Space, Time, and Datum Forensics
Aligning GIS Data on a Dynamic Earth
Michael L. Dennis, RLS, PE
Projections are easy
Datums are hard
Speaking the same language

- Coordinate system MUST have a “datum”
- Coordinate system MAY have a “map projection”
- “Datum” for this discussion…
  - = “Geographic coordinate system”
  - = “Geometric reference frame”
  - Modern ones 4-dimensional (3-D position PLUS time)
- “Map projection”
  - Curved geographic → planar projected \((x, y\) or \(east, north\))
  - Horizontal ONLY
- Vertical datums (coordinate systems)
  - An even more complex topic for another time…
Projections are easy.
Datums are hard.

- Aligning data **REQUIRES** consistent datums
  - The map projection does **NOT** matter
- Datum (geographic) transformation
  - Method for converting between datums
- Datums can have multiple “realizations”
  - Definition is same but coordinates change
- NAD 83 has at least **FOUR** historic realizations
  - Three current realizations based on location (epoch 2010.0)
- WGS 84 has **SIX** realizations
Our good friends
WGS 1984
and
NAD 1983
A (very) brief history of NAD 83

• Original realization completed in 1986
  - Consisted (almost) entirely of classical (optical) observations

• “High Precision Geodetic Network” (HPGN) and “High Accuracy Reference Network” (HARN) realizations
  - Most done in 1990s, essentially state-by-state
  - Based on GNSS but classical stations included in adjustments

• National Re-Adjustment of 2007
  - NAD 83(CORS96) and (NSRS2007)
  - Simultaneous nationwide adjustment (GNSS only)

• New realization: NAD 83 (2011/PA11/MA11) epoch 2010.00
NAD 83(2011/PA11/MA11) epoch 2010.00
National adjustment of passive control
Total of 80,872 stations in 5 networks

Passive & non-CORS active
- 79,677 stations
  * GNSS vectors (424,711 total)
    - Enabled (403,112 = 94.9%)
    - CORS constrained (1195 total)
      - Computed (973)
      - Modeled (222)

CONUS Primary
CONUS Secondary
Alaska
Pacific (MA11)
Pacific (PA11)
North America plate
Caribbean plate
Australia plate
Tectonic plate boundary
A (very) brief history of WGS 84 datum

- Original realization completed in 1987
  - “Same” as original NAD 83 (to within \( \pm 1-2 \) m)
- WGS 84 (G730) — adopted Jan 1994
  - Aligned with ITRF91
- WGS 84 (G873) — adopted Sep 1996
  - Aligned with ITRF94
- WGS 84 (G1150) — adopted Jan 2002
  - Aligned with ITRF2000 (at epoch 2001.00)
- WGS 84 (G1674) — adopted Feb 2012
  - Aligned with ITRF2008 (at epoch 2005.00)
- WGS 84 (G1762) — adopted Oct 2013
  - Also aligned with ITRF2008 (at epoch 2005.00)
  - **Note that current NAD 83 is epoch 2010.00**
How do you get WGS 84 coordinates?

- Only true access: Broadcast orbits
  - Accuracy ~3 to 5 meters horizontal
- Can assume equal to civilian global frames
  - International Terrestrial Reference Frame (ITRF)
  - International GNSS Service (IGS) frame

Sources:
- Satellite Based Augmentation Systems (SBAS)
  - E.g., WAAS, OmniSTAR
- Various positioning services
  - E.g., OPUS, AUSPOS,
So, you think you have WGS 84 coordinates...

- If accuracy worse (larger) than ~3 m:
  - Can consider same as “generic” NAD 83
  - Don’t need realization or epoch date
  - No need to transform to NAD 83

- If (stated) accuracy better (smaller) than ~3 m:
  - Must include realization (e.g., G1762)
  - Must include epoch date (e.g., 2005.00)
  - Otherwise can NOT be at accuracy stated
  - May not be able to accurately transform to NAD 83
What to do...?
Datum (geographic) transformations in Esri software

**ArcGIS 10.3.1 documentation (for 10.1, dated Mar 2012)**

- 1368 datum (geographic) transformations
  - 886 involve “WGS 84”
  - 115 involve “NAD 83”
  - 26 between “NAD 83” and “WGS 84”
  - *And transformations can be combined for even more!*

**Where is the Esri documentation?**

- `C:\Program Files (x86)\ArcGIS\Desktop10.3\Documentation`
  - “geographic_coordinate_systems.pdf”
  - “geographic_transformations.pdf”
Back to our good friends “WGS 84” and “NAD 83”

• Geospatially empower yourself!
  - You are not helpless!
  - You are not a victim!

