

Earth Centered Earth Fixed
A Geodetic Approach to Scalable
Visualization without Distortion

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The Hydrographic Society - Houston Chapter

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No notes.

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

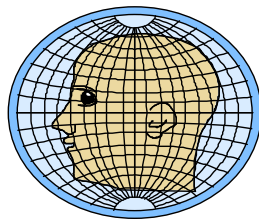
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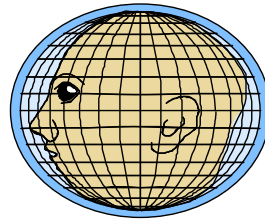
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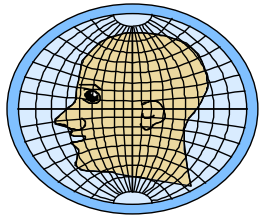
Map Projections Change Shapes



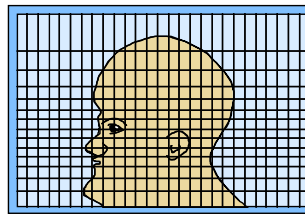
Globular projection



Orthographic projection



Stereographic projection



Mercator projection

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The simple point to be made with this introductory 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.

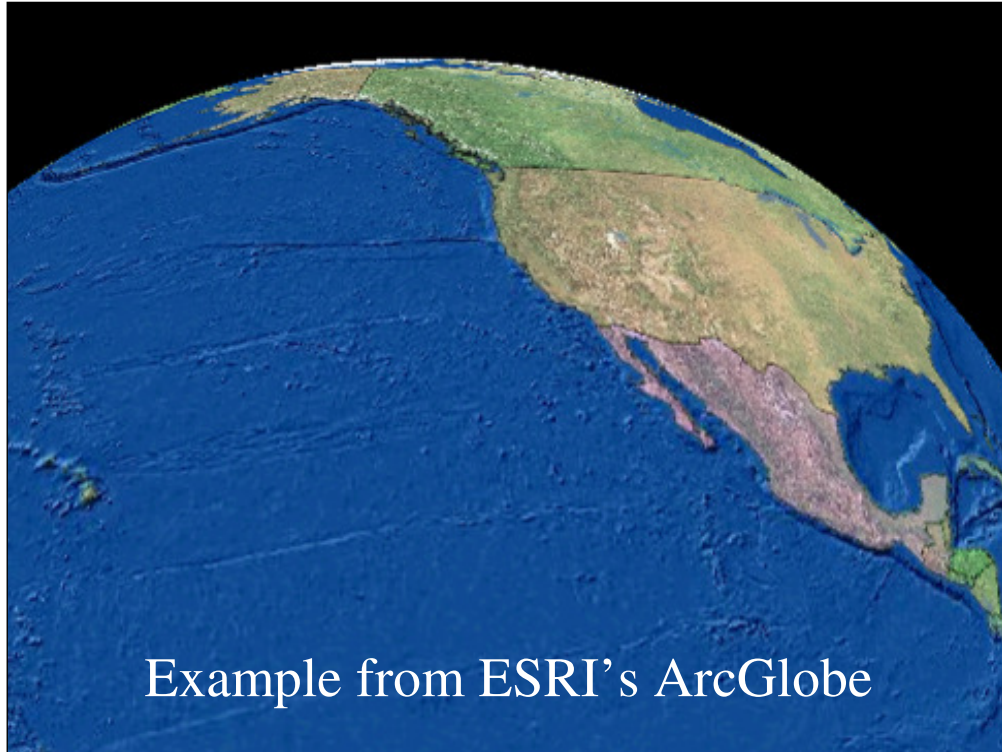
Example from Google Earth



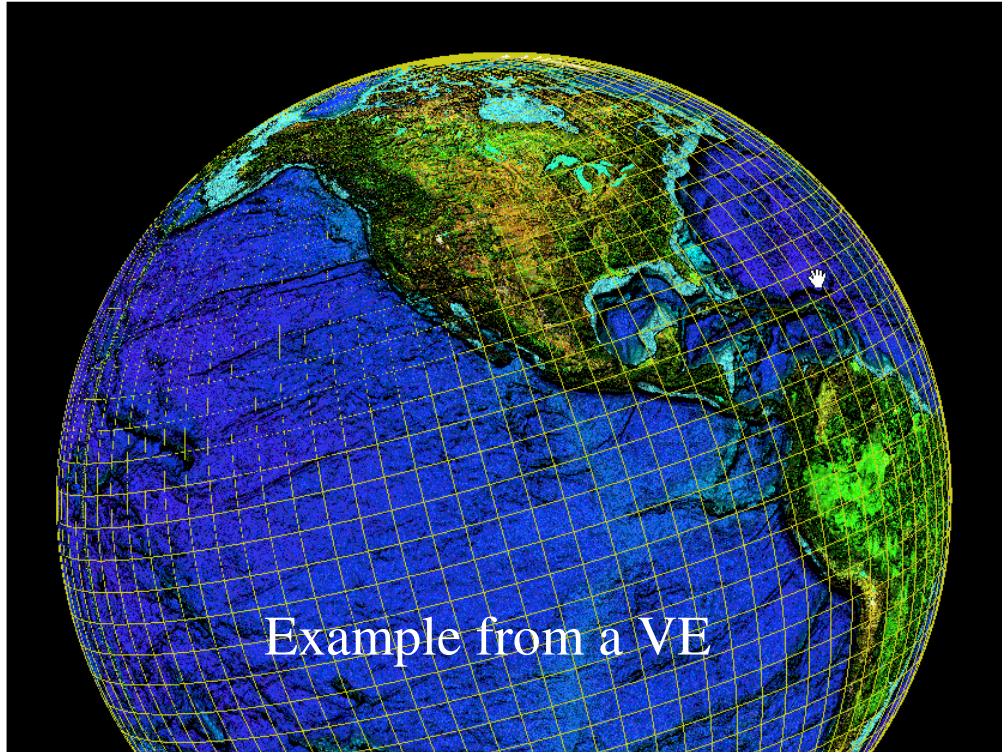
Nowadays a very different perspective is provided by Google Earth, for example. The Earth is presented as spherical (or ellipsoidal) and it can be rotated with your cursor to any viewing perspective. Any particular area of interest can be viewed normally (that is, perpendicularly) without distortion.

