Best Practices in GNSS Surveying

Todd Horton, PE, PLS
February 2017

Global Navigation Satellite Systems

GPS:  Space Segment

- 32 GPS satellites
- Each satellite continuously broadcasts data stream.
- Satellites receive broadcast data from ground control stations.

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GPS: Space Segment

6 orbital planes inclined at 55°
Average altitude 12,500 miles (medium earth orbit)
12 hour (sidereal) orbital period (11:58 solar time)

GPS Orbital Planes

- 5-6 satellites in each plane
- Near-circular orbits
- Planes do not spin with the earth.

GPS Orbital Plane

Orbital planes do not spin with the earth.
Satellite Ground Tracks

The earth spins beneath the satellites, yielding the oscillating ground tracks seen here.


Satellite Sky Plot

Lat. 44.8205°
Long. 93.1605°
Date: 5/12/2014
Starting: 6:00 AM CDT
Duration: 24 hours

The skyplot shows each satellite path in the sky during the time period.
Center represents 0° zenith.
Each ring is 30°.
Cutoff angle is 10°.
Outer ring is horizon.

http://www.trimble.com/GNSSPlanningOnline/#/Settings

GPS: Control Segment

The Control Segment tracks the GPS satellites, updates their orbiting position and synchronizes their clocks.
GPS: User Segment

- The user’s desired accuracy will determine:
  - Receiver Type
  - Cost
  - Complexity
  - Methodology
  - Limitations
  - Knowledge
  - Application
  - Users

GPS Radio Signals

- Three transmission frequencies:
  - 1575.42 MHz (L1)
  - 1227.60 MHz (L2)
  - 1176.45 MHz (L5)

- Transmission codes:
  - P (precision)
  - CA (course acquisition)

GPS Raw Data

- Satellites broadcast several pieces of information including:
  - Ephemeris - satellite orbit equations used to calculate position and velocity of the satellite
  - Timing data for clock synchronization

Recreation / Navigation
Geodetic
Mapping
GNSS Principle: Range

Range = Speed of Light × Travel Time

Positioning by Multilateration

Positioning with 1 Satellite

We are somewhere on a sphere of the radius, R1
Positioning with 2 Satellites

2 Spheres intersect as a circle

Positioning with 3 Satellites

3 Spheres intersect at 2 points

Positioning with 4 Satellites

4 Spheres intersect at a point
Range Measurement

Let’s put some numbers to it:
Altitude (of satellite) = 12,500 mi.
Speed of light = 186,000 mi/sec
12,500 mi / 186,000 mi/sec = 0.067 sec
Transmission Time = 0.067 sec

Measurement Error

What is the effect of a timing error?
0.0000001 sec error * 186,000 mi/sec = 0.0186 mi error
0.0186 mi error = 98 foot error

GNSS Errors: Clock Sync

Satellite and receiver clocks are not synchronized.
Receiver clocks are not as accurate as satellite clocks.
Atomic Clocks

- 1 second = 9,192,631,770 cycles of the standard Cs-133 transition

GNSS Clock Synchronization

PRN Code SV27 broadcast

Out of sync

PRN Code SV27 in memory

Receiver requires 4 satellites to fully synchronize with atomic clocks.
Positioning & Navigating

Each satellite is an orbiting radio station.

\[ P(\phi, \lambda, h) \]
\[ P(X, Y, Z) \]

International GNSS Service (IGS) Tracking Network

igscb.jpl.nasa.gov/

GNSS Errors: Orbital Accuracy

- Broadcast ephemeris (almanac file from satellite)
  - 100 cm GPS orbit accuracy PREDICTED

- Ultra-rapid ephemeris (6-hour latency from IGS)
  - 5 cm GPS orbit accuracy

- Rapid ephemeris (13-hour latency from IGS)
  - 2.5 cm GPS orbit accuracy

- Final ephemeris (12 to 14 day latency from IGS)
  - 2.5 cm GPS orbit accuracy
  - 5 cm GLONASS orbit accuracy
Surveying during periods of high DOP generally yields less accurate positions than during periods of low DOP.

