Reservoirs to Regions

A Geodetic Approach to Scalable Visualization without Distortion

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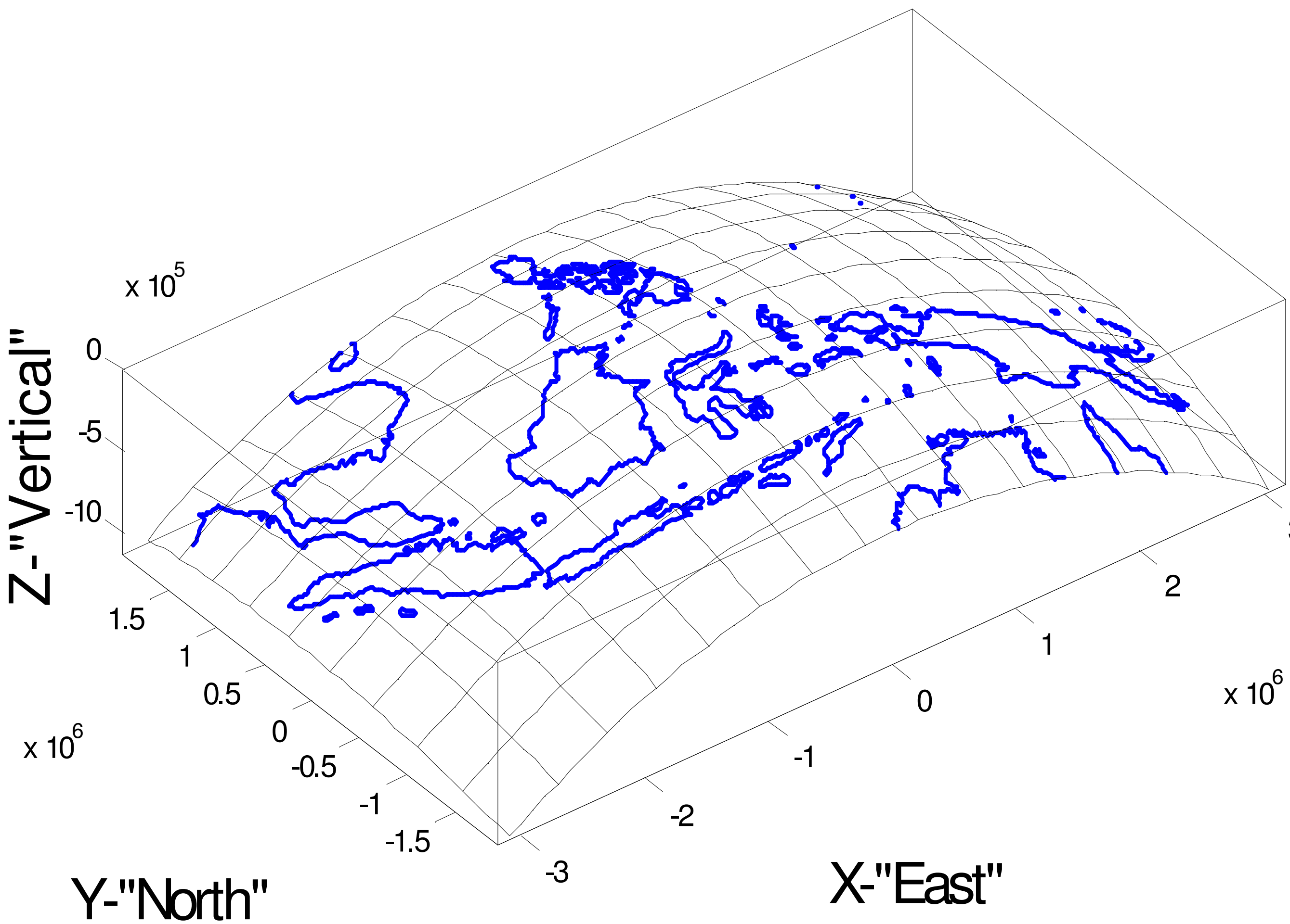
Indonesia Viewed Without Distortion in a 3D ECEF-LH CRS



Statement of the Issue - 1

- Scalability from reservoirs to regions is a desired feature in earth science software
- Seismic systems use 2-D projected coordinates in the horizontal and 1-D depth (or time) coordinates 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

Statement of the Issue - 2

- Geological modeling 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 reservoir-to-region scalability
  - Provide a new perspective on the data

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Executive Summary

Visualization Environments offer both opportunity and challenge in the simplicity of their cubical CRS. Earth-Centered Earth-Fixed (ECEF) geocentric Cartesian coordinates system are cubical (3D), well-described geodetically, and free of distortion. They can be rotated to any local horizontal (LH) and scaled without re-computation from reservoirs to regions. ECEF and ECEF-LH coordinates will present a different perspective to the geoscientist. There will be issues preparing data for this perspective. Matlab prototypes of ECEF and ECEF-LH are presented herein.

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- Statement of the Issue and Summary
- *Coordinate Reference System (CRS) Primer*
- Earth-Centered Earth-Fixed (ECEF) CRS
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- Current Geoscience and Engineering Practice
- Prototyping ECEF in Matlab
  - Rotation to Local Horizontal (ECEF-LH)
  - Orthographic projection (separation contours)
- Issues and Proposed Solutions

A CRS Primer

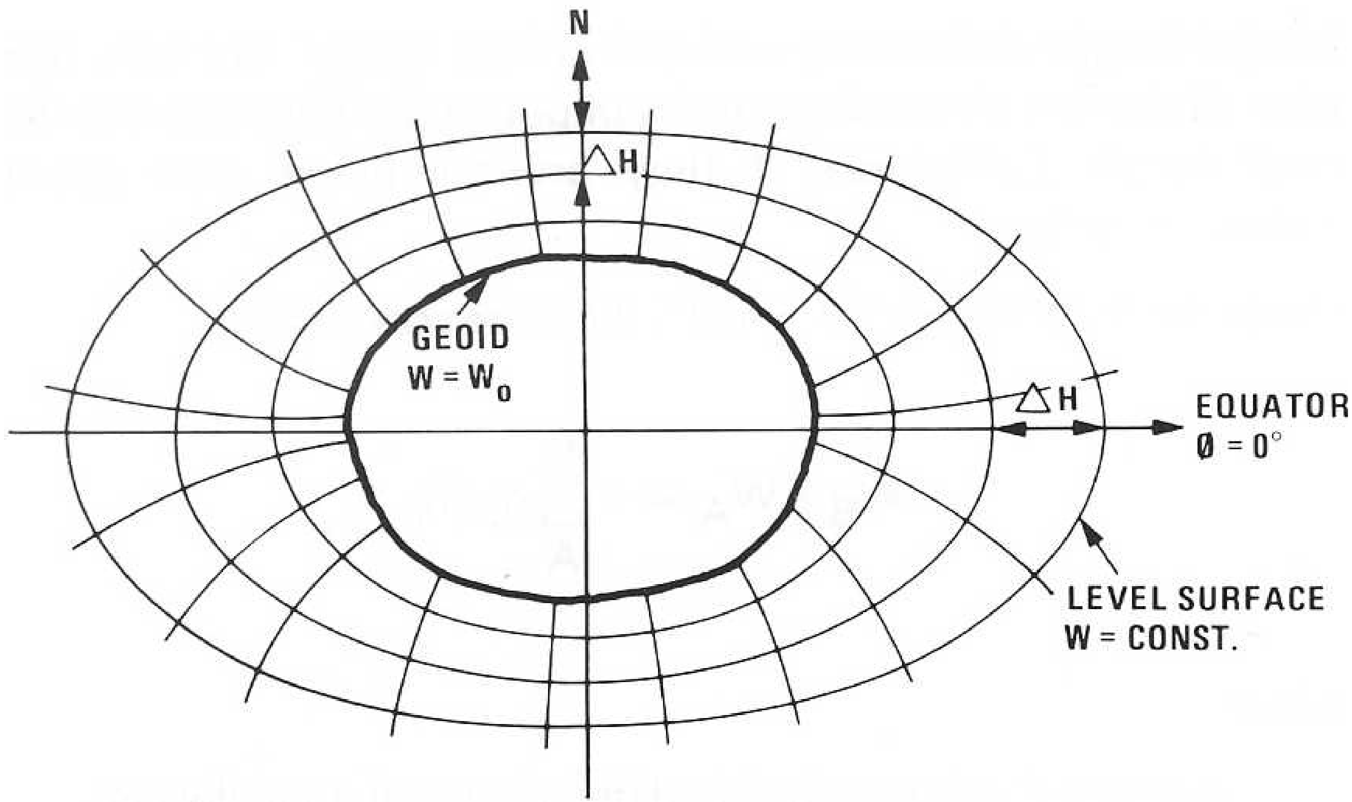
- The EPSG* database of the OGP** identifies these Coordinate Reference Systems (CRSs):
  - Geographical 2D (lat/lon) and Geographical 3D (lat/lon/height with respect to the ellipsoid)
  - Vertical (elevation or depth w.r.t. the geoid)
  - Projected 2D (mapping of an ellipsoid onto a plane)
  - Geocentric (Earth-Centered Earth-Fixed Cartesian)
  - Engineering (local "flat earth")
  - Compound (combinations of the above)

* EPSG is the (former) European Petroleum Survey Group, now part of OGP
** OGP is the International Oil and Gas Producers Association

Geographical CRS

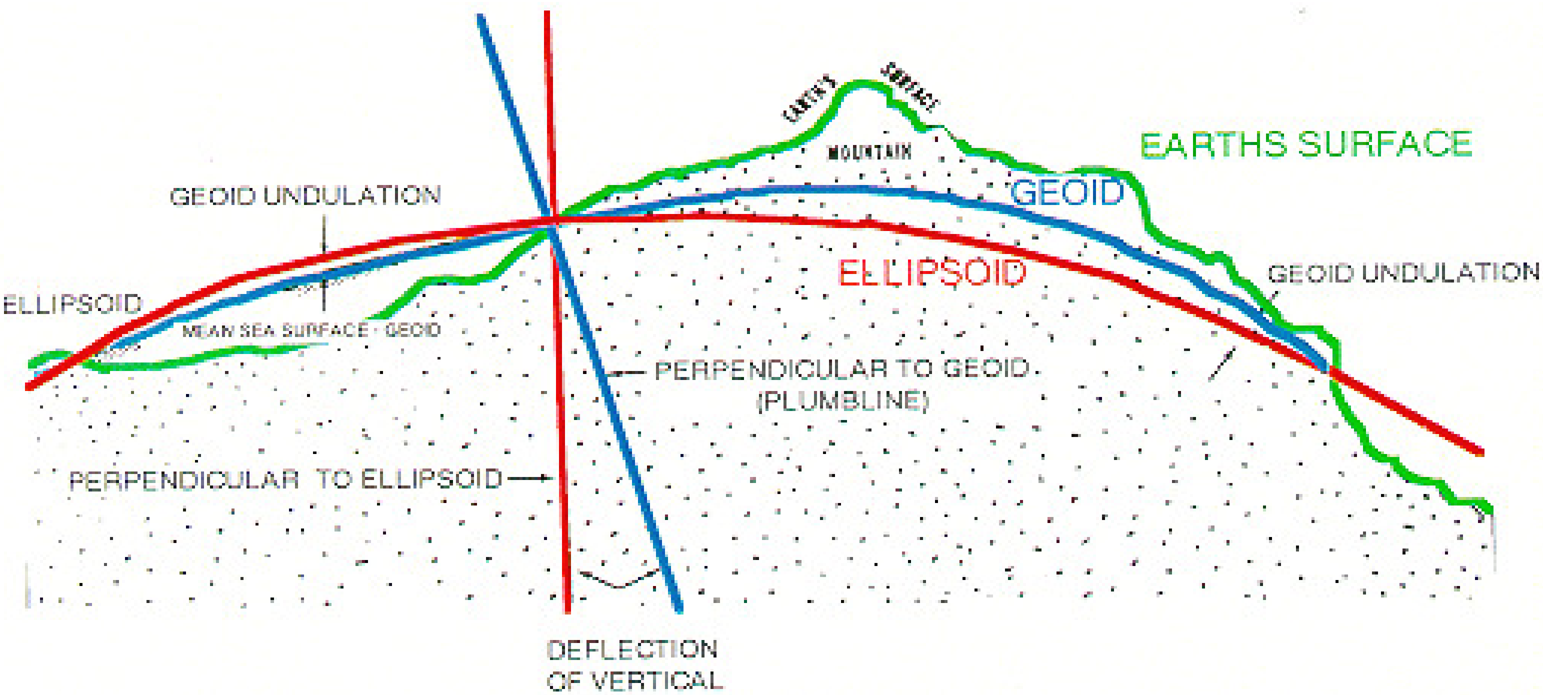
A graticule of curved parallels and curved meridians (latitudes and longitudes) intersect orthogonally on the ellipsoid. Height is measured along the normal, the straight line perpendicular to the ellipsoid surface.

