An NGS Illustrated Guide to Geodesy for GIS Professionals

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Why should we care about geodesy?
The Plan

- Introducing the **National Geodetic Survey**
- GIS and the **National Spatial Reference System (NSRS)**
- Geodetic concepts – *illustrated!*
- Focus today is on geometric ("horizontal") datums
  - Connecting data to the Earth: *Datums*
  - A complicated topic: *Datum transformations*
  - Nothing is constant except change: *Time dependence*
  - Specific example: "**WGS 84** ‡ **NAD 83**"
- Other topics of Great Interest but not enough time to pursue
  - How data are displayed and analyzed: *Map projections*
  - How high? How deep? Where will water go? *Heights*
  - How good is it? How do you know? *Accuracy vs. Precision*
NGS: Who we are is where you are

• Been around a long time (since 1807)
  – Became National Geodetic Survey in 1970 (when NOAA created)

• Keepers of the National Spatial Reference System (NSRS)
  – Define, maintain, provide access for US and territories
  – Position, height, scale, gravity, orientation
  – ...and how they change with time

• Products & Services
  – Geodetic control (active and passive)
  – Data, models, and imagery (gravity, geoid, aerial imagery)
  – Tools and services (online and desktop software and services)
  – Standards, specifications, guidelines, and education
The NSRS is the foundation for GIS
What is a (geometric) “datum”? 

- Geometric (“horizontal”) datums
  - a.k.a. “geographic coordinate systems”
  - Basis for determining positions on the Earth
  - Modern ones are 4-D (time is 4th dimension)
    - Lat, lon, height (or Earth-Centered, Earth-Fixed XYZ), velocities
    - Ellipsoid (“spheroid”) by itself is NOT a datum
      - ~Same ellipsoid for NAD 83 and WGS 84, but differ by ~2 m
- Includes “local” and “global” datums
  - “Local” (regional) datums (e.g., NAD 83)
  - “Global” datums (e.g., WGS 84)
- Vertical datums another topic for another time...
The Figure of the Earth

Best-fit spherical Earth model

Too big by 9 miles at the poles

Too small by 4 miles at the equator

Point #1: San Diego

Equatorial plane

Mean Earth radius, $R \approx 3959$ miles

Earth mass center

Geoid ("mean sea level")
Earth model: Ellipsoid of revolution

Best-fit ellipsoid (e.g., GRS-80, WGS-84)

- Equatorial plane
- Earth mass center
- Point #1: San Diego
- Geoid ("mean sea level")

Ellipsoid flattening:
- \( f = \frac{a - b}{a} \approx 0.335\% \)
- \( 1/f \approx 298.25722 \)

Ellipsoid fits geoid to within about ±100 m worldwide

- Semi-major axis, \( a = 6,372,137.000 \text{ m} \approx 3963 \text{ mi} \)
- Semi-minor axis, \( b = 6,356,752.314 \text{ m} \approx 3950 \text{ mi} \)
**Geospatial Codependence**

*the first step is admitting you have a problem*

- Datums must be “realized”
  - Connected to Earth by observations (e.g., GNSS)
  - New realizations improve accuracy of coordinates
  - A single datum can have multiple realizations
- Interrelationships given by “datum transformations”
  - Mathematical methods for converting between datums
  - Needed if combining data based on different datums
  - There are many different kinds and they can vary greatly
- **Modern datum definitions are accurate but complex**
  - Will focus on two here: NAD 83 and WGS 84.
A (very) brief history of NAD 83 datum

• Original realization completed in 1986
  – Almost entirely classical (optical) observations
• “High Accuracy Reference Network” (HARN) realizations (1990s)
  – Done essentially state-by-state
  – Based on GNSS but classical stations included
• National Re-Adjustment of 2007
  – NAD 83(NSRS2007/CORS96) epoch 2002.00
  – Nationwide adjustment (GNSS only)
• NAD 83 (2011/PA11/MA11) epoch 2010.00
  – Also nationwide GNSS-only adjustment
  – This is NOT a new datum! (still NAD 83)
GIS is only for low spatial accuracy?