**DOP Flavors**

- **GDOP** (Geometric: N, E, H, t)
- **PDOP** (Positional: N, E, H)
- **HDOP** (Horizontal: N, E)
- **VDOP** (Vertical: H)
- **TDOP** (Time: t)

**Good PDOP**

Volume of enclosed figure is high.
DOP is always changing

PDOP < 3 gives best results

www.trimble.com/GNSSPlanningOnline/#/Settings
GNSS Errors: Ionospheric Delay

• Slows GNSS signal.
• Has weather
  – Variable over time
  – Variable over distance
• Errors are modeled, not measured.

Elevation Mask

Data received below the mask angle contains too much signal noise to be reliable.

Set rover elevation mask between 10° and 15°.
GNSS Error: Multipath

Reflected signals yield poor accuracy.

GNSS Errors Summary

• Orbital error
  – Predicted versus as-flown trajectories
  – Dilution of precision
• Ionospheric error
• Clock synchronization error
• Multipath error

Largest Error Source

Real Time Kinematic Methods
**Autonomous Positioning**

**Differential Positioning**

Concept: Detect and cancel identical errors with simultaneous observation.

\[ F + \varepsilon = G + \varepsilon \]

**Static & RTK Computations**

- Static survey: post process data in office
- RTK survey: process data immediately at rover

Key Element = Simultaneous Observation
**Ionospheric Effects**

Ionospheric effects cancel when receivers are within 10 km (6.1 mi).

Conditions vary with time and distance.

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**Real-Time Kinematic Positioning**

- **Base** receives and rebroadcasts GPS data as RTK message.
- **Rover** receives GPS data and RTK message to compute vector.

---

**Single Base RTK Corrections**

Known Position

Corrected Position

Sensed Position

Sensed Position

---
Single Base RTK Corrections

Single base unit broadcasts uniform RTK corrections in all directions.

RTK Positional Error

RTK positional error increases with distance from the base.

Trimble R8 Accuracy Specs

<table>
<thead>
<tr>
<th></th>
<th>Code differential GNSS positioning¹</th>
<th>Static and FastStatic GNSS surveying¹</th>
<th>Kinematic surveying¹</th>
<th>Initialization reliability¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>0.2 mm + 0.1 ppm RMS</td>
<td>0.3 mm + 0.4 ppm RMS</td>
<td>10 mm + 1 ppm RMS</td>
<td>typically &gt;99.9%</td>
</tr>
<tr>
<td>Vertical</td>
<td></td>
<td></td>
<td>20 mm + 1 ppm RMS</td>
<td></td>
</tr>
</tbody>
</table>


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RTK Vector Errors

- Vector is the line from base to rover.
  - 10 mm + 1 ppm horizontal error for RTK vectors is typical.
  - 10 mm = 0.033 ft = constant error
  - 1 ppm = scalar error (distance dependent)
    - 1 part error to 1,000,000 parts measurement
    - 1 mm error / 1 km RTK vector
    - 0.005 ft error / 1 mile RTK vector

- This error approximates the misfit between a uniform RTK correction and reality.
  - RTN eliminates most of this.

Differential Position Errors

<table>
<thead>
<tr>
<th>RTK vector (miles)</th>
<th>E_{const} (feet)</th>
<th>E_{scalar} (feet)</th>
<th>E_{dist} (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.033</td>
<td>0.005</td>
<td>0.033</td>
</tr>
<tr>
<td>2</td>
<td>0.033</td>
<td>0.011</td>
<td>0.034</td>
</tr>
<tr>
<td>4</td>
<td>0.033</td>
<td>0.021</td>
<td>0.039</td>
</tr>
<tr>
<td>8</td>
<td>0.033</td>
<td>0.042</td>
<td>0.053</td>
</tr>
<tr>
<td>16</td>
<td>0.033</td>
<td>0.084</td>
<td>0.091</td>
</tr>
<tr>
<td>32</td>
<td>0.033</td>
<td>0.169</td>
<td>0.172</td>
</tr>
</tbody>
</table>

\[ E_{dist} = \sqrt{E_{const}^2 + E_{scalar}^2} \]
RTK relative accuracy

Base can occupy a known point or an unknown (assumed) point.