Vertical CRS



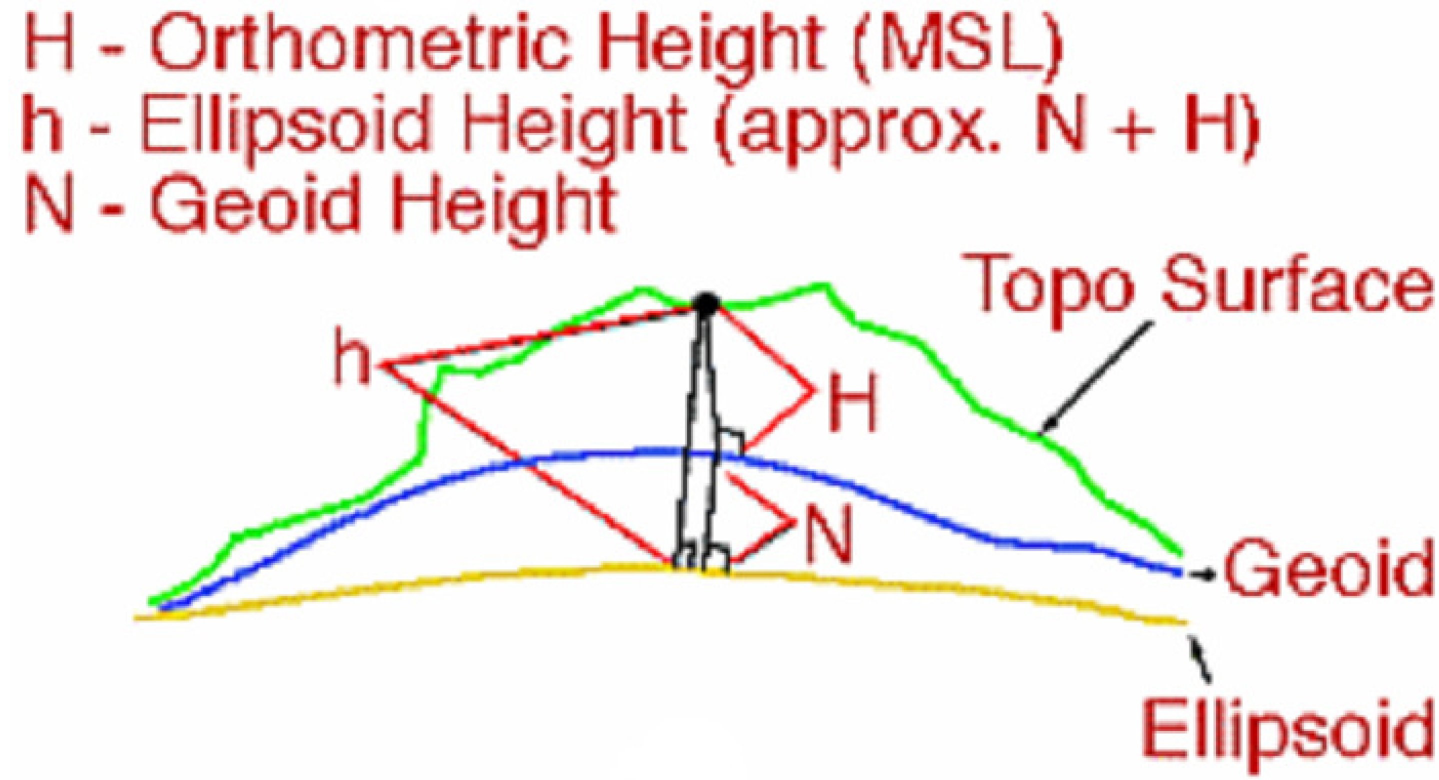
Elevation is measured along the (slightly curved) vertical, which is perpendicular to the irregularly layered geopotential surfaces of the earth. The geopotential surface at mean sea level is called the geoid. (Graphic from Hoar, 1982.)

Vertical CRS



Geoidal undulation (or geoidal height) is the difference between the surface of geoid and the surface of the ellipsoid. EGM96 is the best public-domain model of world-wide geoidal heights. Some local datums have poor information about geoidal height.

Different Height Measurements



A more closer look at relationships among elevation (orthometric height), ellipsoidal height and geoidal height (undulation). Geoidal heights are determined with a geoidal model such as EGM96.

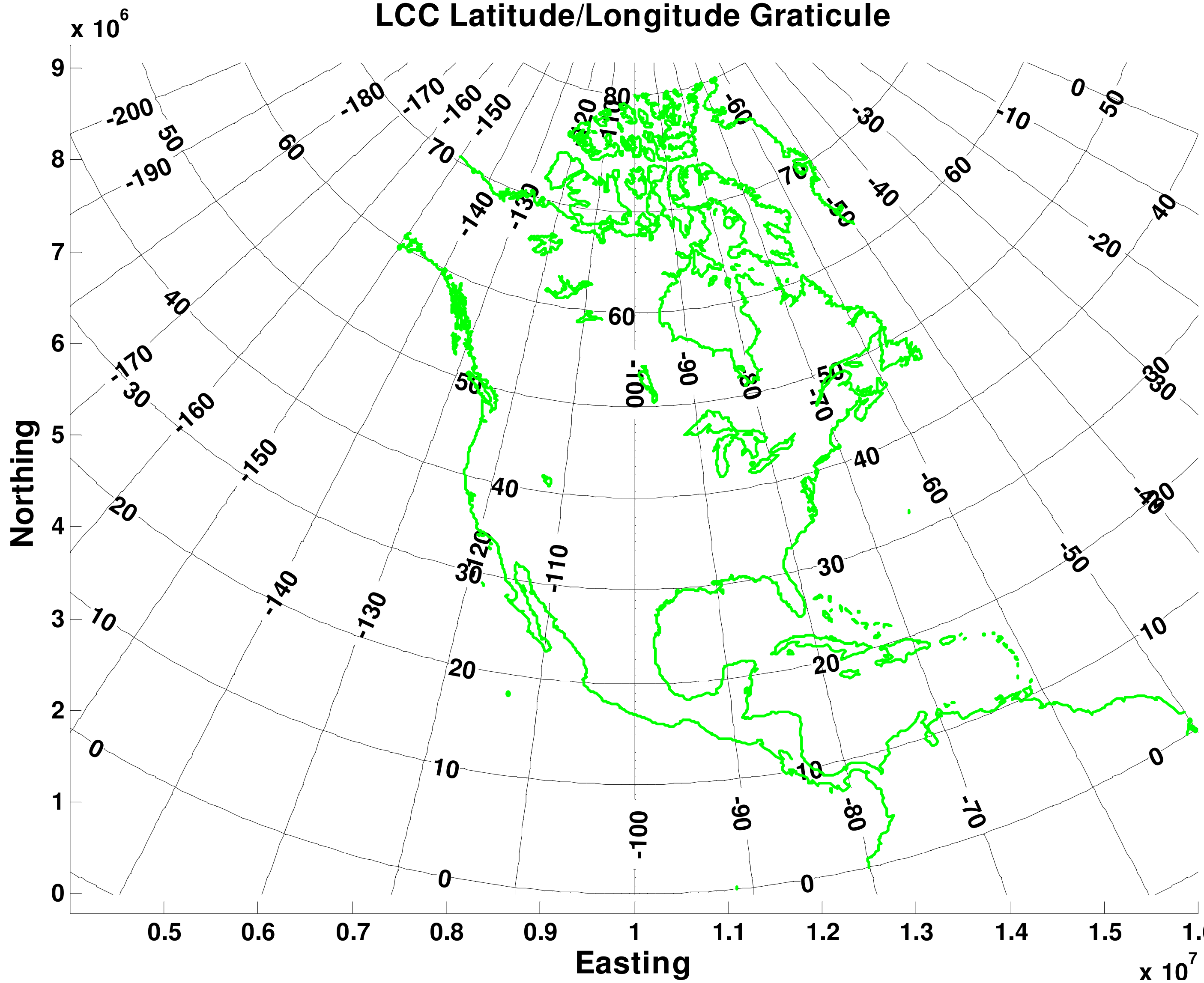
Projected CRS

- Projections of an ellipsoid onto a plane <u>preserve some ellipsoidal properties and distort others</u>
  - Angle - and local shapes can be shown correctly (e.g., all 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 is $\propto$ distance^2

Example of 2D Projected CRS

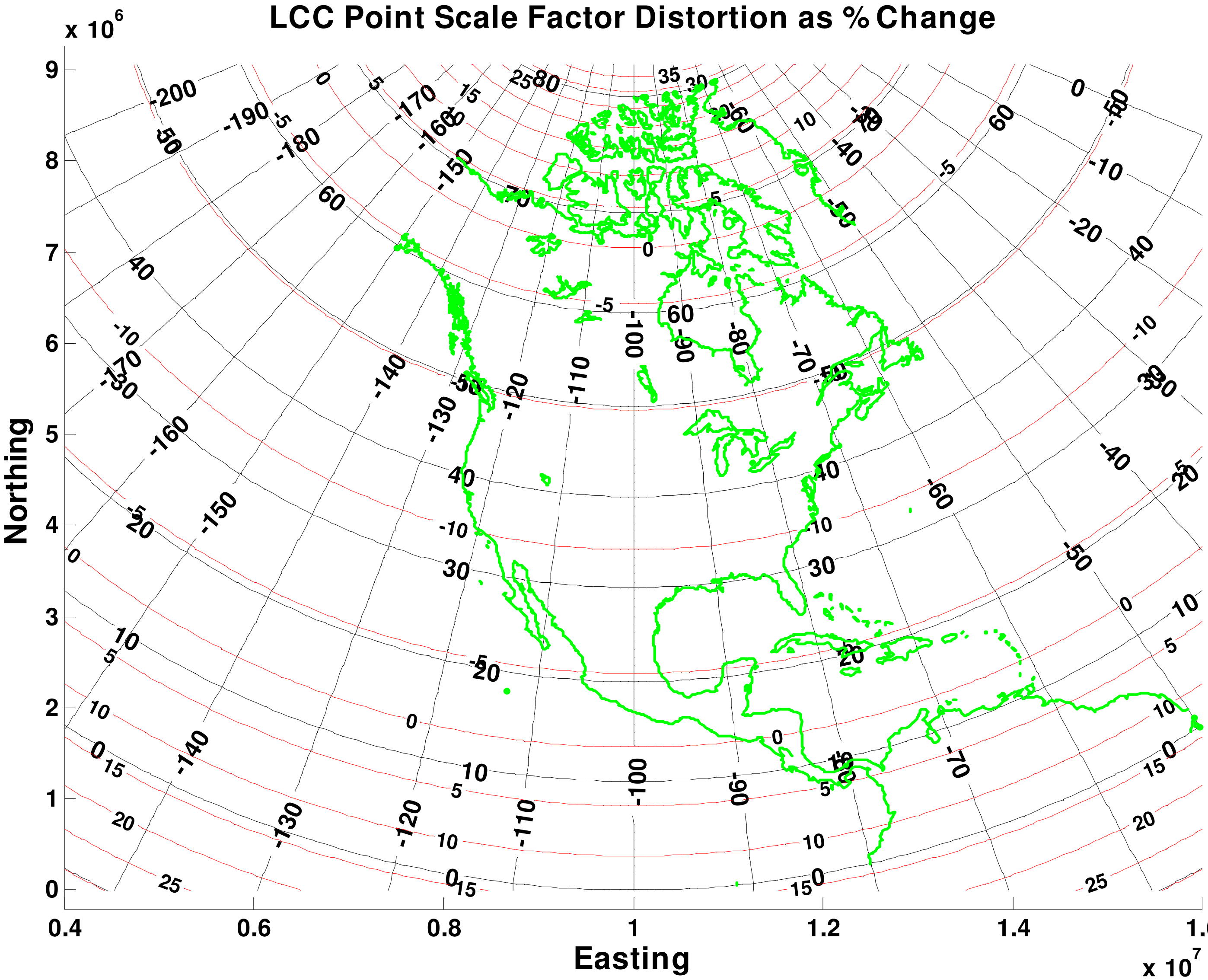
- Lambert Conformal Conic (LCC) Projection
  - Preserves angular intersections and local shape, thus
  - Simplifies trigonometric computations, but ...
  - Distorts linear scale, area and azimuth
  - Due to simple formulae, LCC is better suited for regions (large areas) than the Transverse Mercator
- The following slides quantify common distortions of map projections (3D => 2D) in a large area with LCC as an example