• You CAN check the transformations
  - NAD 83 is defined by NGS
  - NAD 83 formally related to IGS08 (= “current” WGS 84)
  - Current WGS 84 defined as equivalent to ITRF2008
  - IGS08 functionally equivalent to ITRF2008

• Can use NGS control to check transformation
How to check “WGS 84” ⇔ “NAD 83”
Consider NGS CORS “POINT LOMA 5” (PLO5)

- NGS Datasheets
  - Gives NAD 83 (2011) \textit{epoch} 2010.00
  - Use HTDP to transform to WGS 84/ITRF2008/IGS08

- NGS CORS
  - Gives NAD 83 (2011) epoch 2010.00
  - Gives IGS08 = ITRF2008 = WGS 84 (G1674/G1762) at \textit{epoch} 2005.00

- NGS OPUS
  - Gives NAD 83 (2011) epoch 2010.00
  - Gives IGS08 = ITRF2008 = WGS 84 (G1674/G1762) at \textit{current epoch}
Notifications

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 26, 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 05.15.2014

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 world standards for high-accuracy use of Global Navigation Satellite System (GNSS) data, and the NGS provides the primary North American reference. More information...
**The NGS Datasheet**

**DI0894 CORS** - This is a GPS Continuously Operating Reference Station.
**DI0894 DESIGNATION** - POINT LOMA 5 CORS ARP
**DI0894 CORS_ID** - PLO5
**DI0894 PID** - DI0894
**DI0894 STATE/COUNTY** - CA/SAN DIEGO
**DI0894 COUNTRY** - US
**DI0894 USGS QUAD** - POINT LOMA (1994)

**DI0894**

<table>
<thead>
<tr>
<th><em>CURRENT SURVEY CONTROL</em></th>
</tr>
</thead>
</table>

**DI0894**

<table>
<thead>
<tr>
<th><strong>NAD 83(2011) POSITION</strong></th>
<th>32 39 55.50397(N) 117 14 34.85949(W)</th>
<th>ADJUSTED</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NAD 83(2011) ELLIP HT</strong></td>
<td>-21.774 (meters)</td>
<td>(08/??/11) ADJUSTED</td>
</tr>
<tr>
<td><strong>NAD 83(2011) EPOCH</strong></td>
<td>2010.00</td>
<td></td>
</tr>
<tr>
<td><strong>NAVD 88 ORTHO HEIGHT</strong></td>
<td><strong>(meters)</strong></td>
<td><strong>(feet)</strong></td>
</tr>
</tbody>
</table>

**DI0894**

| **NAD 83(2011) X** | -2,460,295.155 (meters) |
| **NAD 83(2011) Y** | -4,778,388.922 (meters) |
| **NAD 83(2011) Z** | 3,422,768.630 (meters)  |

| **GEOID HEIGHT** | -35.51 (meters) |

**DI0894 Network accuracy estimates per FGDC Geospatial Positioning Accuracy Standards:**

<table>
<thead>
<tr>
<th><strong>FGDC (95% conf, cm)</strong></th>
<th><strong>Standard deviation (cm)</strong></th>
<th><strong>CorrNE</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Horiz</td>
<td>Ellip</td>
<td>SD_N</td>
</tr>
<tr>
<td><strong>NETWORK</strong></td>
<td>0.95</td>
<td>3.23</td>
</tr>
</tbody>
</table>
Antenna Reference Point (ARP): POINT LOMA 5 CORS ARP

PID = DI0894

IGS08 POSITION (EPOCH 2005.0)
Computed in Aug 2011 using data through gpswk 1631.
X = -2460295.762 m  latitude = 32 39 55.51335 N
Y = -4778387.728 m  longitude = 117 14 34.90119 W
Z =  3422768.470 m  ellipsoid height = -22.520 m

IGS08 VELOCITY
Computed in Aug 2011 using data through gpswk 1631.
VX =  -0.0299 m/yr  northward =  0.0193 m/yr
VY =   0.0287 m/yr  eastward  = -0.0397 m/yr
VZ =   0.0154 m/yr  upward    = -0.0016 m/yr

NAD_83 (2011) POSITION (EPOCH 2010.0)
Transformed from IGS08 (epoch 2005.0) position in Aug 2011.
X =  -2460295.155 m  latitude = 32 39 55.50397 N
Y =  -4778388.922 m  longitude = 117 14 34.85949 W
Z =   3422768.630 m  ellipsoid height = -21.774 m