Absolute & relative accuracy

- **Absolute accuracy**
  - Accuracy relative to map surface
- **Relative accuracy**
  - Accuracy relative to adjacent positions
- Position = coordinate

Absolute & relative accuracy

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Absolute Accuracy</th>
<th>Relative Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: known</td>
<td>±5'</td>
<td>±0.05'</td>
</tr>
<tr>
<td>B: unknown</td>
<td>±15'</td>
<td>±0.05'</td>
</tr>
</tbody>
</table>

- Poor absolute accuracy
- Good relative accuracy

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Absolute Accuracy</th>
<th>Relative Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: known</td>
<td>±0.05'</td>
<td>±0.05'</td>
</tr>
<tr>
<td>B: unknown</td>
<td>±0.07'</td>
<td>±0.05'</td>
</tr>
</tbody>
</table>

- Good absolute accuracy
- Good relative accuracy
Continuously Operating Reference Stations

- CORS is a permanently mounted survey-grade GPS receiver which broadcasts RTK corrections.
- Each CORS collects GPS data 24 hours per day, 7 days per week, 365 days per year.
- Stored data from each CORS is available for download to enable survey post-processing.

- The CORS network is the anchor of our National Spatial Reference System.
  - Much higher accuracy than first order monuments.
  - Actively monitored.
  - Tracks crustal motion.
  - Data is used for research.
This is a GPS Continuously Operating Reference Station.

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AJ5565 CORS

AJ5565 DESIGNATION - KALAMAZOO CORS ARP
AJ5565 CORS_ID = KALM
AJ5565 PID = AJ5565
AJ5565 STATE/COUNTY - MI/KALAMAZOO
AJ5565 UNGS QUAD - PORTAGE (1978)
AJ5565 *CURRENT SURVEY CONTROL

AJ5565 NAD 83(2011) POSITION
AJ5565 [42 13 33.09000(N) 085 32 00.82005(W) ADJUSTED]
AJ5565 NAD 83(2011) ELLIP HT - 232.548 (meters) 871.53 (feet) ADJUSTED
AJ5565 NAD 83(2011) EPOCH - 2010.00
AJ5565 NAVD 88 ORTHO HEIGHT - 265.642 (meters) 871.53 (feet) ADJUSTED

AJ5565 GEOID HEIGHT - GEOID12B - 33.081 (meters)
AJ5565 NAD 83(2011) X - 368,376.475 (meters) COMP
AJ5565 NAD 83(2011) Y - 4,715,982.275 (meters) COMP
AJ5565 NAD 83(2011) Z - 4,264,370.500 (meters) COMP
AJ5565 VERT ORDER - FIRST CLASS II

Network accuracy estimates per FGDC Geospatial Positioning Accuracy Standards:

<table>
<thead>
<tr>
<th>NETWORK</th>
<th>SD_N</th>
<th>SD_E</th>
<th>SD_h</th>
<th>CorrNE</th>
</tr>
</thead>
<tbody>
<tr>
<td>NETWORK</td>
<td>0.65</td>
<td>2.03</td>
<td>0.29</td>
<td>0.23</td>
</tr>
</tbody>
</table>

The coordinates were established by GPS observations and adjusted by the National Geodetic Survey in August 2011.

NAD 83(2011) refers to NAD 83 coordinates where the reference frame has been affixed to the stable North American Tectonic Plate.

The coordinates are valid at the epoch date displayed above which is a decimal equivalence of Year/Month/Day.

The orthometric height was determined by differential leveling and adjusted by the NATIONAL GEODETIC SURVEY in October 2009.

No vertical observational check was made to the station.

The XYZ, and position/ellipsoidal ht. are equivalent.

The following values were computed from the NAD 83(2011) position.

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Station velocities

How to read datasheets?

www.ngs.noaa.gov/cgi-bin/ds_lookup.pl?item=DSDATA.TXT
Single Base RTK Solutions

- Uniform RTK correction within each zone
- Potential for mismatched corrections

Network RTK (RTN) Solutions

- Interpolated RTK correction within polygon
Network RTK (RTN) Solutions

- Reference Station 1
- Reference Station 2
- Reference Station 3

RTK Correction interpolated for rover location

RTN Flavors

- All RTN solutions provide a single vector solution from a physical reference station.
- Common RTN solution methods:
  - Non-physical Reference Station (VRS)
  - Master Auxiliary Corrections (MAC)

RTN Solution

1. Data from the reference stations streams to the processing and control center.
2. The RTK rover sends its approximate position.
3. The processing center selects reference stations forming a polygon around the rover.
4. The processing center transmits correction data to the rover.
**Master Auxiliary Corrections (MAC)**

- **Rover** computes vector from nearest reference station.
- Streaming GPS data

**MAC & VRS**

- MAC networks make the rover compute RTN corrections.
- VRS networks compute RTN corrections at the control center.