Lambert Conformal Conic Projection



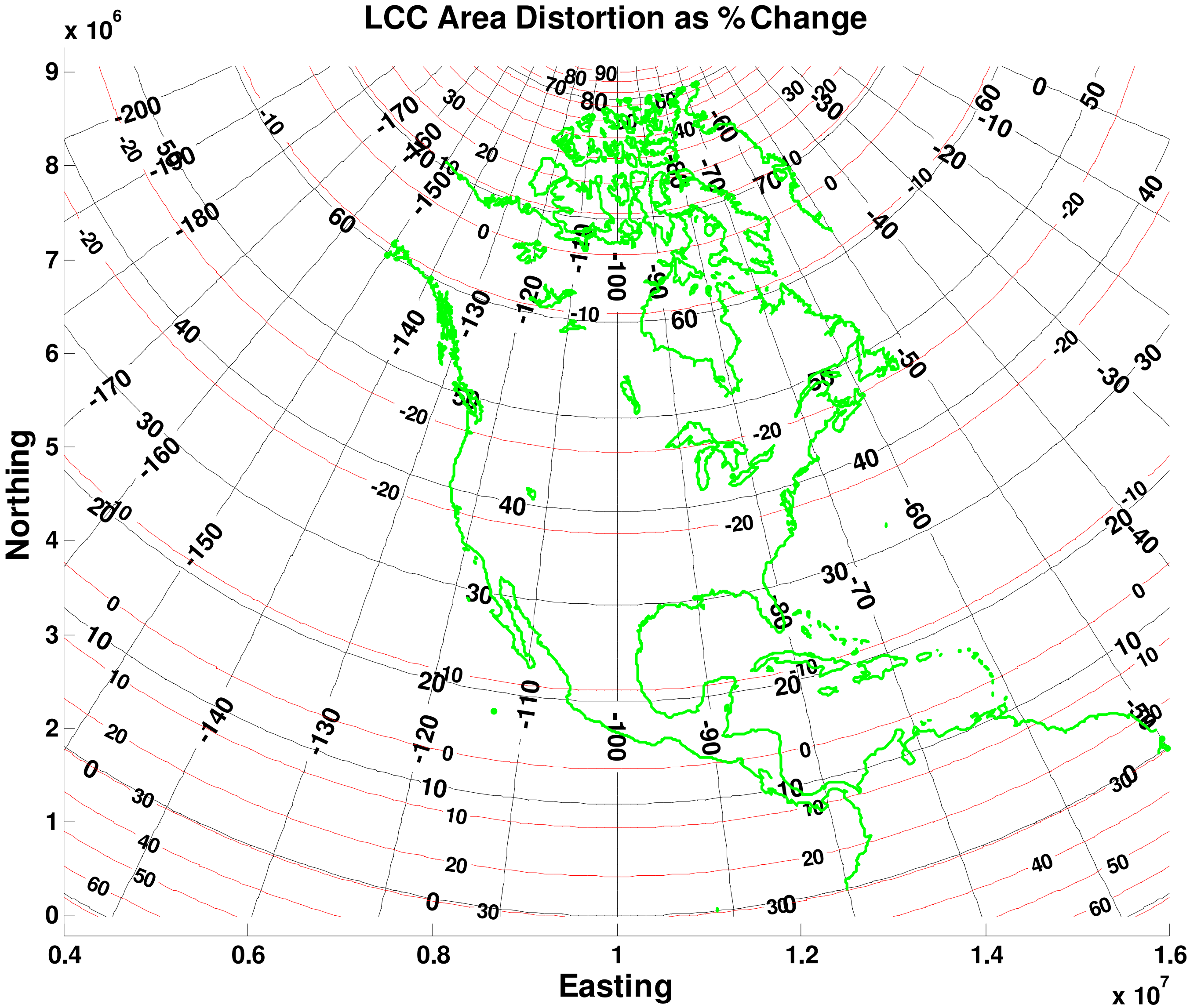
Meridians are straight lines and parallels are curved. They intersect orthogonally. Distortion is managed by selection of grid parameters

LCC Scale Factor Distortion



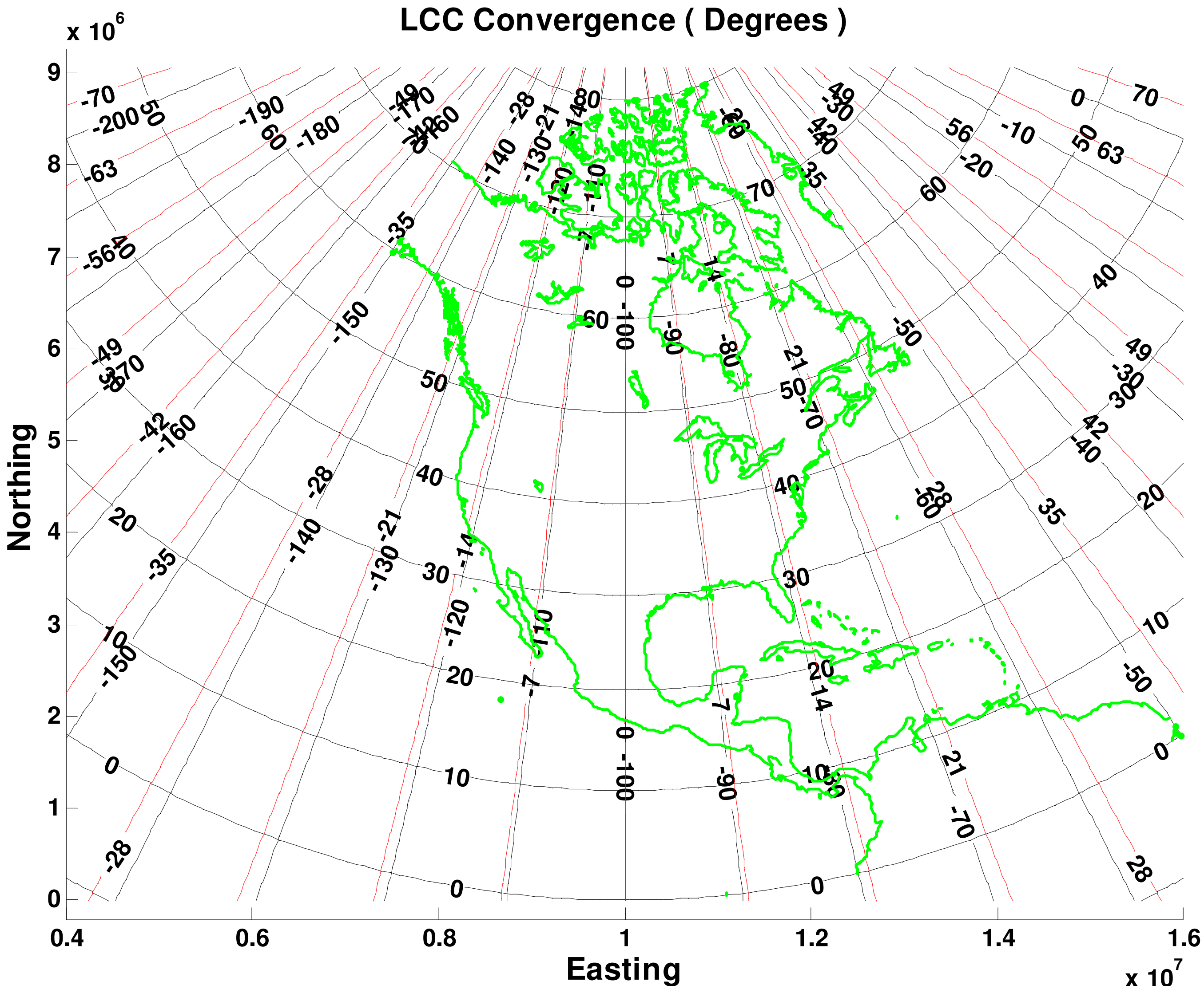
The red lines contour <u>linear scale change</u> as a percentage, varying (N to S) from +35% => 0% => -10% => 0% => +15%.

LCC Area Distortion



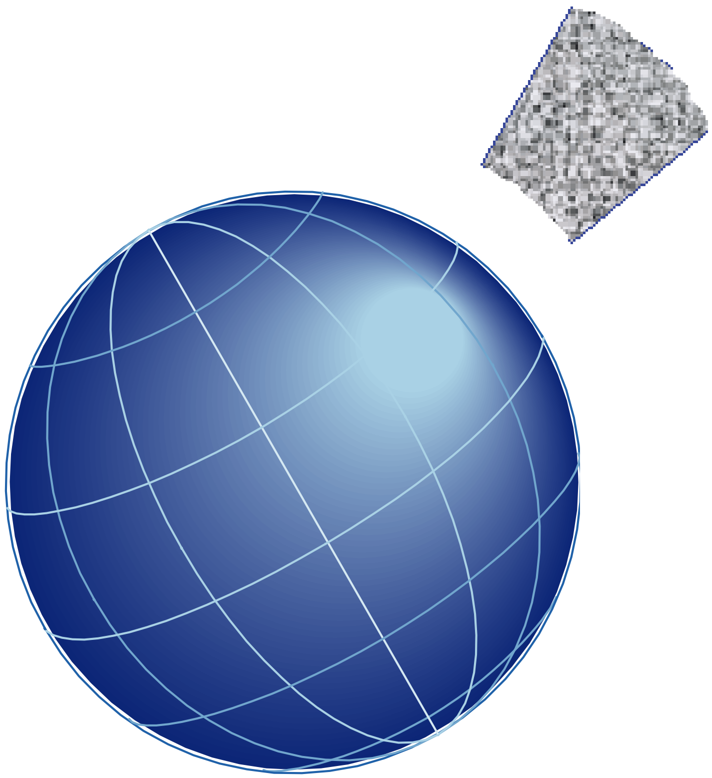
The red lines contour <u>area change</u> as a percentage, varying (N to S) from +80% => 0% => -20% => 0% => +30%.

