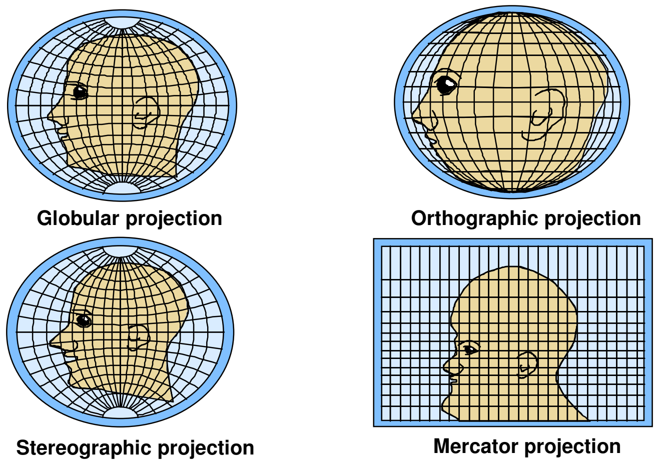
A map projection is a mathematical “mapping” of 3D ellipsoidal space onto a 2D planar space. Distortions are inevitable. But we can preserve selected properties of the 3D surface by our choice of mapping equations.

In this slide I’ve listed some of the desirable preservations.

We can preserve some features, but will unavoidably distort other features.

Distortions increase proportionally to the square of the distance.

# Projected CS Distorts

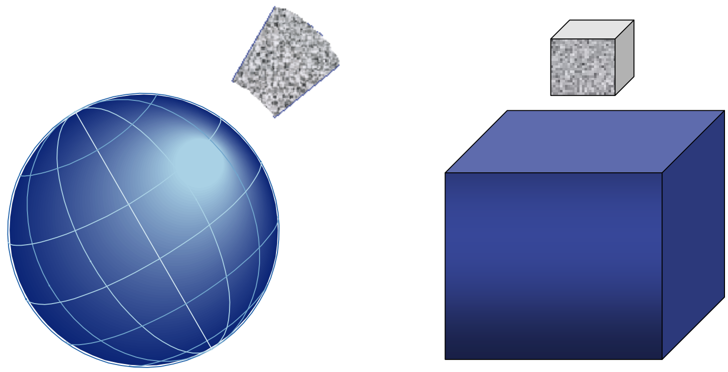



**Rule of thumb: map distortion $\propto$ distance$^2$**

Hydrometronics LLC 19

Not only do different projections depict shape differently, but re-projection from one projection to another (even if conformal) changes shape.

# Engineering CRS ("Flat-Earth")



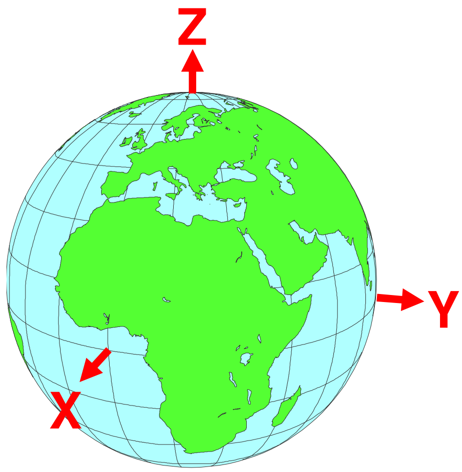
Our project extracted from an ellipsoidal earth

Our project extracted from a cubical, flat earth



The Engineering CRS presents the world as a cube, which is an approximation valid only over a small, local area. Nevertheless, this cubical concept permeates our thinking about our projects over larger areas. For example, geophysical data processing presumes that all verticals are parallel. In fact, verticals converge.

# 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.



Earth-Centered Earth-Fixed (ECEF) is also known as Geocentric CRS. Any point on or near the surface of the earth is represented in a 3D, rectilinear, right-handed XYZ coordinate frame fixed to the Earth. The origin (0, 0, 0) is the geocenter. The positive X-axis extends from the geocenter through the intersection of the Greenwich Meridian with the Equator. The positive Y-axis extends from the geocenter through the intersection of the 90E meridian with the Equator. The positive Z-axis extends from the geocenter through the North Pole.