My campaign for ECEF began before the advent of Google Earth, but Google Earth certainly provides the ECEF perspective. Google Earth's popularity has informed Earth scientists in the value of this perspective. I don't know whether Google Earth works its magic with the geodetic rigor of ECEF or not.

A perspective required of 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.

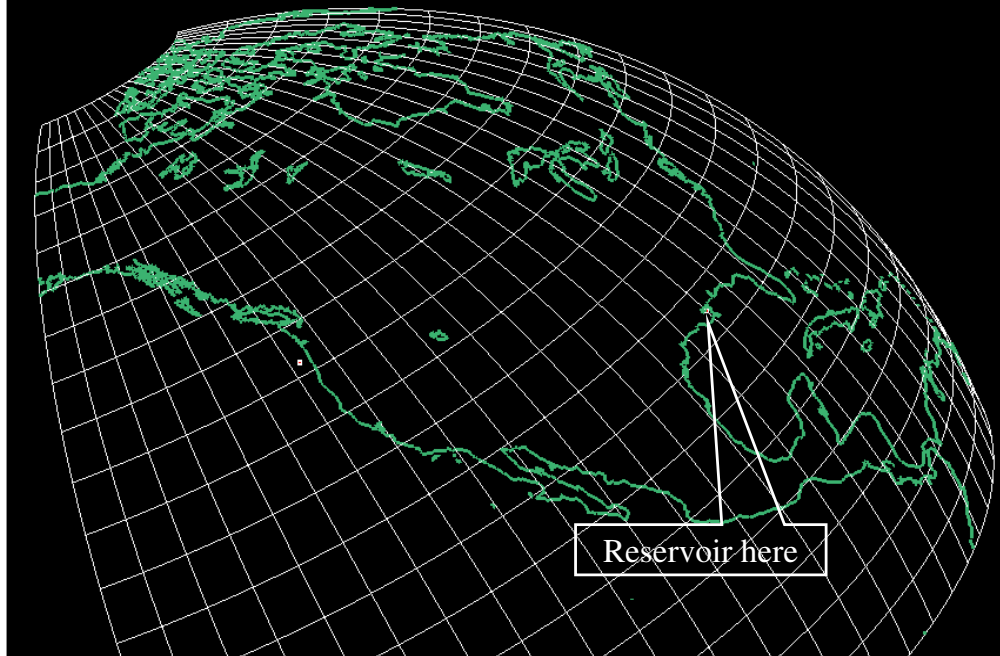


ArcGlobe is a 3D companion product to ESRI's 2D ArcGIS. It provides a perspective similar to Google Earth. ArcGlobe works its magic with a "cubic" projection.



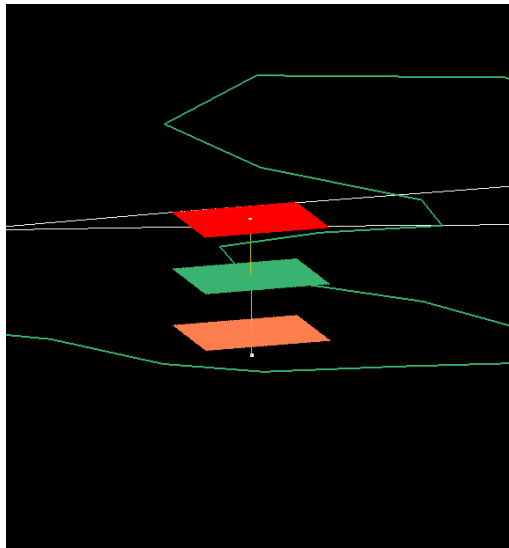
This graphic is of a latitude/longitude graticule and some low density satellite imagery in ECEF in a GoCAD 3D geoscience visualization environment (VE). As will be described later, ECEF maintains geodetic rigor. As with Google Earth this image can be rotated with the cursor to any distortion-free perspective.

Regional Cartoon in a VE



This is another GoCAD image of the North American coastline and the graticule of the North American octosphere. Two cartoon reservoirs are placed in this image, one off of Louisiana and one off of Washington State in the Pacific.

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.

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Here we zoom into the cartoon of the reservoir off of Louisiana, which is described above. The points to me made with this graphic are that (1) one can zoom into data at depth in the Earth for whatever analysis is required and (2) the local presentation of the reservoir in ECEF is much like what we would expect in a “normal” 2D (horizontal) + 1D (vertical) perspective. This same perspective is achieved with the reservoir off of Washington State even though the two reservoirs are orientated differently with respect to one another in a 3D ECEF Earth.