NAD_83 (2011) VELOCITY
Transformed from IGS08 velocity in Aug 2011.
VX =  -0.0151 m/yr  northward =  0.0307 m/yr
VY =   0.0291 m/yr  eastward  = -0.0267 m/yr
VZ =   0.0243 m/yr  upward    = -0.0028 m/yr
All computed coordinate accuracies are listed as peak-to-peak values.
For additional information: http://www.ngs.noaa.gov/OPUS/about.jsp#accuracy

USER: mld@geodetic.xyz                        DATE: July 03, 2015
RINEX FILE: plo5152a.15o                            TIME: 16:37:34 UTC
SOFTWARE: page5 1209.04 master53.pl 022814      START: 2015/06/01 00:00:00
EPHEMERIS: igs18471.eph [precise]                  STOP: 2015/06/01 08:00:00
NAV FILE: brdc1520.15n                            OBS USED: 19863 / 20594 : 96%
ANT NAME: TRM41249USCG    SCIT             # FIXED AMB:    82 /    89   :  92%
ARP HEIGHT: 0.000                            OVERALL RMS: 0.009(m)

X:     -2460295.149(m)   0.011(m)          -2460296.081(m)   0.011(m)
Y:     -4778388.929(m)   0.002(m)          -4778387.433(m)   0.002(m)
Z:      3422768.628(m)   0.011(m)           3422768.633(m)   0.011(m)

LAT:   32 39 55.50387      0.008(m)        32 39 55.51983      0.008(m)
E LON:  242 45 25.14083      0.010(m)       242 45 25.08274      0.010(m)
W LON:  117 14 34.85917      0.010(m)       117 14 34.91726      0.010(m)
EL HGT:          -21.772(m)   0.009(m)               -22.530(m)   0.009(m)
ORTHO HGT:           13.733(m)   0.027(m) 

[NAVD88 (Computed using GEOID12B)]
The NGS Geodetic Toolkit

Horizontal Time Dependent Positioning

HTDP - Horizontal Time Dependent Positioning

Horizontal velocities across the western United States. Colors specify speed in mm/yr and arrows specify corresponding directions of motion relative to the North American Datum of 1983.

The HTDP software enables users to predict horizontal displacements and/or horizontal velocities related to crustal motion in the United States and its territories. The software also enables users to update positional coordinates and/or geodetic observations to a user-specified date. HTDP supports these activities for coordinates in the North American Datum of 1983 (NAD_83) as well as in all official realizations of the International Terrestrial Reference System (ITRS), and all official realizations of the World Geodetic System of 1984 (WGS_84). Hence this software may be used to transform geodetic coordinates between any pair of these reference frames in a manner that rigorously addresses differences among the definitions of their respective velocity fields.

More Info:
- View User's Guide [pdf format] and/or Revision Log [pdf format]
- Download a Zip'ed (md5 813d003503a5dc680c9b2483576fd2b7) archive of the HTDP Fortran-90 source code, the User's Guide, Revision Log, and some sample data files
- This archive also contains the HTDP executable code, which should work on most computers having a recent Windows operating system.
- Relevant publications
Transformations from “WGS 84” ÷ “NAD 83”
Station “POINT LOMA 5”

IGS08
epoch 2015.41

0.46 m

IGS08
epoch 2005.00

1.12 m

NAD 83 (2011)
epoch 2010.00

1.2 – 1.3 m

0.2 –

0.3 m

#1-6

#7

#8

#9

#10

#1-6
Where can you find these transformations?

www.geodesy.noaa.gov/CORS/coords.shtml

Read the bottom of the webpage!

**Transformation Parameters** are applied using the equations shown below to transform from IGS08 to the various NAD 83

**WARNING and RECOMMENDATION:**

Because the Earth's crust does not behave as a perfect rigid body, e.g., earthquakes, models for crustal deformation are needed, especially in California and Alaska. Therefore, the equations written below DO NOT account for a rigorous transformation. NGS strongly recommends that to obtain an accurate transformation between frames users use HTDP software which combines the transformation parameters and deformation models.