# 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

Hydrometronics LLC 22

The validity of map projections are constrained in two ways. First, distortions increase as the square of distance. Second, the algorithmic implementation of some projections (especially the Transverse Mercator) introduces computational errors as one moves from the center or central meridian of the projection.

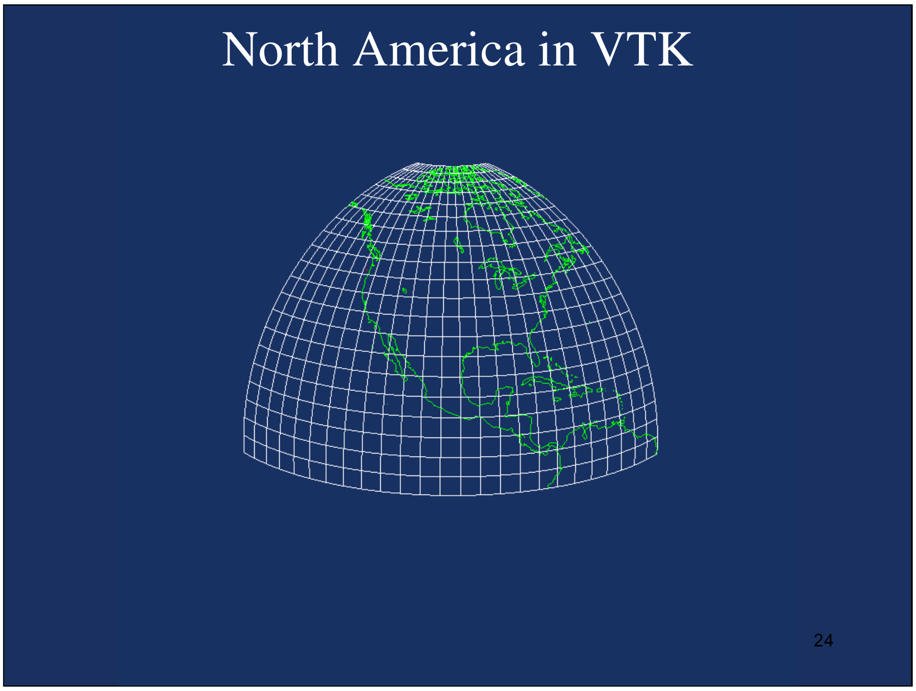
The geographical ⇔ geocentric (ECEF) conversion does not suffer this problem.

# So, Why ECEF?

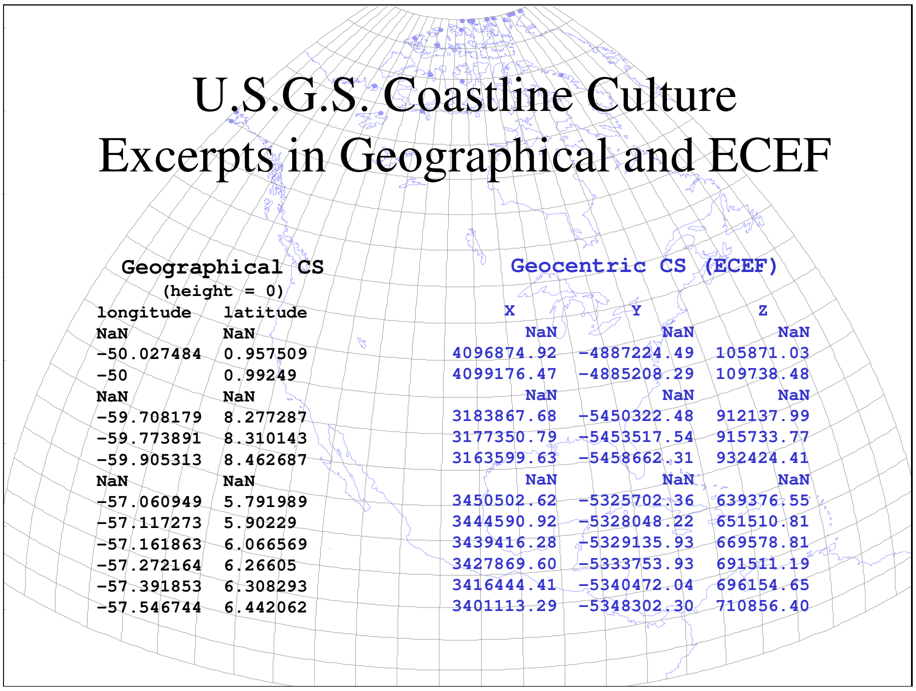
- ECEF is the geodetic CS native to a 3D VE
- ECEF in a 3D VE is a globe in your hands
- Given the proper perspective (turning the globe), ECEF coordinates have no distortion
- ECEF is scalable from plates to pores
- No geodetic “smarts” are required in the VE



No notes.