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)

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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

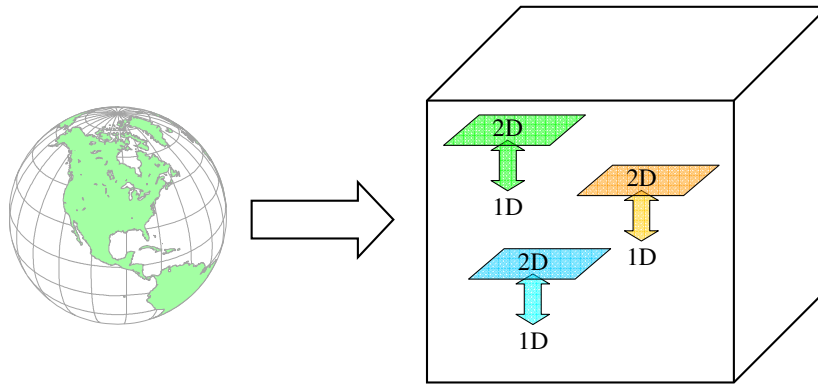
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Path to Heritage Applications



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

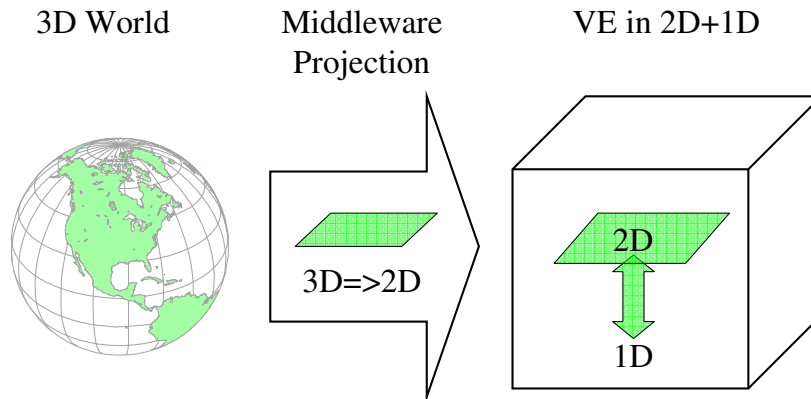
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Examples of heritage geophysical applications are Schlumberger's GeoFrame and Landmark's OpenWorks. Multiple 2D projections and multiple datums coexist side by side in these applications. Projects can be moved from datum to datum or from projection 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.

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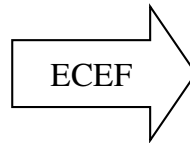
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Examples of visualization environments (VE) are Schlumberger’s Petrel and Paradigm’s GoCAD. Only one datum and projection lives inside a VE at any one time. Projection distortions cannot be managed in a VE, which is best suited to reservoir-sized prospects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

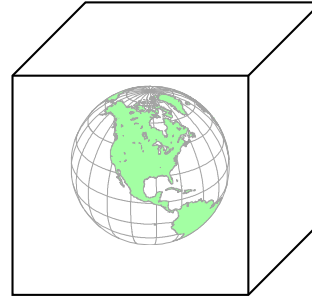
Update: Petrel projects can be flushed from the VE and reloaded in a different projection or datum as data management requirements dictate.

Proposed Path to VE via ECEF

3D World



VE in true 3D



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!

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This slide depicts the (perhaps) revolutionary step proposed in this presentation. That is, use the ECEF coordinate system (described mathematically 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.

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)

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

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.

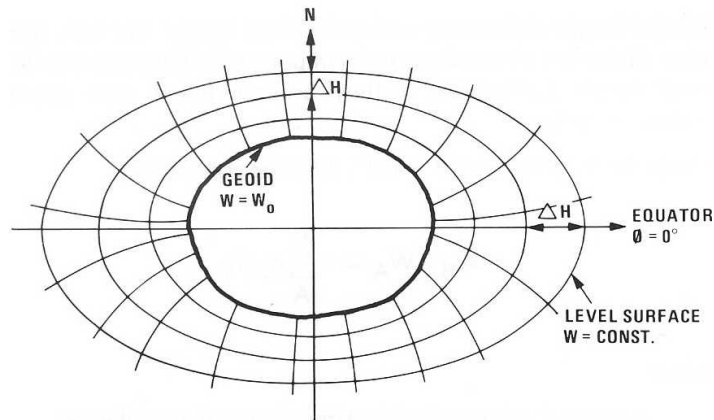
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Vertical CRS: elevation



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.)

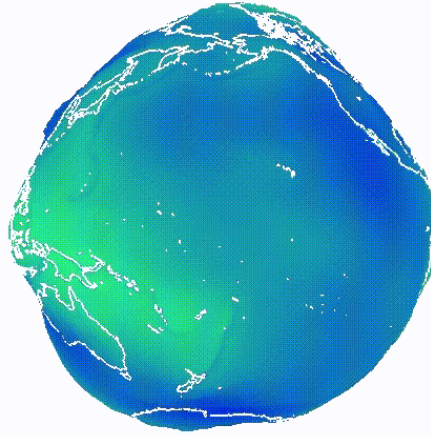
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EGM2008 Geoid times 10000



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This animated cartoon of the Earth Gravity Model 2008 exaggerated 10,000 times, depicted in ECEF and rotating is 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, the 2D+1D perspective that assumes the horizontal is flat is misleading. Second, it shows that the gravity-based vertical dimension can be well represented in ECEF and this is important for the integration of the vertical in ECEF.

Before one can represent the ECEF Earth in a 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.

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 distance²**

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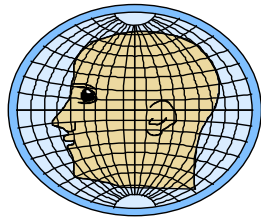
A map projection is a mathematical “mapping” of 3D ellipsoidal space onto a 2D planar space. Distortions are inevitable. But we can preserve selected properties of the 3D surface by our choice of mapping equations.