- \( x_{\text{NAD} \ 83}(t) = T_x(t) + [1 + s(t)] \cdot x_{\text{IGS08}}(t) + \omega_x(t) \cdot y_{\text{IGS08}}(t) - \omega_y(t) \cdot z_{\text{IGS08}}(t) \)
- \( y_{\text{NAD} \ 83}(t) = T_y(t) - \omega_x(t) \cdot y_{\text{IGS08}}(t) + [1 + s(t)] \cdot y_{\text{IGS08}}(t) + \omega_x(t) \cdot z_{\text{IGS08}}(t) \)
- \( z_{\text{NAD} \ 83}(t) = T_z(t) + \omega_x(t) \cdot y_{\text{IGS08}}(t) - \omega_y(t) \cdot z_{\text{IGS08}}(t) + [1 + s(t)] \cdot z_{\text{IGS08}}(t) \)

Where:  
- \( T_x(t), T_y(t), T_z(t) \) are the translation vectors in the NAD 83 coordinate system.
- \( s(t) \) is the scale factor.
- \( \omega_x(t), \omega_y(t), \omega_z(t) \) are the angular velocities.
- \( m_r \) is the conversion factor from milli-arcseconds (mas) to radians.

The sense of the rotations is counterclockwise (anticlockwise) positive.

Note: The equations given above serve to transform IGS08 positional coordinates \( (x_{\text{IGS08}}, y_{\text{IGS08}}, z_{\text{IGS08}}) \) whose epoch date is at time \( t \) to NAD 83 positional coordinates \( (x_{\text{NAD} \ 83}, y_{\text{NAD} \ 83}, z_{\text{NAD} \ 83}) \) for this same epoch date.

Positional coordinates for a different epoch date (and for a particular reference frame) can only be obtained by knowing the velocity of the point in this reference frame.
For example, if the IGS positional coordinates are given at a different epoch \( t' \neq t \), their positions should be updated to epoch \( t \) using the HTDP software. For more information about the implementation of these equations consult the following article Soler and Sny, 2004.
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.
Horizontal error (cm) of IGS08 to NAD 83 (2011) transformation if epoch 1997.00 used for both frames with respect to the transformation IGS08 epoch 2005.00 to NAD 83 (2011) epoch 2010.00 (per HTDP v3.2.3)
This 7-parameter transformation equivalent to following commercial vendor transformations:

- **Esri:** “WGS_1984_(ITRF08)_To_NAD_1983_2011” (WKID 108363)
  - *NOT* “WGS_1984_(ITRF00)_To_NAD_1983_2011”, or the 25 other NAD 83 → WGS 84 transformations in ArcGIS 10.x
- **Trimble:** “ITRF_to_NAD_1983 (2011)”
Horizontal error (cm) of IGS08 to NAD 83 (2011) transformation if epoch 2010.00 used for both frames with respect to the transformation IGS08 epoch 2005.00 to NAD 83 (2011) epoch 2010.00 (per HTDP v3.2.3)
Horizontal error (cm) of IGS08 to NAD 83 (2011) transformation if epoch 2005.00 used for both frames with respect to the transformation IGS08 epoch 2005.00 to NAD 83 (2011) epoch 2010.00 (per HTDP v3.2.3)
Questions to ask before performing a datum transformation

- What is the spatial accuracy?
- What is the datum (geographic coordinate system)?
  - Are you sure? How do you know?
- What datum do you want to convert to?
  - What transformation method will you use?
  - What is the accuracy of the transformation?
  - What if there are several to choose from?
- Are there temporal issues?
  - What is the date (epoch) of the input and output data?
  - How do you know the epoch?
- Are you really sure you want to do this?
Does this stuff really matter?

- Significant for accuracies better than ~2 m
  - Requires understanding of modern datums
- Be careful when using “WGS 84”
  - Which realization? At what epoch? At what accuracy?
  - Just because it comes from GPS does NOT mean it’s “WGS 84”
- Things are moving, and it can make a difference
  - e.g., San Diego moving 4.0 cm/yr NW w.r.t. Phoenix, AZ
- What if the US Supreme Court said the data was in WGS 84?
Where do we go from here?

- Modern GNSS becoming more *precise*
  - Autonomous positions soon better than 1 m
  - Many position services now at cm precision
- But *accuracy* another issue…
  - With respect to what? And at what point in time?
- Standardization is needed
  - Solutions are regional (e.g., HTDP is for US only)
  - No agreement yet on global models
Conclusions

• Be VERY careful with datum transformations
  - Know what you have first
  - Understand limitations
  - Metadata may not be correct
  - Check if at all possible
  - Avoid if you can

• Your data likely NOT “WGS 84” at cm accuracy
  - GPS source does NOT mean it’s WGS 84
  - Date of data may not equal epoch of data

• “Precision” may NOT equal “accuracy”
  - What good is cm precision if offset from other data by 2 m?
  - Transformations can degrade accuracy