Median accuracy (95% conf.):
0.9 cm horiz, 1.5 cm height
A (very) brief history of WGS 84 datum

• Original realization completed in 1987
  – “Same” as original NAD 83 (to within ±1-2 m)

• WGS 84 (G730) — adopted Jan 2, 1994
  – Aligned with ITRF91

• WGS 84 (G873) — adopted Sep 29, 1996
  – Aligned with ITRF94

• WGS 84 (G1150) — adopted Jan 20, 2002
  – Aligned with ITRF2000 (at epoch 2001.00)

• WGS 84 (G1674) — adopted Feb 5, 2012
  – Aligned with ITRF2008 (at epoch 2005.00)

• WGS 84 (G1762) — adopted Mar 1, 2014
  – Also aligned with ITRF2008 (at epoch 2005.00)
  – Note that current NAD 83 is epoch 2010.00
Positions for entire Earth (or large part of Earth)
  – For modern datums these are 3-D
    • With velocities they are 4-D
  – Here concerned with \textit{geometric coordinates}

Two main types:
  – Latitude, longitude, and ellipsoid height: $\varphi, \lambda, h$
  – Earth-Centered, Earth Fixed (ECEF) Cartesian: $X, Y, Z$
    • Used for many types of geodetic computations
  – Can covert between both types without error
Earth-Centered Earth-Fixed (ECEF) coordinates

Ellipsoid (e.g., GRS-80, WGS-84)

+Z axis (parallel to axis of rotation)

+Y axis (90°E)

+X axis (Prime meridian)

Earth mass center

Geoid ("mean sea level")

Point #1, San Diego

Coordinates: 

\((-X_1, -Y_1, +Z_1)\)

\((\phi_1, \lambda_1, h_1)\)

Equatorial plane

-\(X\) axis (180°W)

-\(Y\) axis (90°W)

-\(Z\) axis

-\(Y\) axis (90°W)

\((-X_1, -Y_1, +Z_1)\)

\((\phi_1, \lambda_1, h_1)\)
Earth-Centered Earth-Fixed (ECEF) coordinates

Ellipsoid
(e.g., GRS-80, WGS-84)

+Z axis (parallel to axis of rotation)
+Y axis (90°E)

Point #1, San Diego

Coordinates:
\((-X_1, -Y_1, +Z_1)\)
\((\phi_1, \lambda_1, h_1)\)

Where is San Diego Conference Center?

\(X = -2,451,510\) m
\(Y = -4,780,100\) m
\(Z = +3,426,640\) m

...is the same as:

Latitude, \(\phi = 32 ° 42′ 25″\) N
Longitude, \(\lambda = 117°09′ 05″\) W
Ellipsoid height, \(h = -30\) m
Datum transformations

• Typical datum transformations
  – 3-parameter: 3-dimensional translation of origin as $\Delta X, \Delta Y, \Delta Z$
  – 7-parameter: 3 translations plus 3 rotations (one about each of the axes) plus a scale
  – 14-parameter: A 7-parameter where each parameter changes with time (each has a velocity)
  – Transformations that model tectonic displacement and other distortion (e.g., NGS models in HTDP, GEOCON, and NADCON)

• Vertical datum transformations
  – Can be simple shift or complex operation that models distortion (e.g., GEOCON, VERTCON)
Datum transformations

\[ \Delta X, \Delta Y, \Delta Z \]
Datum transformations

If datum changes with time, each component has a velocity...

14-parameter datum transformation
What to do...?
Based on 7 constant transformation parameters published by NGS (7 time-dependent parameters ignored), at input time = output time of 1997.0 (so tectonic velocities irrelevant).

This is how the transformation is implemented in most commercial geospatial software.
Based on 14 transformation parameters published by NGS at input time = output time of 2010.0 (so tectonic velocities irrelevant)
Based on 14 transformation parameters published by NGS at input time = output time of 2005.0 (so tectonic velocities irrelevant)
Based on 14 transformation parameters published by NGS at input time of 2005.0 ≠ output time of 2010.0 (5 years of tectonic movement).