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

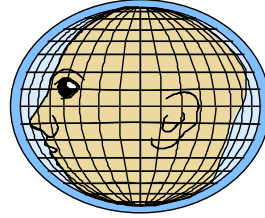
We can preserve some features, but will unavoidably distort other features.

Distortions increase proportionally to the square of the distance.

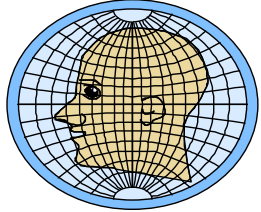
Reprojection Changes Shapes



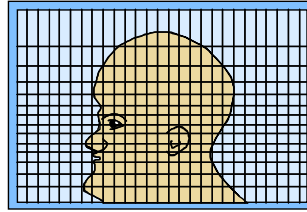
Globular projection



Orthographic projection



Stereographic projection



Mercator projection

Rule of thumb: map distortion \propto distance²

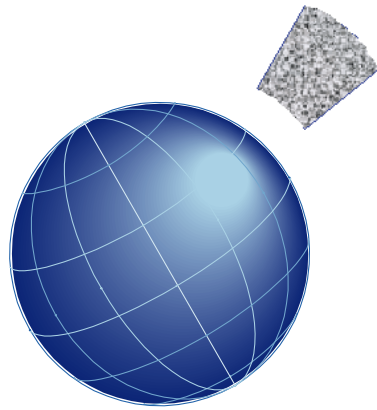
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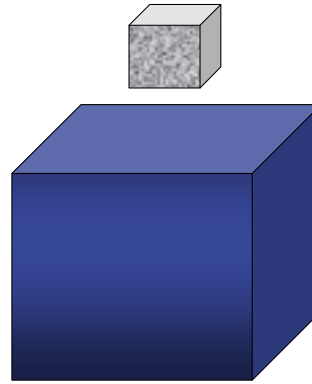
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Not only do different projections depict shape differently, but reprojection from one projection to another (even if conformal) changes shape.

Engineering CRS (“Flat-Earth”)



Our project extracted
from an ellipsoidal earth



Our project extracted from
a cubical, flat earth

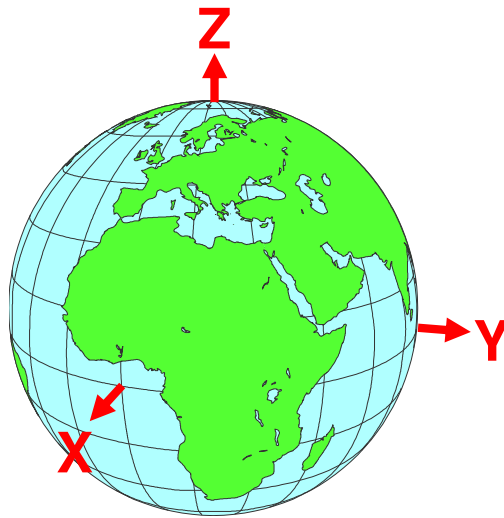
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The Engineering CRS presents the world as a cube, which is an approximation valid only over a small, local area. Nevertheless, this cubical concept permeates our thinking about our projects over larger areas. For example, geophysical data processing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

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

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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 \Leftrightarrow geocentric (ECEF) conversion does not suffer this problem.

Geographical to ECEF Coordinates

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

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

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

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

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

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

This conversion is exact.

ECEF to Geographical Coordinates

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

$$b = a - a \cdot f \quad e^2 = (a^2 - b^2)/a^2 \quad e'^2 = (a^2 - b^2)/b^2$$
$$v = \frac{a}{(1 - e^2 \sin^2 \phi)^{1/2}} \quad p = (X^2 + Y^2)^{1/2} \quad \theta = \tan^{-1}\left(\frac{Z \cdot a}{p \cdot b}\right)$$