This demo is not available in the PDF version of this presentation. It shows a cartoon of the North American octosphere. The image is rotated to show distortion-free perspectives wherever desired.



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

**Geographical CS**
(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 CS (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 |

Here's what ECEF coordinates look like. This is coastline culture downloaded from NOAA (link at the end of this presentation) in Matlab format.

On the left are latitude and longitude. We assume that height is zero. The NaNs mark the beginning and end of connected polygons. Matlab interprets these as "lift pen" commands.

On the right are ECEF XYZ for some small part of North America.

## Translation & Rotation: ECEF to Topocentric

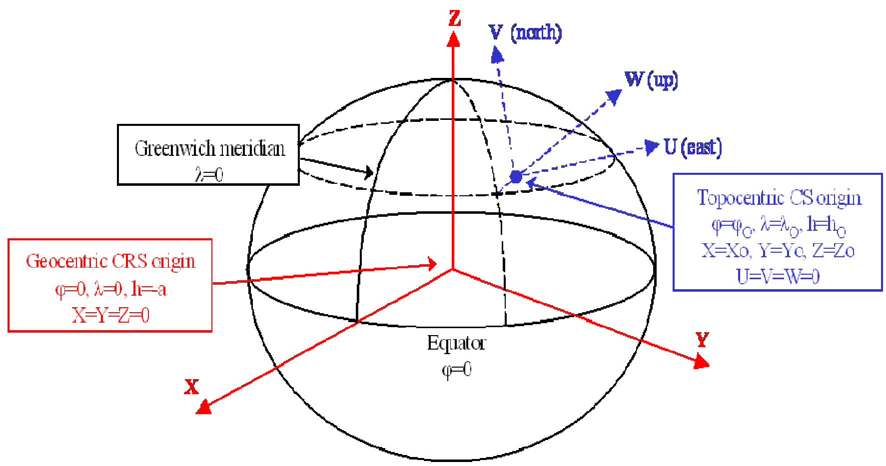
- A journey back to Projected CS because …
- … some users may prefer their data referenced to their local area of interest
- ECEF can easily be translated and rotated to a topocentric reference frame
- This conversion is conformal,
  it preserves the distortion-free curvature of the earth,
  and the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

Hydrometronics LLC 26

This slide marks an important transition in the presentation, the translation and rotation from geocentric ECEF coordinates to topocentric coordinates, called East/North/Up (ENU) in Wikipedia, topocentric horizon by Bugayevskiy & Snyder, local vertical by the Manual of Photogrammetry and local horizontal by myself previously.

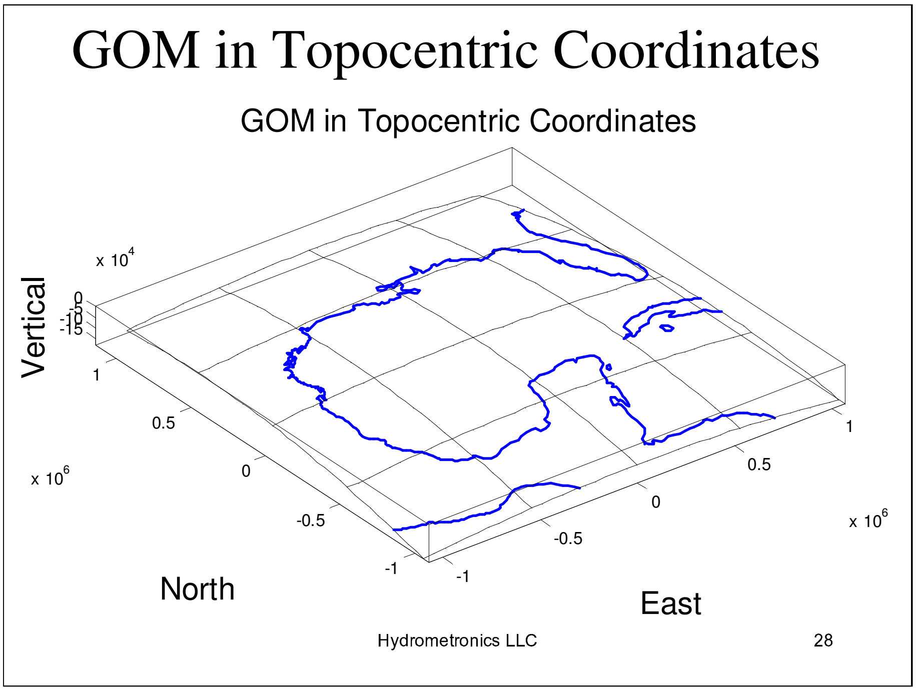
ECEF coordinates present the whole world – or just your local project – from the geocentric perspective. The geocenter may be far away. The geoscientist may prefer a local origin for their project. That is provided by topocentric coordinates (called UVW here), which preserve all the curvature of the Earth. But the perspective is local and more familiar.