This much more complex case is the "correct" transformation.
This 7-parameter transformation is equivalent to the following commercial vendor transformations:

- **ESRI**: “WGS_1984_(ITRF08)_To_NAD_1983_2011” (108363)
- **Trimble**: “ITRF to NAD 1983 (2011)”
  - **NOT** “NAD 1983 (Conus)” (a “zero” transformation used automatically with State Plane)
- **Topcon**: “NAD83”
  - **NOT** “NAD83_NO_TRANS”, another “zero” transformation
Does this stuff really matter?

- Significant for accuracies better than ~1-2 m
  - Can be problem for combining accurate datasets
  - Requires understanding of modern datums
  - Be careful when using “WGS 84”
    - Which realization? At what epoch? At what level of accuracy?

- Things are moving, and it can make a difference
  - e.g., San Diego moving 4.0 cm/yr NW w.r.t. Phoenix, AZ

- Modern GNSS becoming more precise
  - Autonomous positions soon better than 1-2 m
  - But accuracy another issue... with respect to what?
New Datums for the U.S.

• Planned release in 2022
  – Geometric datum: Aligned with ITRF/WGS 84
  – Vertical datum: Based on gravimetric geoid

• How much will NSRS coordinates change?
  – North America plate (CONUS and AK): Approx 0.8 to 1.6 m
  – Pacific plate: Approx 3.4 (Midway) to 4.3 m (American Samoa)
  – Mariana plate: Approx 1.1 to 1.4 m

• How much will NSRS ellipsoid height change?
  – Approx -1.9 m (Puerto Rico) to +2.0 m (Guam)

• How much will NSRS CONUS orthometric height change?
  – Approx +0.1 m (Florida) to -1.3 m (Washington)
Approximate Horizontal Change

North American Plate

- Mariana Plate (Meters)
  - High: 1.4 m
  - Low: 1 m

- North American Plate (Meters)
  - High: 2 m
  - Low: 0 m

- Pacific Plate (Meters)
  - High: 4.3 m
  - Low: 2.3 m

Tectonic Plate Boundaries

NAD 83(2011) to IGS08 at epoch 2022.0
Approximate Horizontal Change

NAD 83(NA11) to IGS08 at epoch 2022.0
NAD 83(2011) to IGS08 at epoch 2022.0
NAVD 88 to new vertical datum
Estimated as NAVD 88 "zero" (datum) surface minus NGS gravimetric geoid
Conclusions

• Geodesy knowledge needed for correct georeferencing
  – Becomes more important as spatial accuracy increases
  – Driven by high precision and low cost of GNSS (a geodetic tool)

• High-accuracy geodetic transformations are complicated
  – Time-dependence especially complex for differential tectonic motion
  – Datasets representing different times difficult to spatially align

• Metadata (documentation) is essential
  – Improves reliability and accuracy of data
  – Increases value and usefulness of spatial data
  – Needed all geospatial data (GIS, surveying, engineering, etc.)
June 30, 2014: The National Geodetic Survey (NGS) Releases new Beta experimental geoid height model “xGEOID14B,” spanning one-quarter of Earth’s surface 06.27.2014

June 28, 2014: NGS Webinar Presentation "A Conversation with the National Geodetic Survey" 06.06.2014

NGS Hosts the North American Comparison of Absolute Gravimeters(NACAG14), September 13-21, 2014 06.16.2014

Heartbleed Vulnerability Notice 05.02.2014

Popular GPS Positioning Service Is Enhanced: OPUS Projects 01.28.2014

In The News

06/26/2014 - NGS Serves Key Role at International GNSS Service Workshop
National Geodetic Survey (NGS) staff presented at the International GNSS Service (IGS) Workshop in Pasadena, California, June 23 to 27. The IGS sets worldwide standards by managing the Global Navigation Satellite System.
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Questions?