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

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

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

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

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

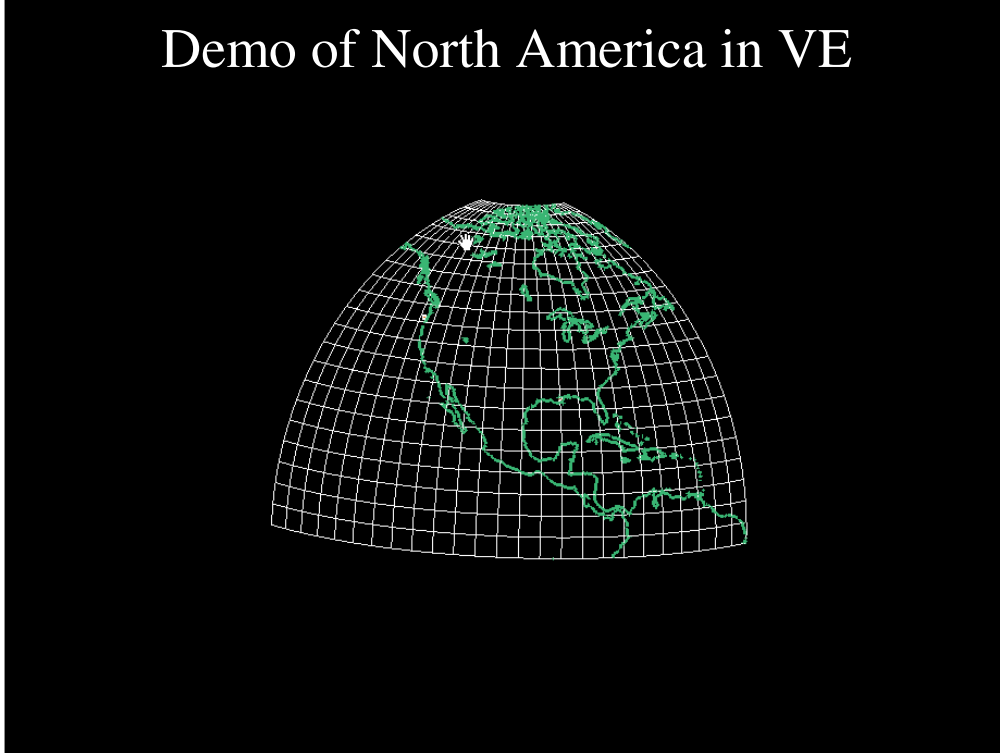
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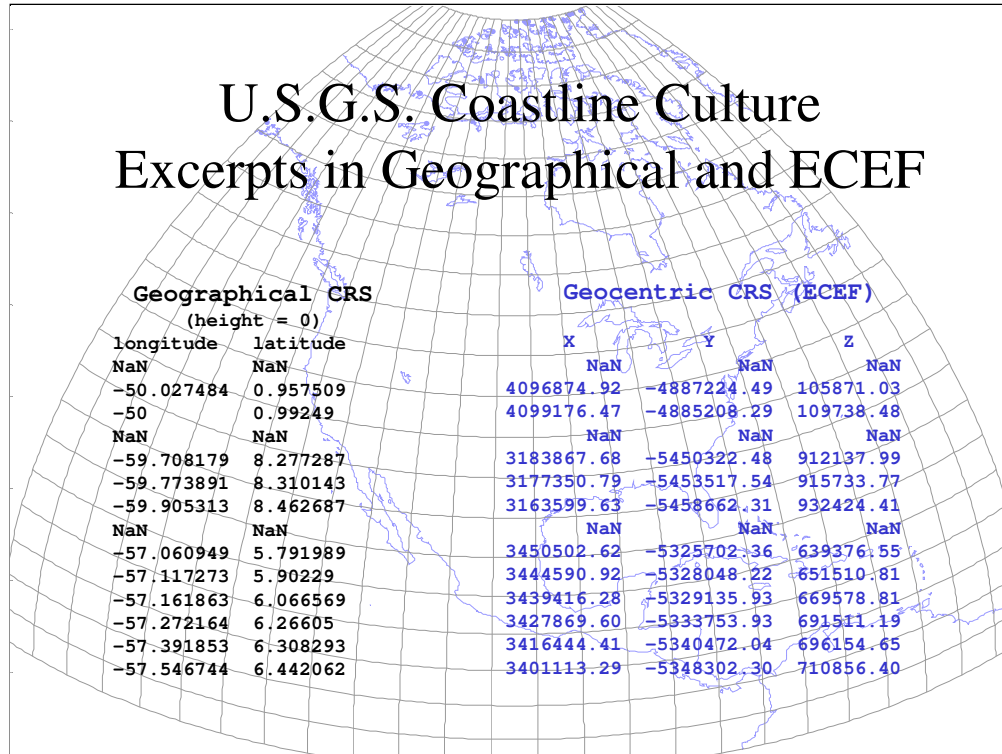
No notes.

Demo of North America in VE



This demo is not available in the PDF version of this presentation. It shows a cartoon of the North American octosphere with two reservoirs. The image is rotated to show distortion-free perspectives wherever desired. We zoom into the reservoirs to show them at the “pore” level as they might appear in a heritage geoscience application.

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



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.

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

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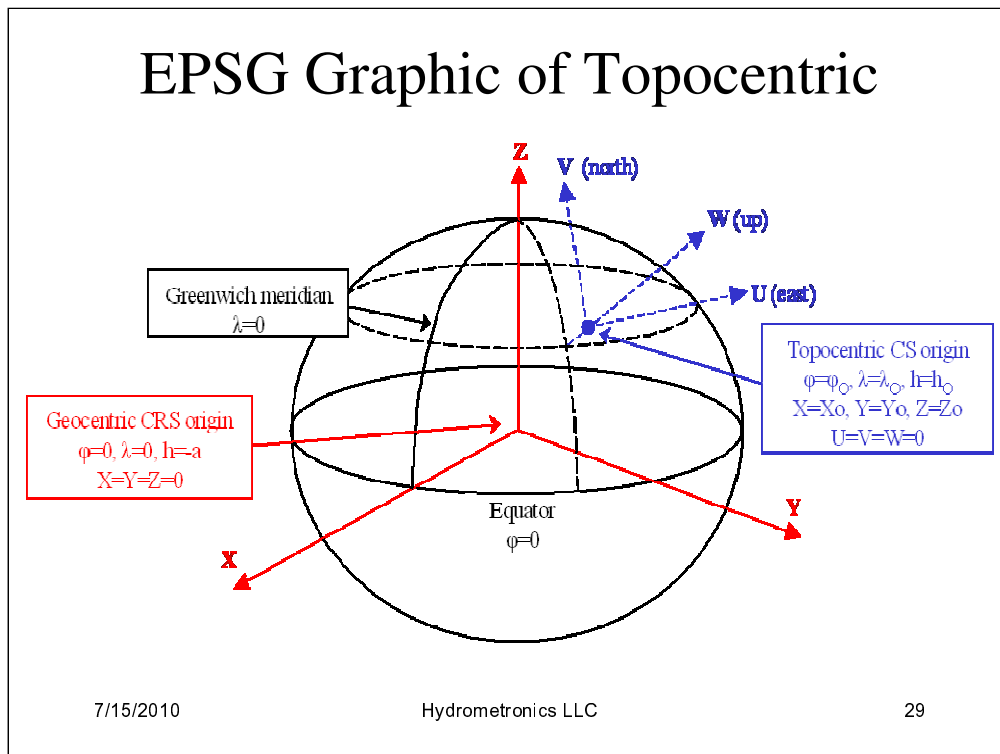
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This slide marks an important transition in the presentation, the translation and rotation from geocentric ECEF coordinates to topocentric coordinates, called East/North/Up (ENU) in Wikipedia, topocentric horizon by Bugayevskiy & Snyder, local vertical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