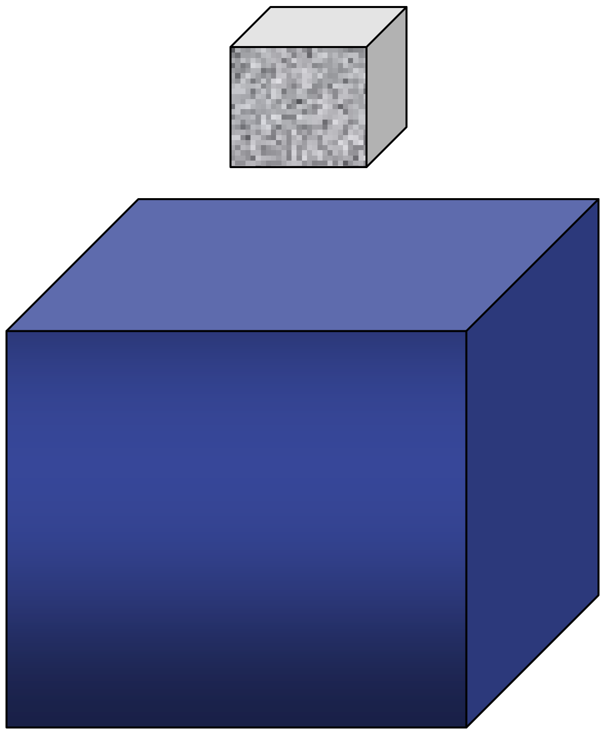
LCC Convergence Distortion



The red lines contour <u>azimuth difference between grid and true north</u> (i.e., convergence of the meridians) in degrees, varying (W to E) from -70º => 0º => +70º

Engineering CRS ("Flat-Earth")



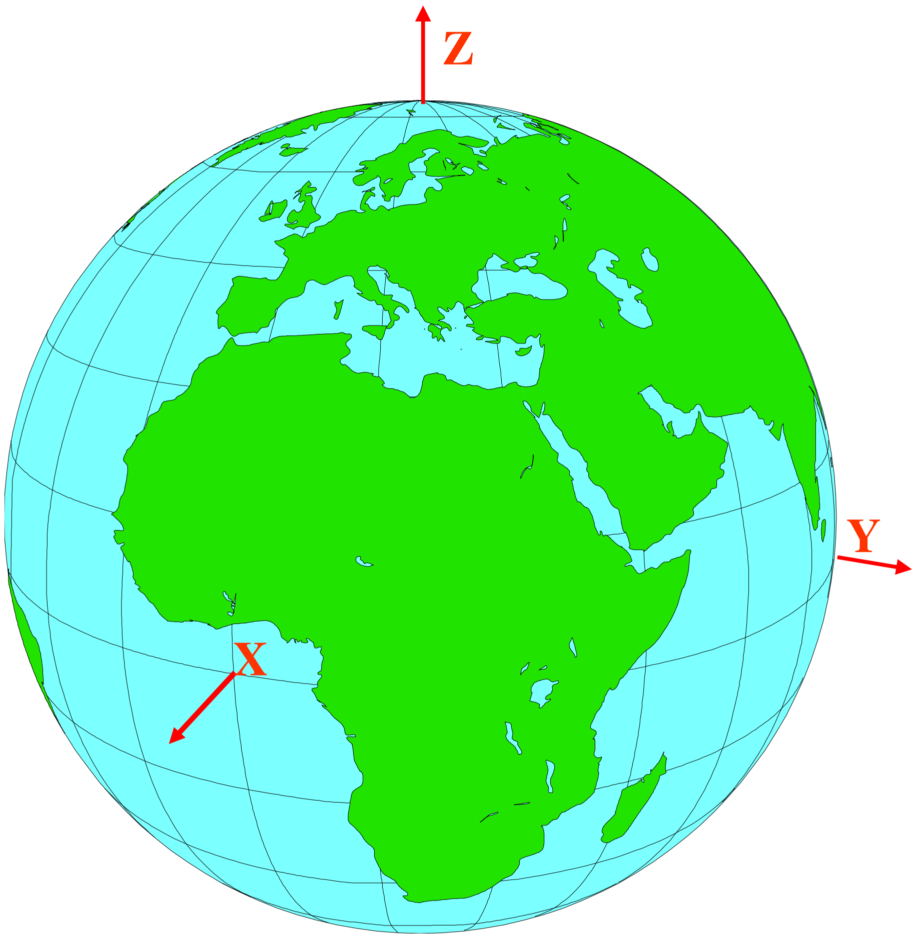


Our project extracted from an ellipsoidal earth

Our project extracted from a cubical, flat earth

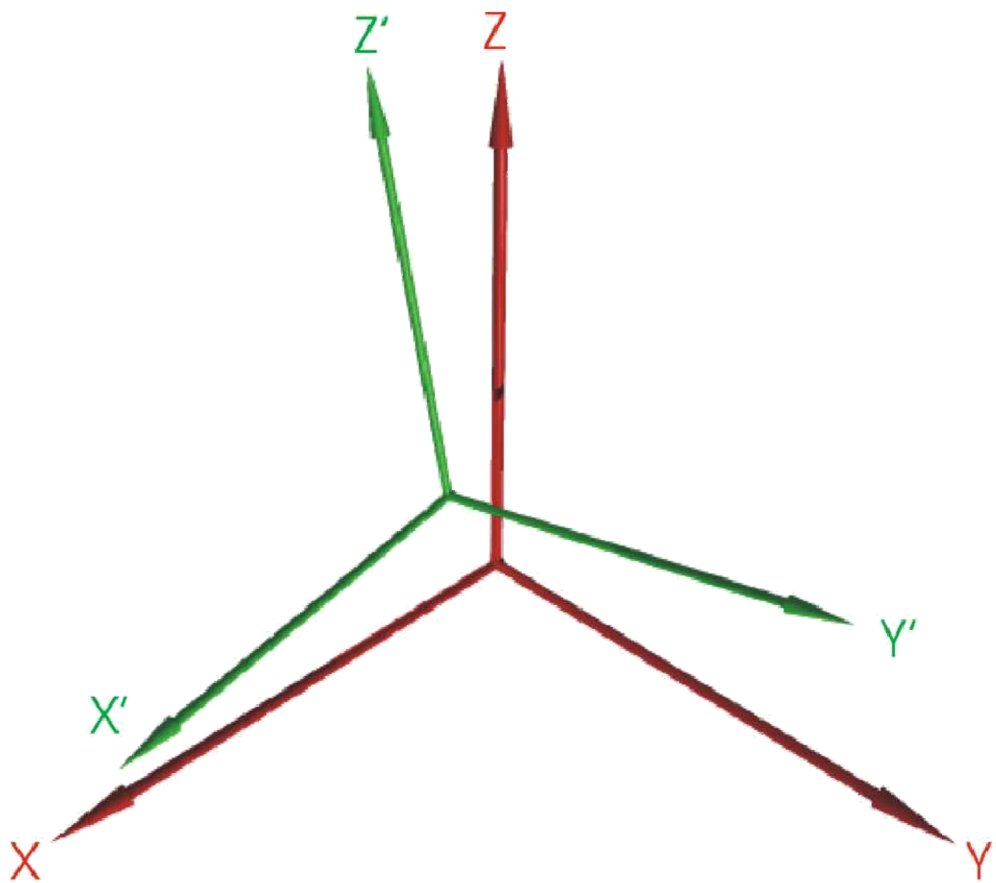
Contents

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.

Geocentric CRS Datum Shift



The relationship between two geodetic datums can be described by the 7 parameters required to transform their Geocentric CRSs into alignment (3 translations, 3 rotations and 1 scale change). For example, the red Geocentric CRS might be WGS84 and the green might be ED50.

Coordinate Conversion

- The mathematics of map projections (3D=>2D) are complicated (especially TM) and only valid over limited geographical extents
- The mathematics of converting Geographical CRS coordinates to Geocentric CRS are simple and valid the world over (see the following)
- The “flat-earth” cubical coordinates of an Engineering CRS are mathematically the simplest, but they have only local validity

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

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

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

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

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

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

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Current Geoscience CRS Practice

Seismic surveys are usually acquired on orthogonal binning grids laid out on conformal projections that preserve orthogonality. Seismic interpretation workstations typically operate in a Compound CRS, namely, a Projected CRS in the horizontal and depth (or time) in the vertical. All Projected CRSs have scale and orientation distortion in the horizontal. Verticals of increasing depth are represented as parallel, not converging, lines. Additional oilfield culture (such as wells, horizons, faults, interpretations, etc.) are entered into this Compound CRS.

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Why ECEF?

- ECEF (Geocentric CRS) is the 3D CRS most similar to the coordinate reference systems already implemented in the new 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 reservoirs to regions
- No geodetic "smarts" are required in the VE

Prototyping ECEF in Matlab

- Matlab provides both 2D and 3D visualization
- Coastline culture in Geographical CRS coordinates (lat/lon) is available on the web
- Lat/lon/hgt (height=0) converted to ECEF
- Displayed in 2D and 3D, in different perspectives showing earth curvature
- ECEF rotated to Local Horizontal (ECEF-LH)

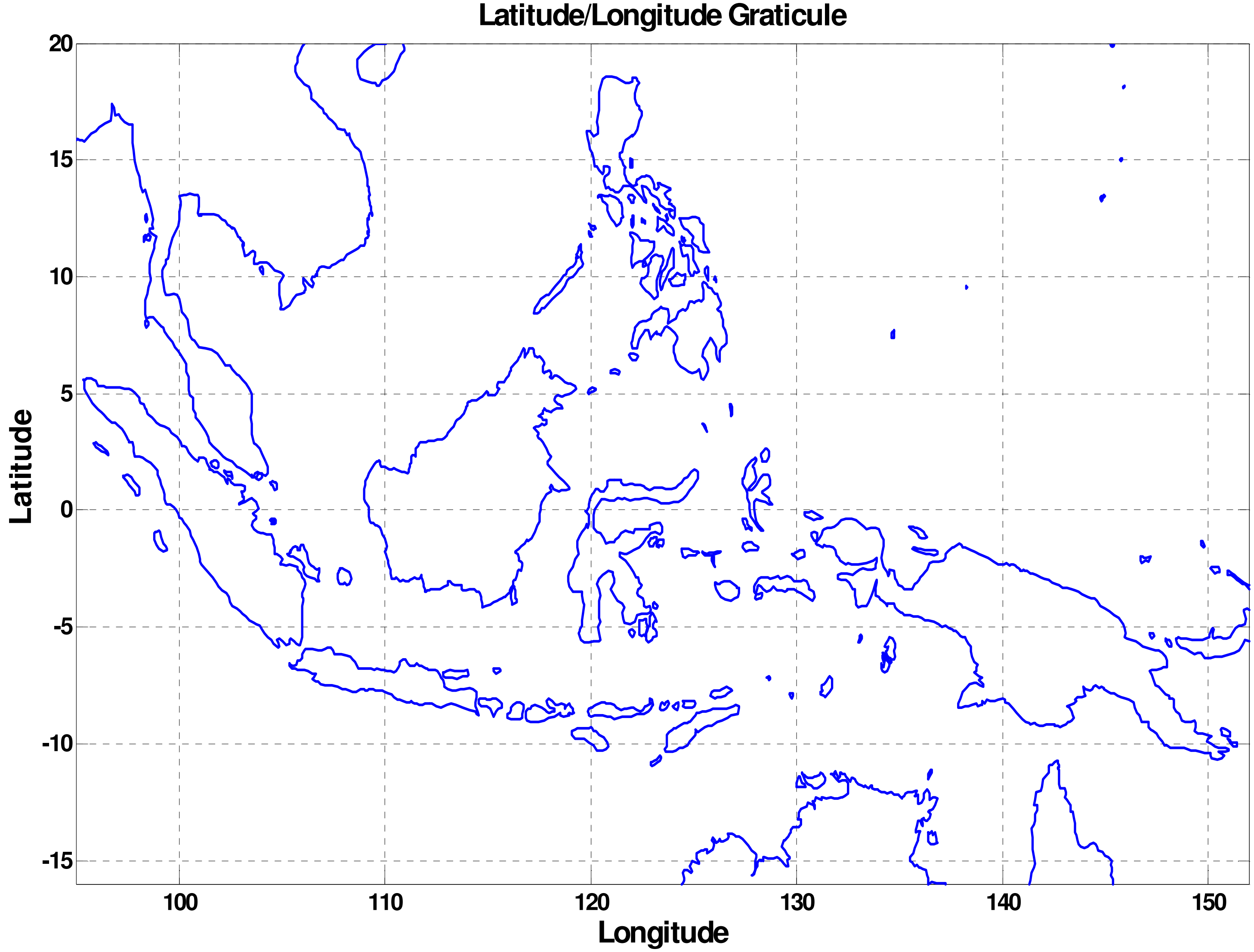
U.S.G.S. Coastline Culture Excerpts in Different CRSs