# EPSG Graphic of Topocentric




Hydrometronics LLC 27

ECEF (XYZ) is shown in the red coordinate frame, topocentric (UVW) in the blue. A translation and a rotation are required to convert one into the other. These equations are well-known and can be found in the EPSG Guidance Note 7 Part 2 (www.epsg.org).




Here's the entire GOM shown in 3D topocentric coordinates. The curvature of the Earth is still visible, just not as much of it. The more local one becomes, the less curvature one sees.

# Topocentric to Orthographic

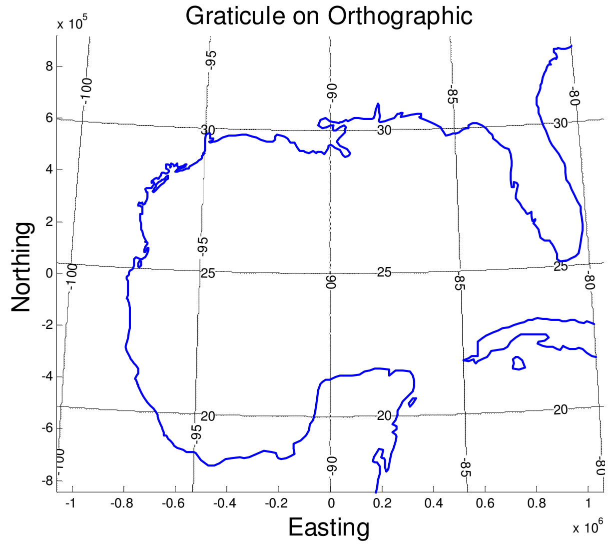
- Continuing the journey
- The orthographic projection is the view from space, e.g. our view of the moon
- Topocentric without the W vertical coordinate (3D=>2D) <u>is</u> the Orthographic projection
- The ellipsoidal Orthographic projection is a bona fide map projection with quantifiable distortions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



This slide marks a second important transition, that from 3D topocentric coordinates to 2D orthographic. The transition is simple. U (of UVW) becomes Easting, V becomes Northing, and W goes away.


Our view of the moon is orthographic.