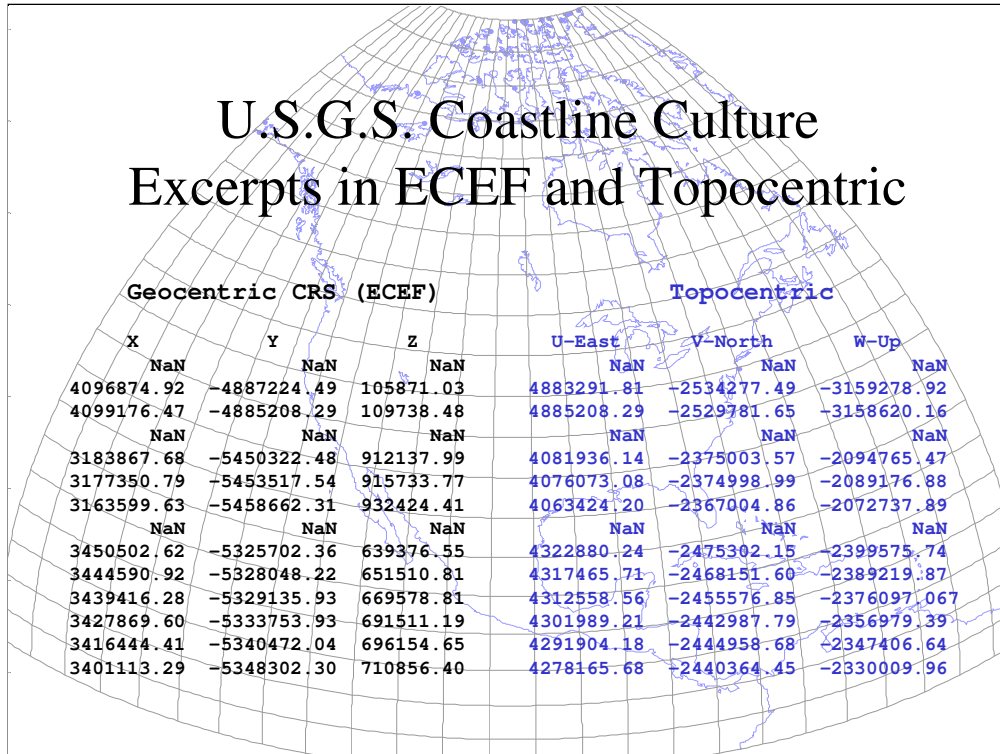
ECEF coordinates present the whole world – or just your local project – from the geocentric perspective. The geocenter may be far away. The geoscientist may prefer a local origin for their project. That is provided by topocentric coordinates (called UVW here), which preserve all the curvature of the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

EPSG Graphic of Topocentric



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).

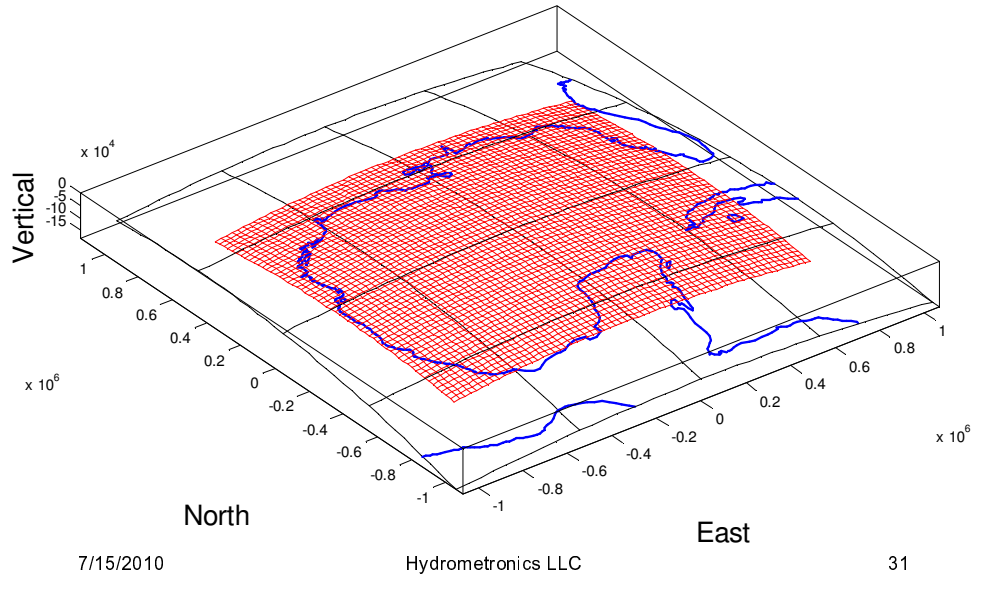
U.S.G.S. Coastline Culture Excerpts in ECEF and Topocentric



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.