Geographical CRS (height = 0)		Geocentric CRS (ECEF)		
longitude	**latitude**	**X**	**Y**	**Z**
nan	nan	NaN	NaN	NaN
134.729458	7.664764	-4448838.50	4491051.62	845050.44
134.738845	7.699966	-4449207.90	4489953.01	848908.63
134.738845	7.622520	-4450011.63	4490764.09	840420.03
134.738845	7.512219	-4451142.37	4491905.19	828327.69
134.705990	7.390184	-4449797.07	4495700.79	814945.45
134.628544	7.357328	-4444043.84	4502043.30	811341.87
134.595688	7.455895	-4440474.83	4503590.35	822151.71
134.607422	7.577931	-4440157.19	4501423.88	835532.08
134.628544	7.610786	-4441478.98	4499444.97	839133.77
134.694255	7.655376	-4446175.65	4493882.55	844021.45
134.729458	7.664764	-4448838.50	4491051.62	845050.44
nan	nan	NaN	NaN	NaN

ECEF Conversion Code

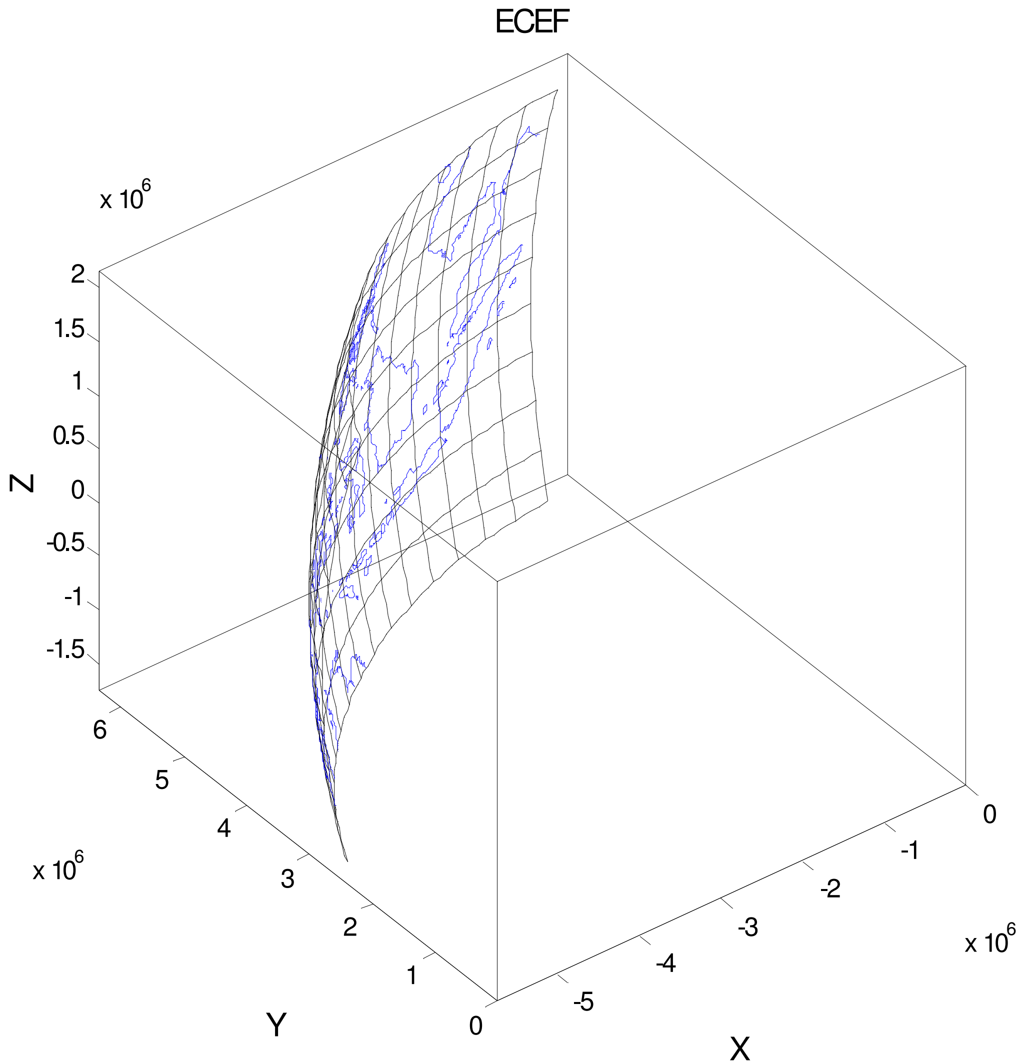
```
function [X, Y, Z] = ECEF01(LATDDD, LONDDD, HGT, A_in, RF_in)
% ECEF01  (02/11/05-nz) Earth-centered Earth-fixed coordinates
% Out variables in bracket to the left
% Input variables in parentheses to the right
% LATDDD, LONDDD are lat/lon in decimal degrees
% HGT is ellipsoidal height
A = A_in;                     % A is semi-major axis
RF = RF_in;                   % RF is reciprocal of flattening
% Radians to degrees; pi is an environment constant in Matlab
d2r = pi / 180;
% Solve for the parameters of the ellipsoid
F = 1 / RF;                   % Solve for flattening
B = A - F*A;                  % Solve for semi-minor axis
E2 = (A^2 - B^2) / A^2;   % Solve for eccentricity squared
EP2 = (A^2 - B^2) / B^2; % Solve for eccentricity prime squared
% Convert to radians
LATRAD = LATDDD * d2r;
LONRAD = LONDDD * d2r;
% Convert geographical coordinates to Cartesians (geocentric)
V = A / sqrt(1 - E2*sin(LATRAD)^2);
X =  (V + HGT)*cos(LATRAD)*cos(LONRAD);
Y =  (V + HGT)*cos(LATRAD)*sin(LONRAD);
Z =  (V*(1 - E2) + HGT)*sin(LATRAD);
```

Culture in Geographical 2D CRS



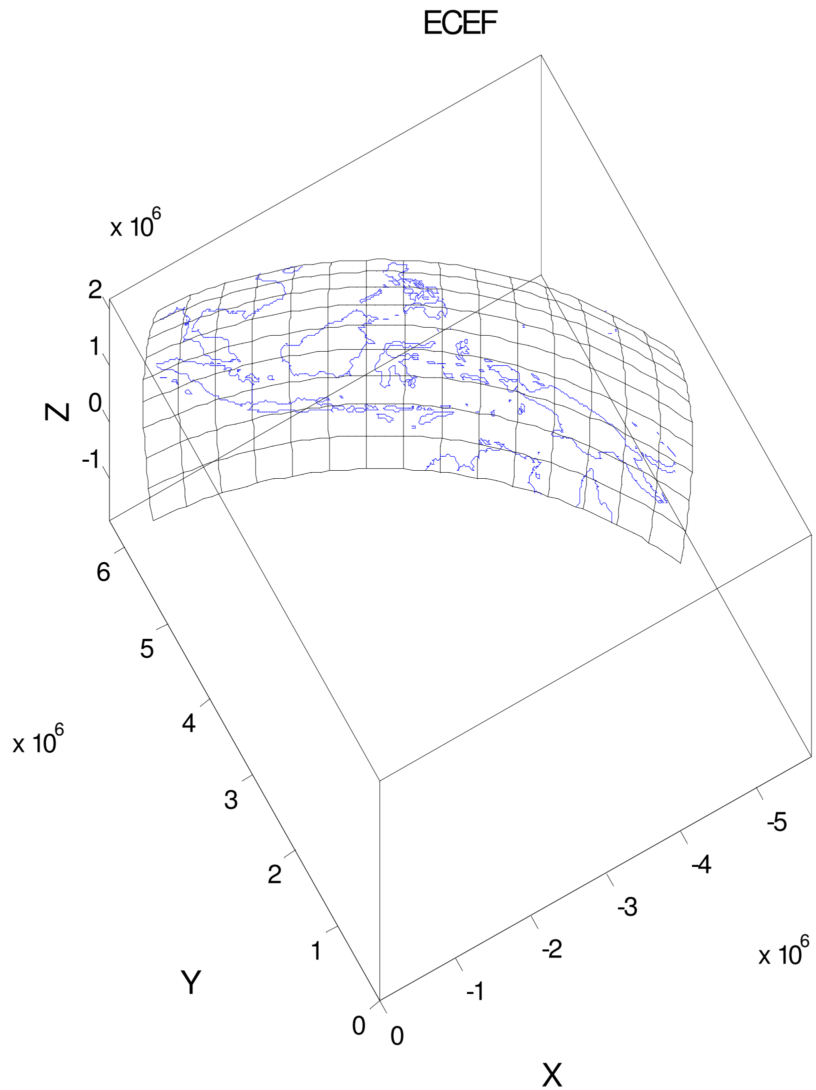
2D plan view with axes of latitude and longitude

Culture in ECEF 3D CRS



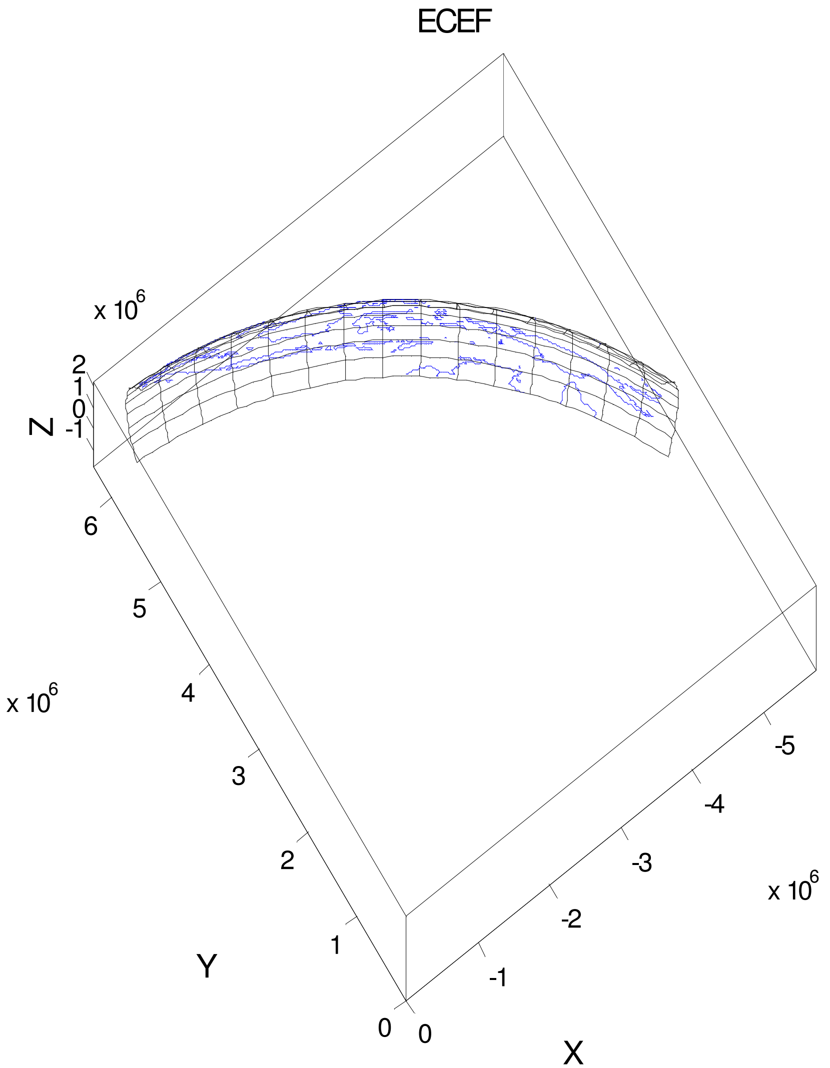
As presented by Matlab

Culture in ECEF 3D CRS



The view high above Australia looking North. The curvature of the earth through the Indonesian archipelago is becoming apparent.