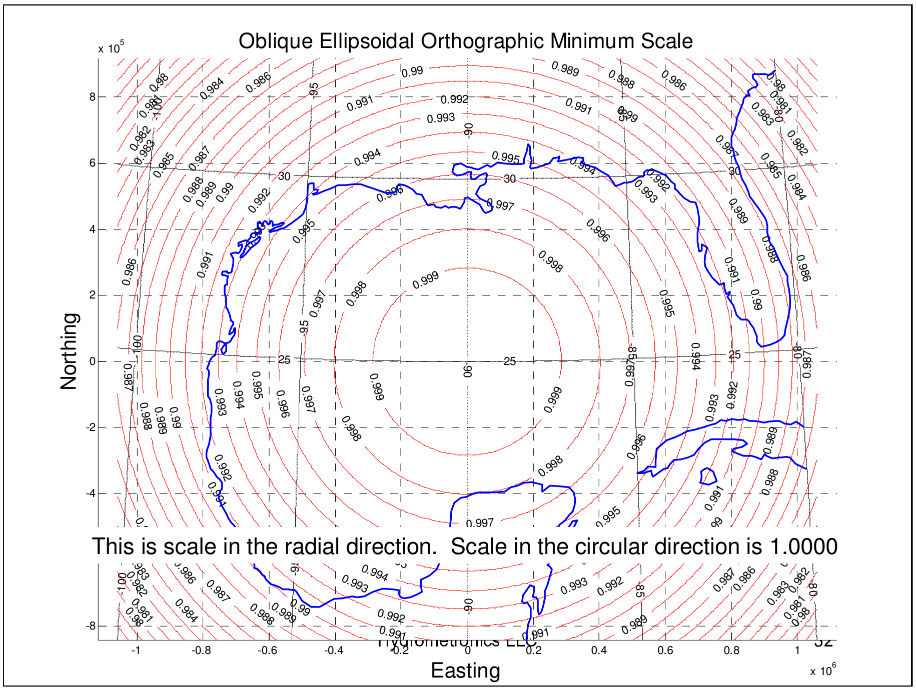
# Orthographic Projection of GOM




Hydrometronics LLC 31

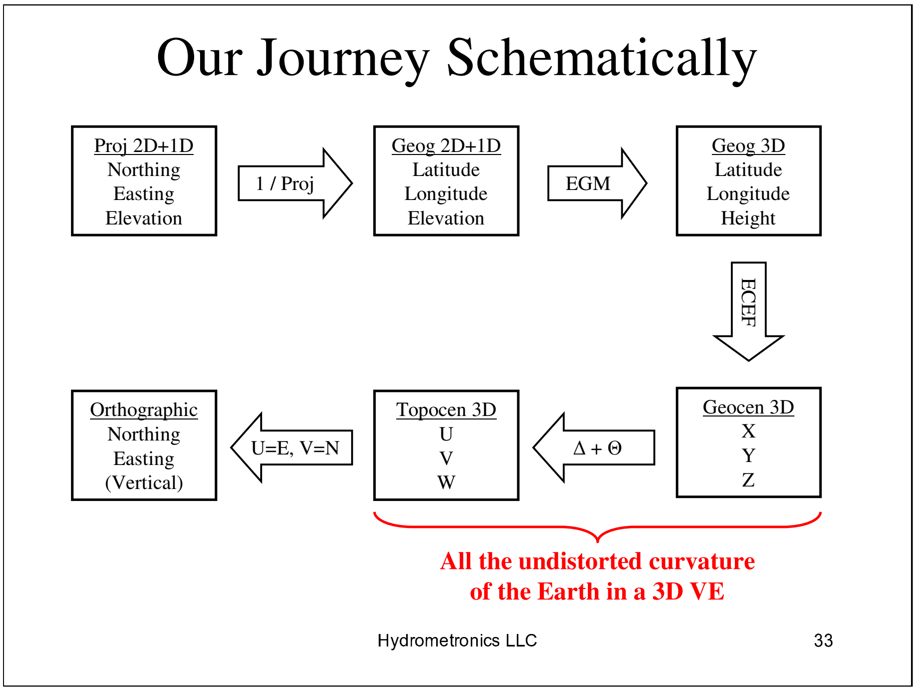
Here’s the GOM shown previously in 3D topocentric coordinates now represented in 2D orthographic (projection) coordinates.

This is a projection with quantifiable (and thus manageable) distortions. The orthographic is neither conformal nor equal area, but near the center distortion is negligible.




This graphic depicts scale distortion on the ellipsoidal orthographic. There is no scale distortion (scale = 1) in the direction perpendicular from a point to the center of the projection. In the direction from a point to the center it is that shown on this graphic. Within 90km of the origin the minimum scale is less than 1 part in 10,000. Within 180km of the origin the minimum scale is less than 4 parts in 10,000 (about that of TM within a UTM zone).

If one needs to work within the 2D+1D paradigm, then consider the Orthographic projection. It's one dimension away from topographic, which is a rotation and a translation away from ECEF.




We've been on a journey this afternoon and this slide presents that journey schematically.

We begin with the 2D+1D geodesy and cartography (G&C) of heritage workstations in the upper left, namely, projected coordinates in the horizontal and a geoid-based elevation in the vertical.