GOM Binning Grid in Topocentric

Binning Grid in Topocentric Coordinates



Here's an enormous seismic binning grid that covers 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 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) is 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

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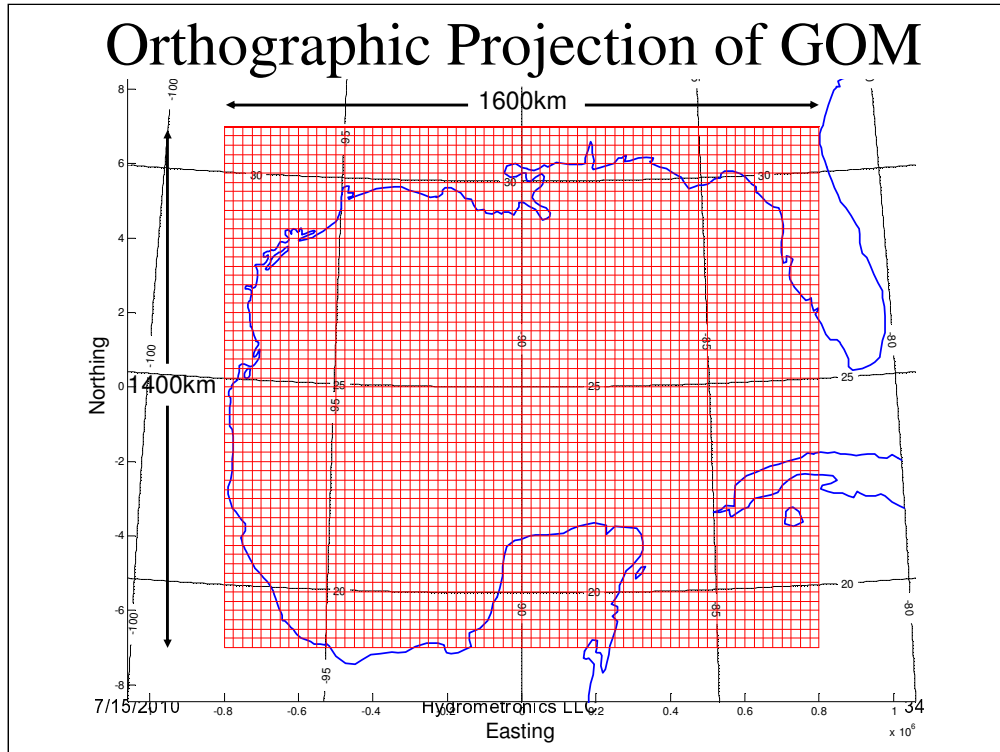
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This slide marks a second important transition, that from 3D topocentric coordinates to 2D orthographic. The transition is simple. U (of UVW) becomes Easting, V becomes Northing, and W goes away.

Orthographic Projection of the Moon

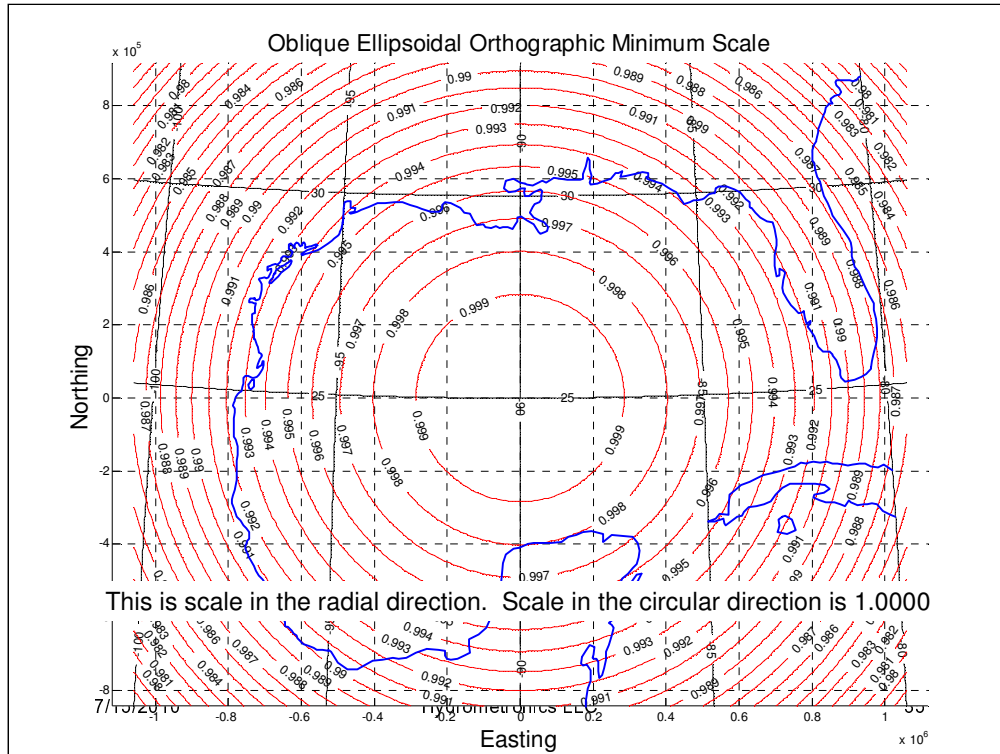


Our view of the moon is orthographic.