Culture in ECEF 3D CRS



The view above Australia looking North, but lower in altitude this time. Now the curvature of the earth through the Indonesian archipelago is very apparent.

Intermediate Summary

The Geocentric CRS (earth-centered earth-fixed Cartesians) is well-described geodetically.

ECEF will spatially reference data that are currently referenced with a Compound CRS (2D in the horizontal and 1D in the vertical) after conversion of latitude, longitude, Northing, Easting, depth, height, elevation, and time into 3D ECEF units of meters.

VEs will inherently handle 3D data referenced this way, although users may prefer a Local Horizontal reference frame (ECEF-LH).

Scalability from reservoirs to regions is achieved within a single, unified coordinate reference system.

Rotation to Local Horizontal

- VE users may prefer their data referenced to their local area of interest
- ECEF can easily be translated and rotated to a Local Horizontal (ECEF-LH) reference frame with the Matlab code on the the next slide
- These equations are conformal, preserve the distortion-free curvature of the earth, and the computational burden is small
- VEs already do something similar to change the viewing perspective

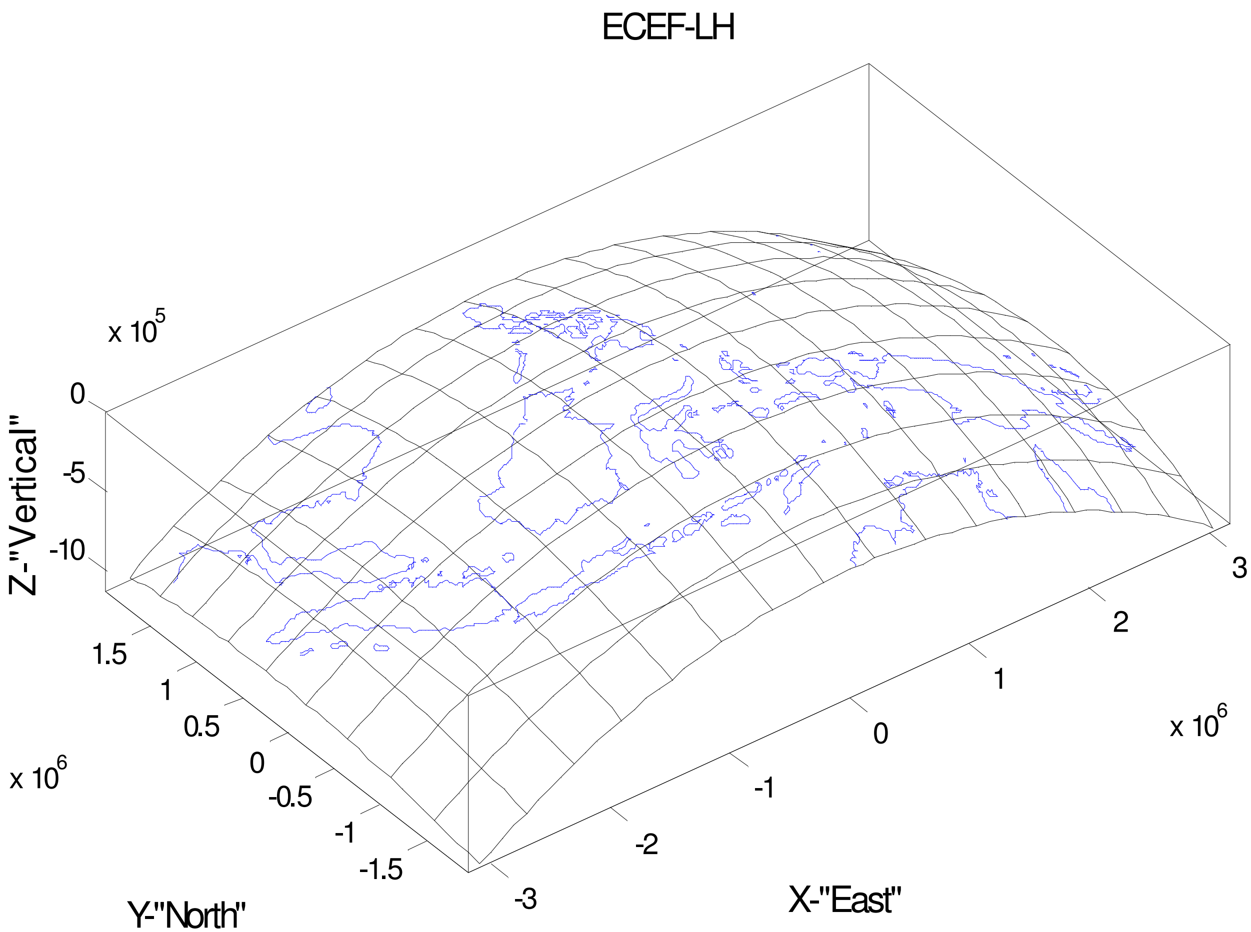
Rotation to Local Horizontal

```
function [LH] = LH02(ECEF, LH0, lat, lon)
% LH03     (02/13/05-nz)   ECEF to EDCEF-LH
% ECEF are the Earth-Centered Earth-Fixed input coordinates
% LH0 are the input ECEF coordinates of the project center
% lat, lon are of the project center in decimal degrees
% LH are the ECEF-LH (Local Horizontal) output coordinates

% Functions of lat/lon required to rotate X/Y/Z(ECEF) to E(X)/N(Y)/U(Z)
fnlat = pi/2-lat*d2r;
fnlon = pi/2+lon*d2r;

% Rotation matrices about the X and Z axes
CX = [ 1   0              0
       0   cos(fnlat)     sin(fnlat)
       0  -sin(fnlat)     cos(fnlat)];

CZ = [  cos(fnlon)   sin(fnlon)   0
       -sin(fnlon)   cos(fnlon)   0
        0            0            1];

% Compound rotation matrix (need only two)
CC = CX*CZ;

% The rotation of ECEF to ECEF-LH
LH = CC*(ECEF-LH0)';
```

U.S.G.S. Coastline Culture Excerpts in ECEF and ECEF-LH

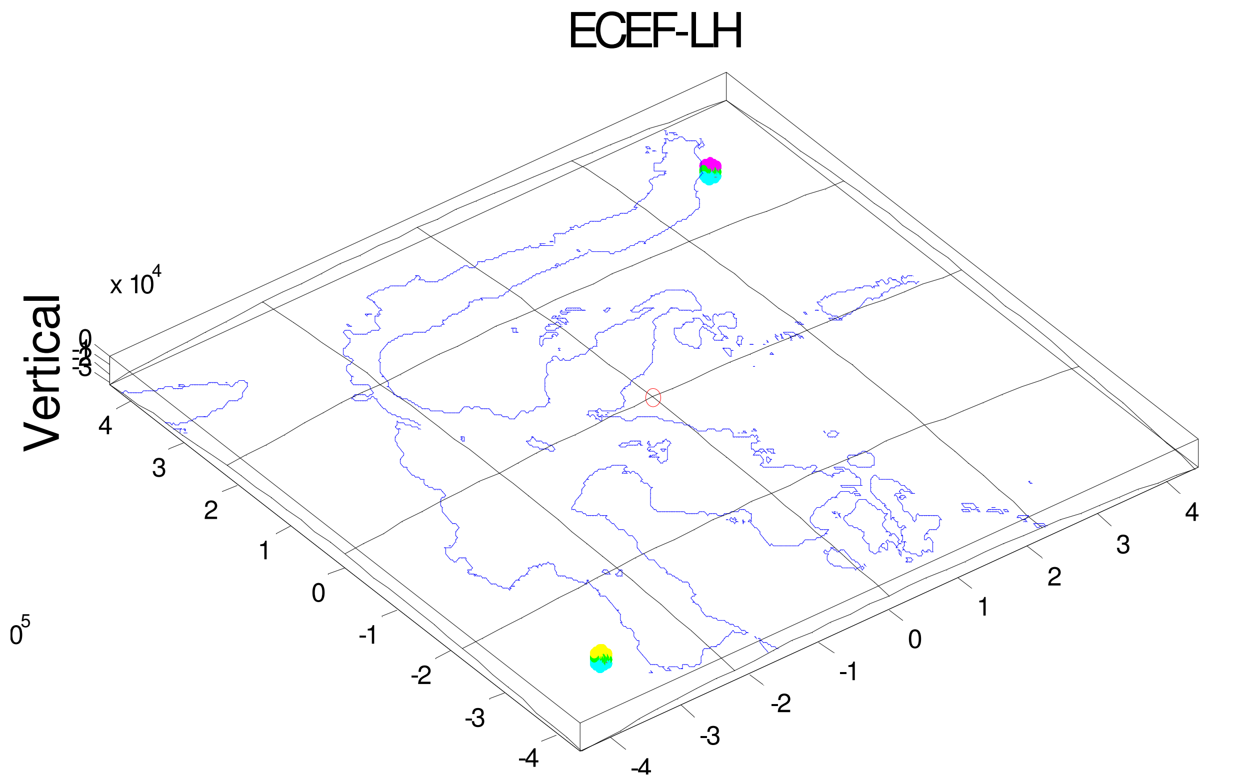
Geocentric CRS (ECEF)			ECEF–LH		
X	Y	Z	X–"East"	Y–"North"	Z–"Vertical"
NaN	NaN	NaN	NaN	NaN	NaN
-4448838.50	4491051.62	845050.44	1176890.07	629263.78	-141393.29
-4449207.90	4489953.01	848908.63	1177810.66	633144.20	-141962.44
-4450011.63	4490764.09	840420.03	1178023.42	624621.61	-141137.51
-4451142.37	4491905.19	828327.69	1178322.76	612481.56	-139982.17
-4449797.07	4495700.79	814945.45	1175084.99	599023.91	-138056.25
-4444043.84	4502043.30	811341.87	1166768.65	595351.29	-136142.25
-4440474.83	4503590.35	822151.71	1162944.71	606179.44	-136477.76
-4440157.19	4501423.88	835532.08	1163892.85	619620.54	-137983.29
-4441478.98	4499444.97	839133.77	1166095.26	623251.49	-138758.50
-4446175.65	4493882.55	844021.45	1173099.44	628205.48	-140571.82
-4448838.50	4491051.62	845050.44	1176890.07	629263.78	-141393.29
NaN	NaN	NaN	NaN	NaN	NaN