Then we use an inverse projection to get to a geographical 2D+1D G&C (latitude / longitude / elevation).

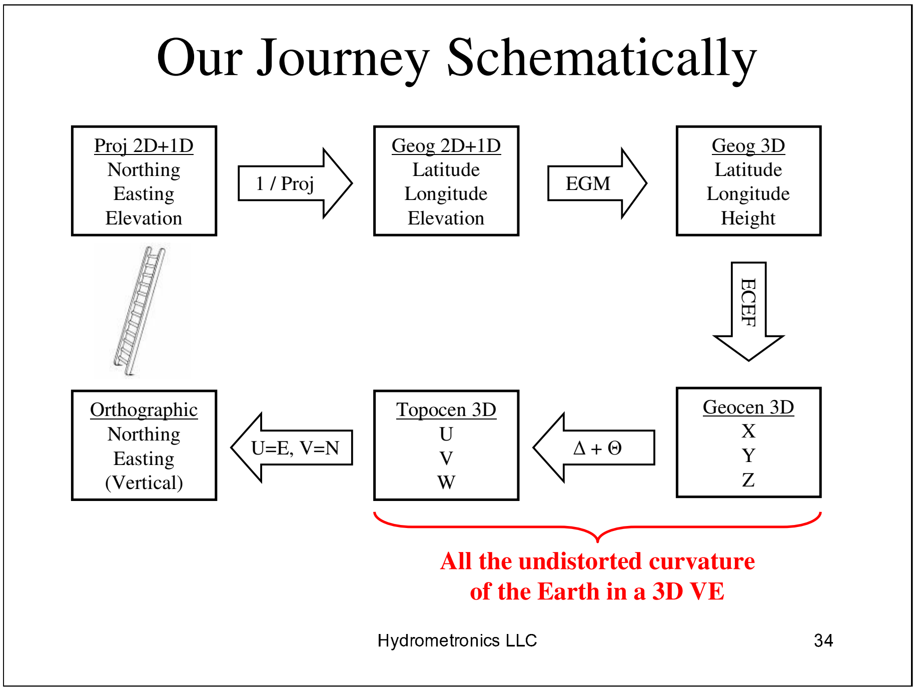
Then we use EGM2008 to get to a truly 3D coordinate system (latitude / longitude / ellipsoid-based height). But this 3D CS is not one that fits well into a VE.

Then we take the biggest step of all from Geographical 3D to Geocentric 3D (or ECEF). At this point all the undistorted curvature of the world fits into a geodetically unaware 3D visualization environment.

The next step localizes the perspective with a translation (Δ) and a rotation (Θ) to a topographic origin while still preserving all the undistorted curvature of the world.

These two steps are our desired destination.

But topocentric 3D is just an extra dimension (W) added onto the Ellipsoidal Orthographic projection, a serviceable piece of cartography.




And here we have a ladder uniting us with the beginning of our journey, a 2D map projection with manageable distortions that may be "good enough for seismic".

## 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)**

Hydrometronics LLC 35

(Read and elaborate.)

# 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!



No notes.

# 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



No notes.

# 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

Noel Zinn’s professional bio.

# Geographical to ECEF Coordinates

Given the ellipsoid semi-major axis ($a$) and flattening ($f$), and latitude ($\phi$), longitude ($\lambda$), and height ($h$)

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

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

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

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

Hydrometronics LLC 40

Intermediate terms are the semi-major axis (b), eccentricity squared (e^2) and the radius of curvature in the meridian (nu).

This conversion is exact.