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What is a VRS?

- A virtual reference station is the center of an area for which an RTN correction applies.
  - First VRS is your first initialization point.
  - Control center creates new VRS points as you move.

Virtual Reference Station (VRS)

[Diagram showing the setup of a virtual reference station and how the rover computes the position using the VRS correction.]
RTN Positional Error

- RTK constant error still applies.
- PPM error (distance dependent) significantly reduced.

Trust but Verify

Truth versus Address

- Physical monument
  - Truth
  - Relatively stable (in most of CONUS)

- Point coordinate
  - Merely an address
  - Contains error
  - Subject to change
New Accuracy Standards for NGS Datasheets

(http://fgdc.er.usgs.gov/standards/status/swgstat.html)

- Local Accuracy: adjacent points
- Network Accuracy: relative to CORS
- Numeric quantities, units in cm (or mm)
- Both are relative accuracy measures
- Will not use distance dependent expression
- Order/Class codes will no longer be used

OLD: Order & Class Codes

NEW: Relative Accuracy
Observed positions and errors

Positions lose their credibility without error estimates.

<table>
<thead>
<tr>
<th>Point</th>
<th>Distance (feet)</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>2000.00</td>
<td>2000.00</td>
<td>±0.10 feet</td>
</tr>
<tr>
<td>100</td>
<td>2000.00</td>
<td>2000.00</td>
<td>±0.04 feet</td>
</tr>
</tbody>
</table>

- 100 distance measurements
- Mean = 2000.00 feet
- Standard deviation = ±0.10 feet

- 100 distance measurements
- Mean = 2000.00 feet
- Standard deviation = ±0.04 feet
Distance Root Mean Square

\[ DRMS = \sqrt{E_1^2 + E_2^2} \]

- 65% confidence
- 39% confidence

Observed Position (address)

Commonly Known As

- HRMS
  - Trimble
  - Topcon
- 2DCQ
  - Leica

Positional Errors

- HRMS = 0.03 ft

1000.00 ft calculated

999.94 ft

1000.06 ft
Effects of Positional Errors

HRMS = 0.03 ft
1000.00 ft calculated

Any of these lines are possible.

Weakness of GNSS

HRMS = 0.03 ft
100.00 ft calculated
99.94 ft
100.06 ft

Match the tool to the task

80.00 ft

• Can you stake this straight boundary line accurately with GNSS?
Match the tool to the task

- GPS methods give greater accuracy over long distances.
- Total station methods give greater accuracy over shorter distances.

Confidence Levels

- 65% confidence = 65% probability that the TRUTH falls within 1 HRMS of the ADDRESS (mean).
- 95% confidence = 95% probability that the TRUTH falls within 2 HRMS of the ADDRESS (mean).

Reported Precision

- 65% displayed at data collector
- 95% specified in contracts, reported in NGS datasheets, and OPUS solutions
### Comparing Results

<table>
<thead>
<tr>
<th></th>
<th>Previous Coordinate</th>
<th>Today’s Coordinate</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northing</td>
<td>1255110.131</td>
<td>1255110.182</td>
<td>+0.051 ft</td>
</tr>
<tr>
<td>Easting</td>
<td>1028009.036</td>
<td>1028008.987</td>
<td>-0.049 ft</td>
</tr>
<tr>
<td>HRMS</td>
<td>0.037 ft</td>
<td>0.040 ft</td>
<td></td>
</tr>
</tbody>
</table>

#### 65% confidence overlap

Radius = 1 X HRMS

#### 95% confidence overlap

Radius = 2 X HRMS
Applying Datum Transformations

Datum Elements

- Coordinate System
  - Map surface

- Location & Orientation Parameters
  - Origin
  - Basis of direction

Geocentric & Geodetic Systems

Ellipsoidal height ≠ elevation

P (X,Y,Z) = P (ϕ,λ,h)