Culture in ECEF-LH 3D CRS



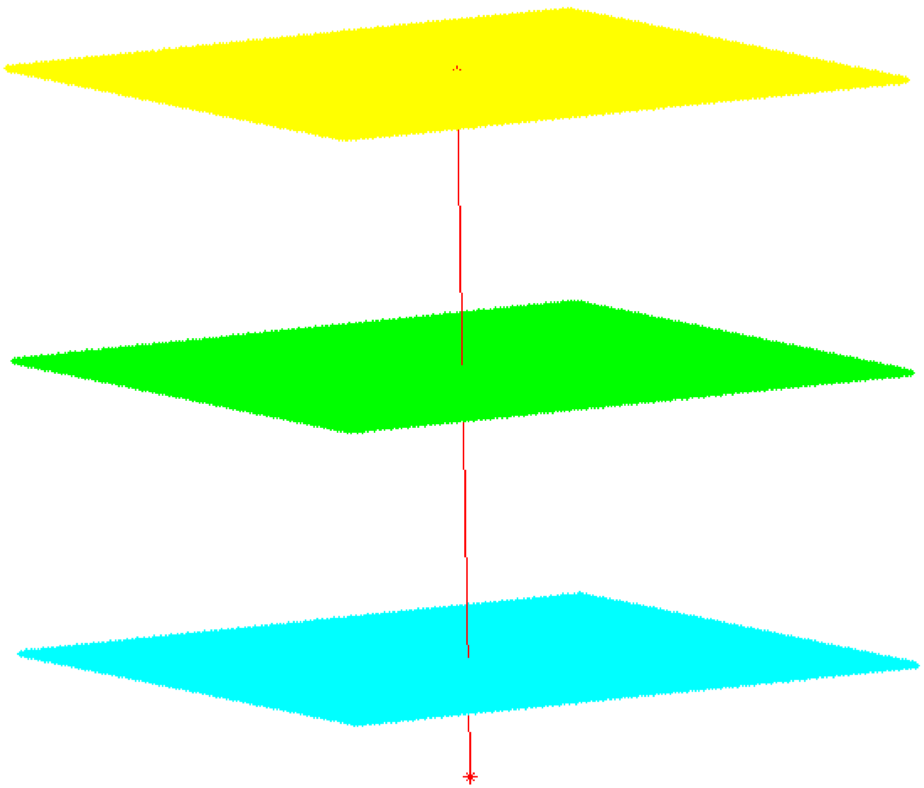
Indonesia in ECEF-LH as presented by Matlab. One can rotate this image in Matlab - or in a VE - to any perpendicular perspective, which will be free of distortion.

A Region with Two Reservoirs



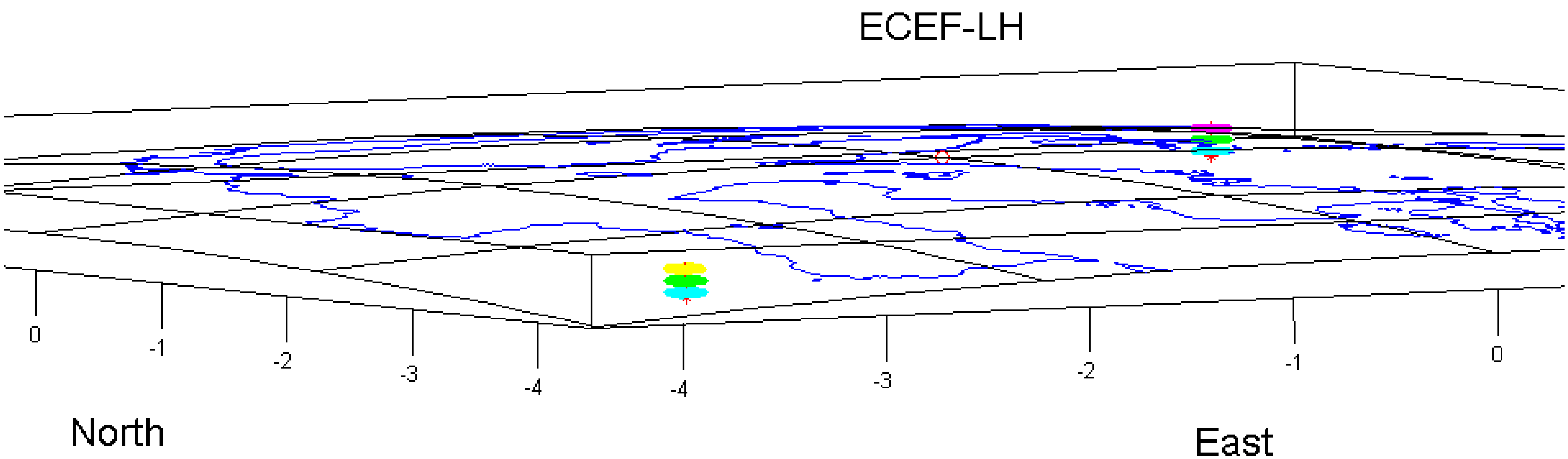
Sulawesi in ECEF-LH. One reservoir is off Ujung Pandang in the Makassar Strait. The other is 900 km to NE off of Manado. The local horizontal center is marked with a red zero.

The Reservoir off Ujung Pandang



This cartoon of the reservoir off Ujung Pandang is in a G&G's typical VE perspective. It is 10km by 10km horizontally in plan view with three interpreted horizons: a yellow sea-level surface, basement 10km deep in blue and one in between in green. A well is drilled through basement.

The Regional Perspective



The curvature of the earth is preserved without any mapping distortion in this regional perspective that captures both reservoirs and - in principle - all the modeled geology in between. The G&G can zoom into any area of interest, in as much detail as desired, and perform any volume computation in true meters. Or the G&G can zoom out in order to evaluate regional trends.

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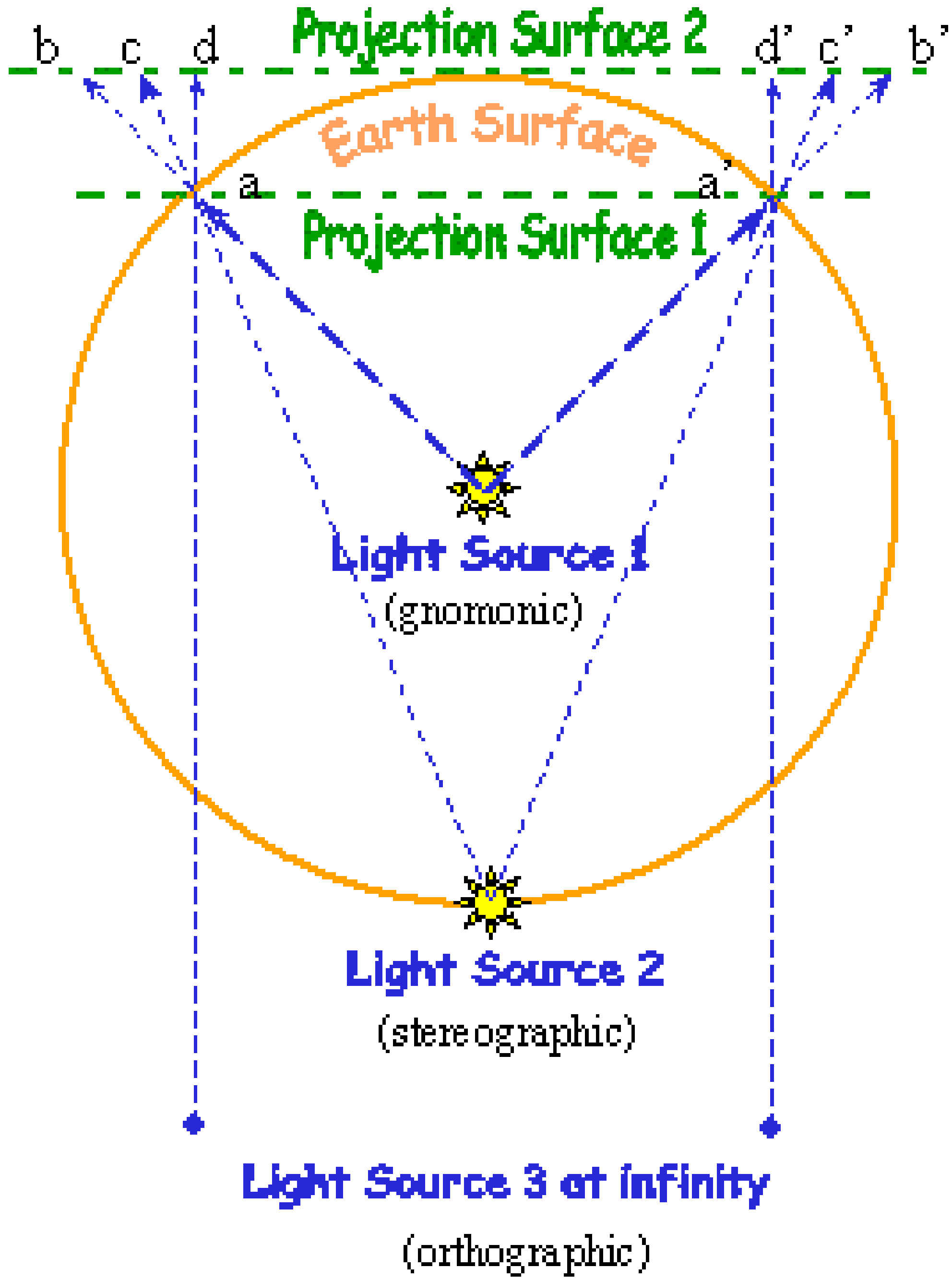
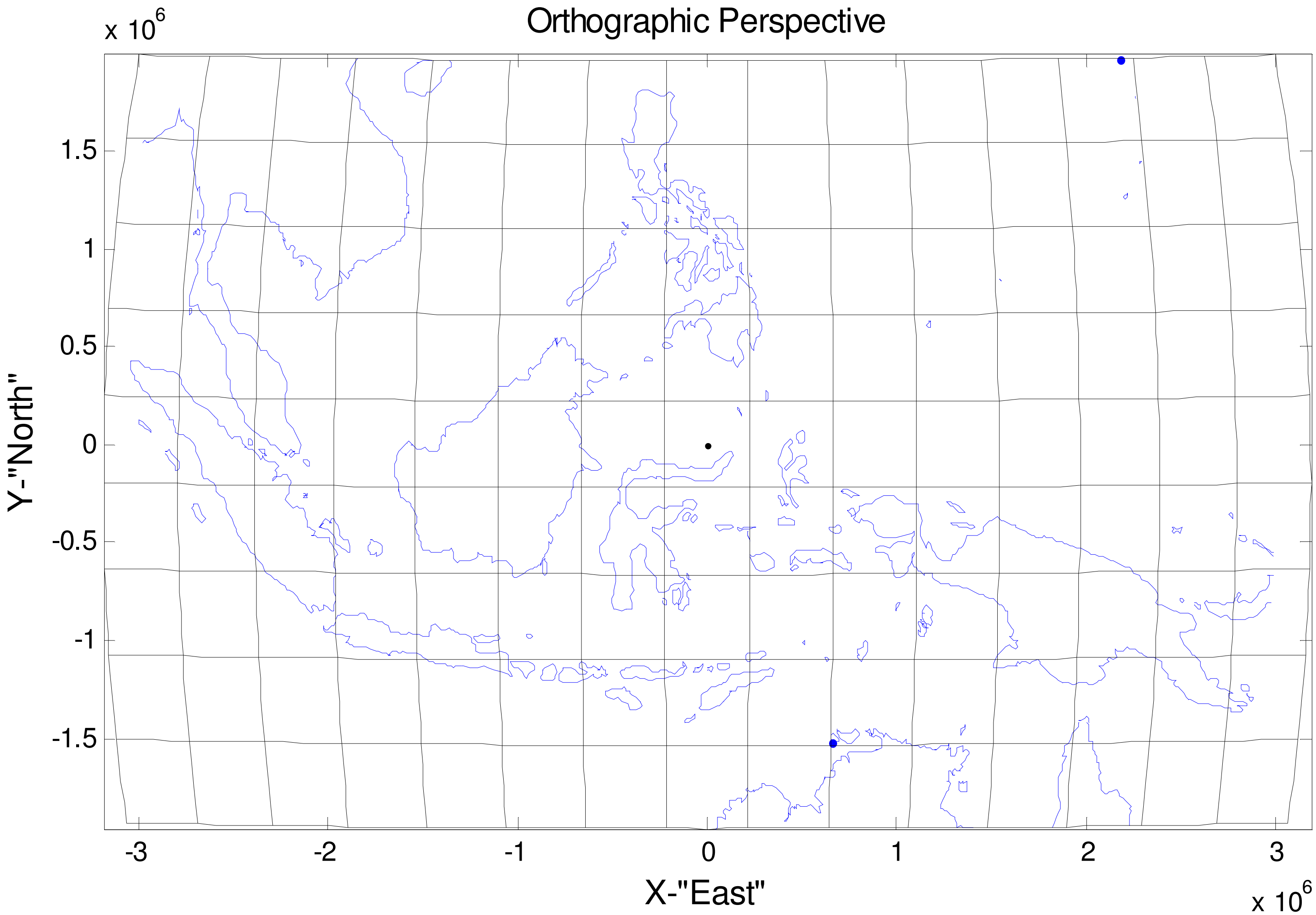
ECEF-LH and the Orthographic Projection