# ECEF to Geographical Coordinates

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

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

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

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

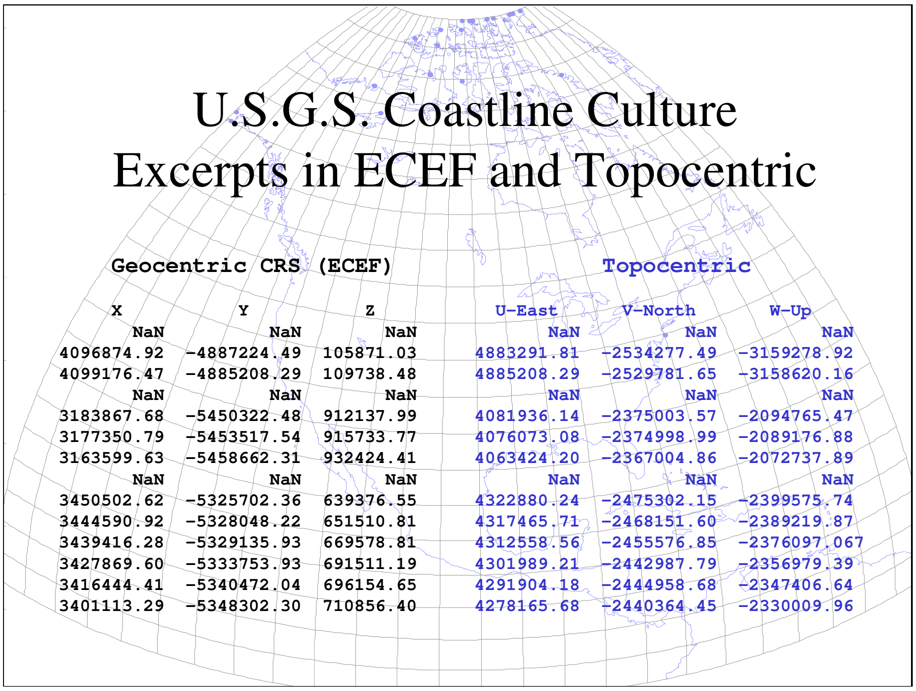
$$\lambda = \tan^{-1}(\frac{Y}{X})$$

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

Hydrometronics LLC 41

Intermediate terms are the semi-major axis (b), eccentricity squared (e^2), eccentricity prime squared (e'^2), the radius of curvature in the meridian (nu), the projection of the point on the Equatorial plane (p) and theta.

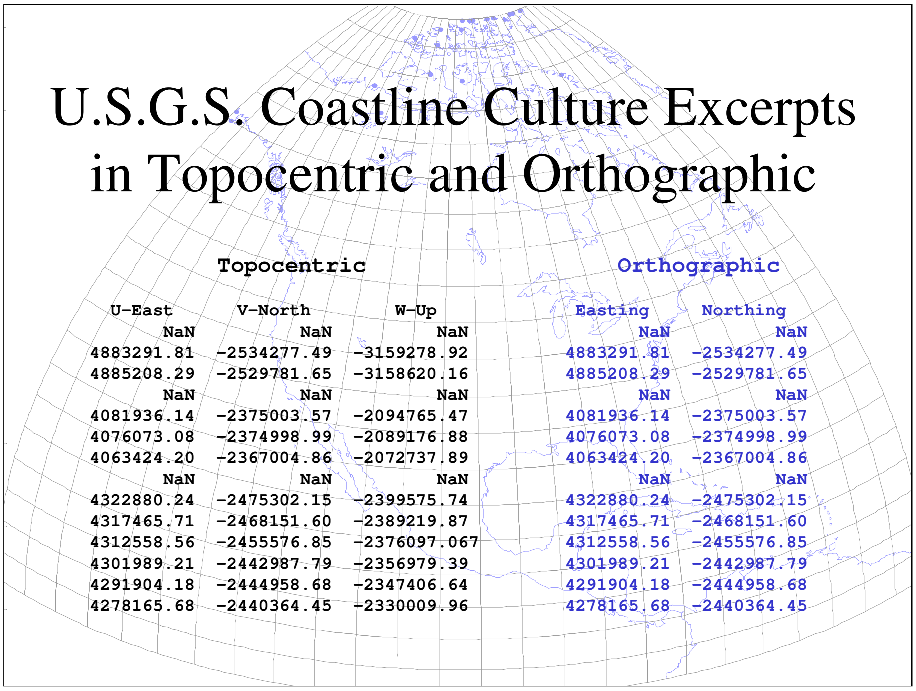
This conversion is acceptably precise within any working distance of the surface of the Earth.



# 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 |

On the left are the ECEF XYZ for some small part of North America that we've seen already. On the right are the topocentric equivalents for an origin of 40N/100W.



# 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 |

Here are the topocentric data we've seen before on the left and the equivalent orthographic data on the right.  Orthographic projection coordinates are just topocentric coordinates without the vertical value.