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

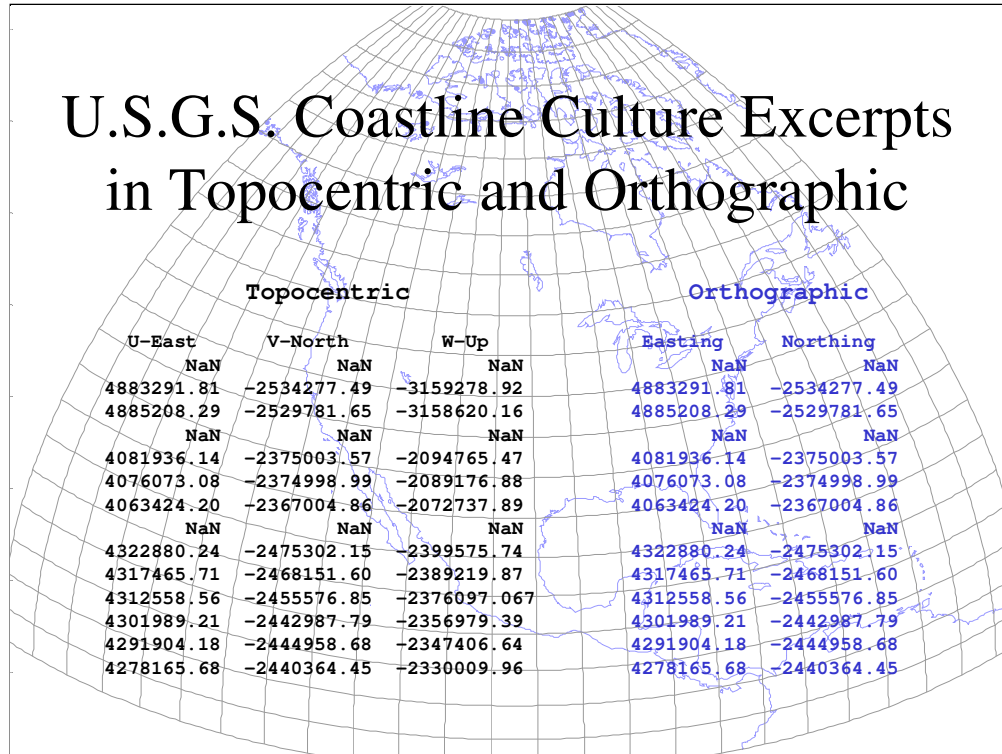
This is a projection with quantifiable (and thus manageable) distortions. The orthographic is neither conformal nor equal area, but near the center distortion is negligible.



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.

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



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.

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

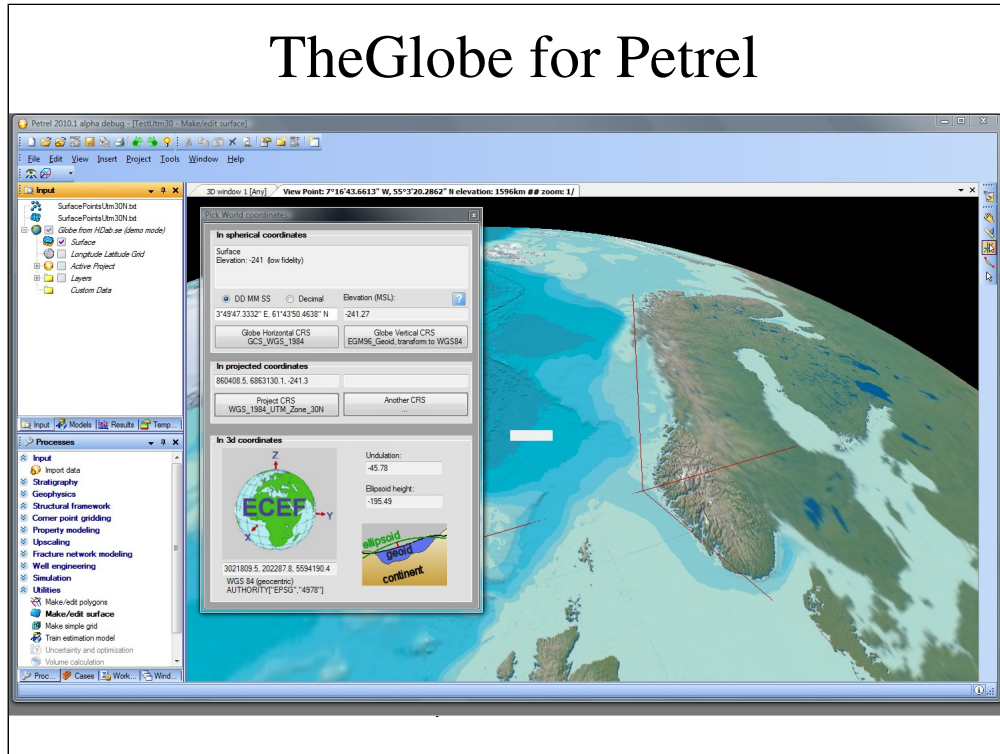
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No notes.

TheGlobe for Petrel



TheGlobe presents a 2D canvas. Its data, algorithms and interactions are accurate within the limitations of the ESRI projection engine. Rendering a global world with contemporary hardware is a tradeoff of memory usage and user expectations. TheGlobe's Earth is constructed from 36 x 18 patches. Each patch is made up of some 500-100 triangles. The corner points of a triangle will always be placed exactly in space; the interior will be slightly distorted. TheGlobe's camera is always pointing at the geocenter (0,0,0) with North upwards in screen space. The user cannot navigate closer than 1km. TheGlobe reports the coordinates of a pick as "low fidelity". However, when choosing a domain object like a well trajectory, TheGlobe passes control to the renderer, which serves up the original coordinates. This assures that all printed numbers are always exact. Line segments will suffer from (unavoidable) projection distortion. TheGlobe reports latitude, longitude, height, ECEF X, Y, Z, EGM96 undulation and DEM terrain elevation for a point and geodetic and Euclidian distances between points.

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

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No notes.

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

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No notes.

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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