- The orthographic projection is the view from space, e.g., our view of the moon
- ECEF-LH without the Z component (3D=>2D) is the ellipsoidal orthographic projection
- The Orthographic Projection is a bona fide map projection (neither conformal nor equal area) intermediate between our normal 2D+1D paradigm and a new ECEF-LH 3D paradigm

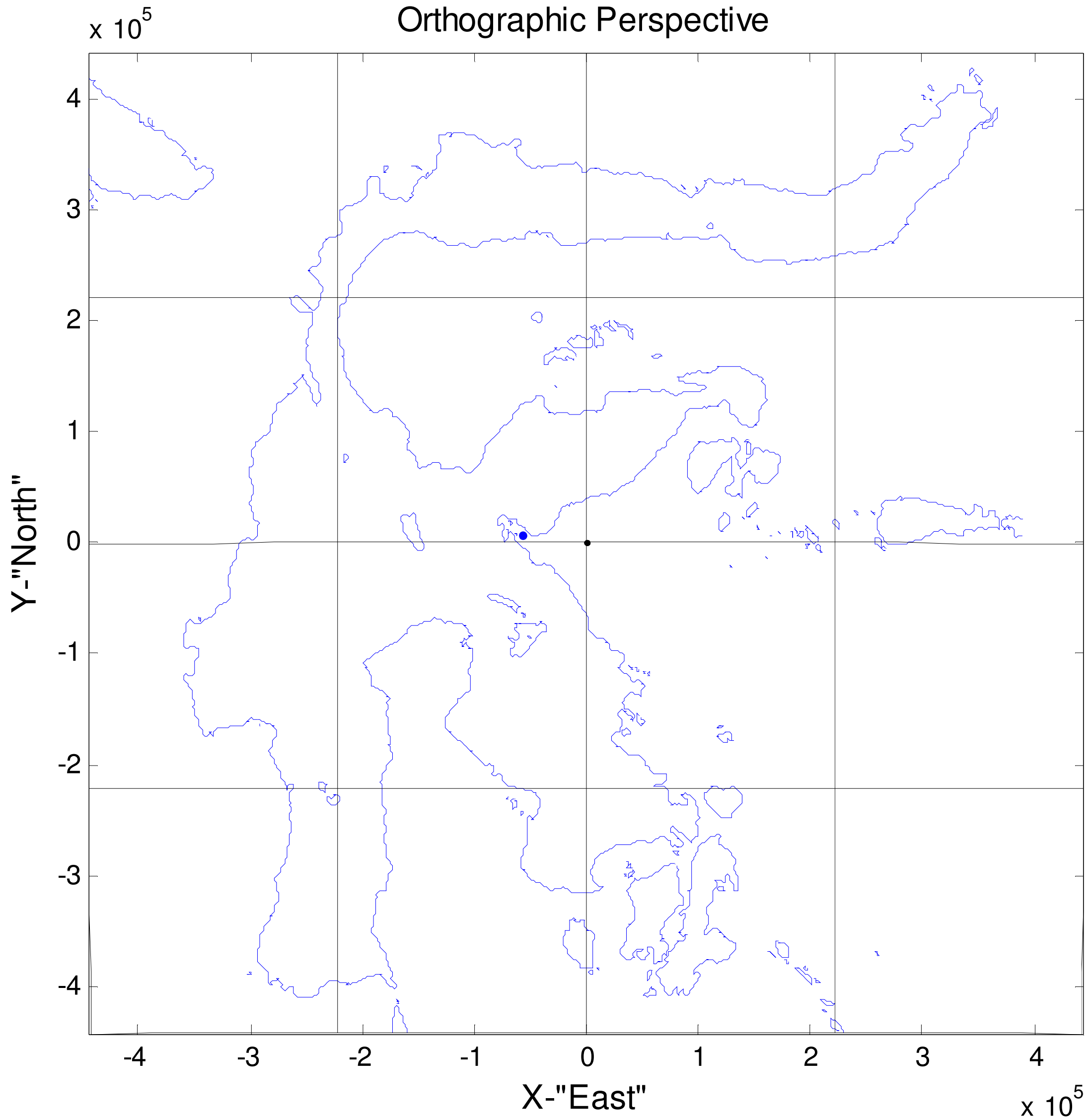


b
c
d
Projection Surface 2
d'
c'
b'
Earth Surface
a
a'
Projection Surface 1
Light Source 1
(gnomonic)
Light Source 2
(stereographic)
Light Source 3 at infinity
(orthographic)

Ellipsoidal Orthographic Projection



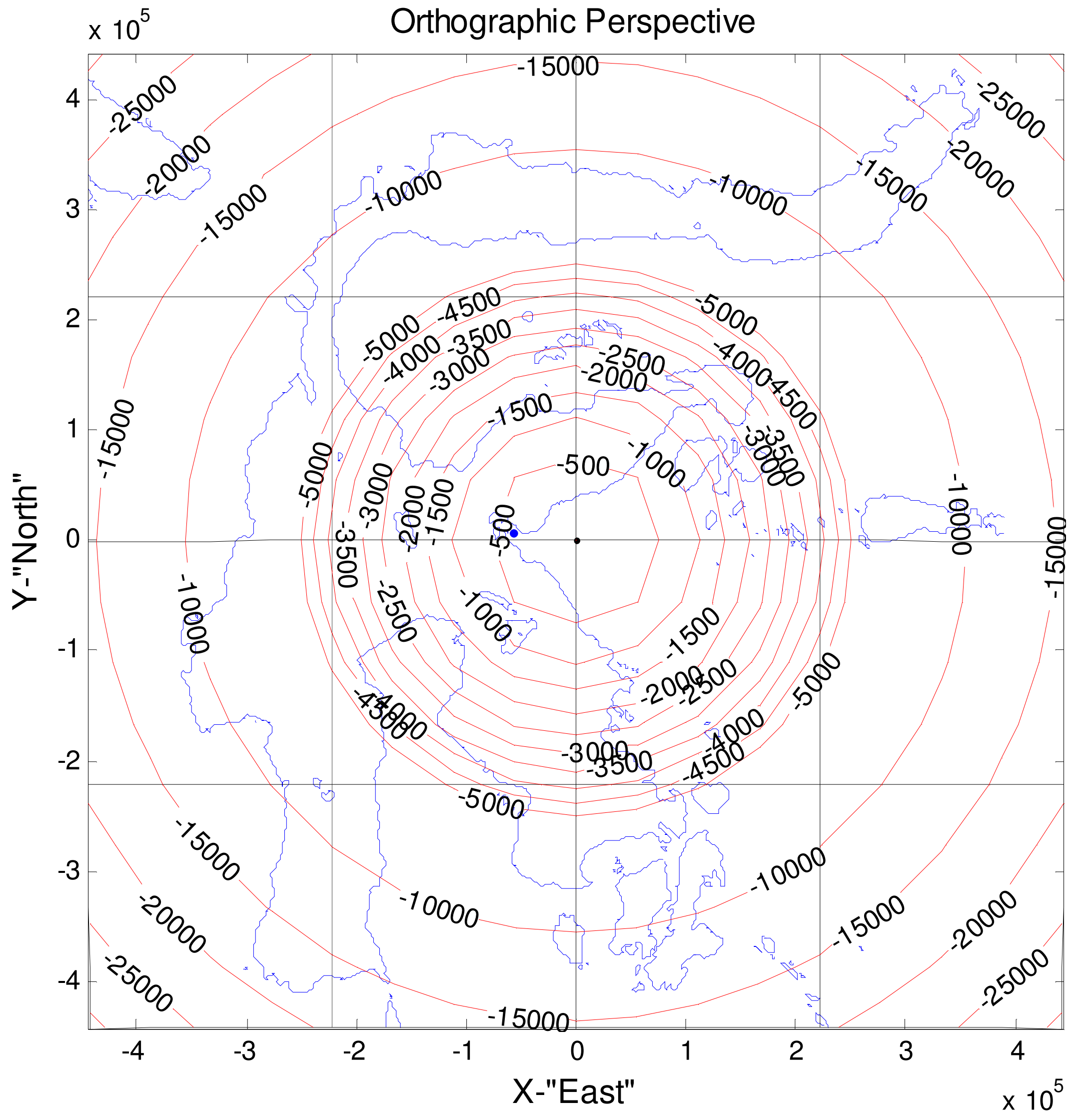
Sulawesi in Orthographic Projection



Separation Contours

- Contours of the “unused “ Z component (distance from the local horizontal plane to the ellipsoidal surface) in an ECEF-LH area
- Rule of thumb: the separation in meters is the distance over the surface in kilometers squared divided by 50
- For example: 1km=>0.02m, 10km => 2m, 100km => 200m, 1000km => 20,000m

Sulawesi Separation Contours



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- *Issues and Proposed Solutions*

Issues and Proposed Solutions - 1

- Data and projects are likely to be stored in a Compound CRS (2D+1D)
  - Data movers and "GeoEngines" need to be able to covert from projected (2D) and vertical (1D) coordinates into ECEF (3D), and back
  - Data stores must specify the vertical datum (e.g., MSL) with as much clarity as the geodetic datum
  - Geoidal models will be needed to convert from elevations (geoidal) to heights (ellipsoidal)

Issues and Proposed Solutions - 2

- My data are in my VE in ECEF. Now what?
  - Need to leverage the skills of experienced geologists and geophysicists to explore the ECEF perspective in the new visualization environments
  - What works? What doesn't?
  - What are the workarounds?
  - What priorities must we forward to the VE developers to better enable this perspective?
  - What priorities must we forward to the data movers to get the correct coordinates?

Issues and Proposed Solutions - 3

- Which way is up?
  - ECEF presents a curved, not a flat, surface that may be disorienting to G&Gs and Engineers
  - For small projects or small parts of a large project, lock into a local horizontal where the differences between a curved and a "flat" earth are negligible
  - Use an intermediate orthographic projection
  - Develop algorithms to relate flat-earth verticals to curved-earth verticals (it's just math!)
  - For large regional projects, the curved-earth presentation may be the most informative

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 and ECEF-LH are a paradigm shift in the way we view our data, perhaps a valuable perspective that will extract new information
- The time is ripe to explore ECEF

Acknowledgements

- Bomford, "Geodesy", 1980
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