Geodetic Reference System of 1980 (GRS-80)
Principal Geodetic Datums

- **International Terrestrial Reference Frame (ITRF)**
  - Global datum used by international partners
  - Uses the GRS-80 ellipsoid (the standard)

- **World Geodetic System of 1984 (WGS 84)**
  - Global datum
  - Uses essentially the same GRS-80 ellipsoid
  - Geocenter is offset about 10 centimeters from ITRF00 geocenter

- **North American Datum of 1983 (NAD 83)**
  - Replaced the North American Datum of 1927 (NAD27)
  - Regional datum
  - Uses the GRS-80 ellipsoid
  - Geocenter is offset about 2.2 meters from WGS84 geocenter

NAD 83 Adjustment Summary

- **1986 original release**
  - Based on terrestrial data only

- **1997 adjustment**
  - Based on terrestrial and GPS data combined

- **2007 adjustment**
  - Based on GPS positions only
  - Fixed to CORS network

- **2011 adjustment**
  - Based on updated CORS network

Effect of NAD83 Adjustments

- Reobservation reduces positional error.
- Datum definitions are stable.
- Point coordinates change relative to datum.
Case Study
KB0684

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Michigan Society of Professional Surveyors

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## Positional Changes: KB0684

<table>
<thead>
<tr>
<th>DATUM</th>
<th>TIME SPAN</th>
<th>POSITION Lat/Lon/Ell Ht</th>
<th>POSITION SHIFT (from previous)</th>
</tr>
</thead>
<tbody>
<tr>
<td>USS/NAD</td>
<td>1901 – 1927</td>
<td>39-31-12.70400 89-02-56.00560</td>
<td></td>
</tr>
<tr>
<td>ITRF 2023 (Predicted – HTDP)</td>
<td>2023</td>
<td>39-31-12.75439 89-02-56.51332</td>
<td>164.103</td>
</tr>
</tbody>
</table>

## State Plane Coordinate Systems (SPCS)

Two types:
- Lambert Conformal Conic Projection
- Transverse Mercator Projection

## Equatorial Mercator Projection

(not used for SPCS)
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Michigan State Plane Coordinate System

Lambert Conformal Conic Projection

Michigan SPCS South Zone (2113)

2012 Michigan Compiled Laws
Chapter 54 — SURVEYORS
Act 9 of 1964 — MICHIGAN COORDINATE SYSTEMS

- 54.235a Michigan coordinate system of 1983; definition; determination of position. Sec. 5a.
- (1) For purposes of more precisely defining the Michigan coordinate system of 1983, the following definition by the NOAA/NGS is adopted:
- (c) The Michigan coordinate system of 1983, south zone, is a Lambert conformal projection of the North American datum of 1983, having standard parallels at north latitude 42 degrees 6 minutes and 43 degrees 40 minutes, along which parallels the scale shall be exact. The origin of coordinates is at the intersection of the meridian 84 degrees 22 minutes west of Greenwich and the parallel 41 degrees 30 minutes north latitude. This origin is given the coordinates: x = 4,000,000 meters and y = 0 meters.
Lambert Conformal Conic Projection

Scale factor changing

Scale Factor Example 1

\[ E1 = 10,000.00 \text{ ft on ellipsoid} \]
\[ \text{Scale} = 0.99998237 \text{ (average of scale at line endpoints)} \]
\[ 10,000.00 \text{ ft} \times 0.99998237 = 9999.82 \text{ ft} \]
Length of line G1 on grid

Scale Factor Example 2

\[ E2 = 20,000.00 \text{ ft on ellipsoid} \]
\[ \text{Scale} = 1.00004234 \text{ (average of scale at line endpoints)} \]
\[ 20,000.00 \text{ ft} \times 1.00004234 = 20,000.85 \text{ ft} \]
Length of line G2 on grid
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Michigan SPCS Central Zone
(2112)

Michigan SPCS North Zone
(2111)

The following values were computed from the NAD 83(2011) position.

<table>
<thead>
<tr>
<th></th>
<th>North</th>
<th>East</th>
<th>Units</th>
<th>Scale Factor</th>
<th>Convergence</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPC MI C</td>
<td>53,358.457</td>
<td>5,473,587.913</td>
<td>M</td>
<td>1.00011559</td>
<td>1.00009072</td>
</tr>
<tr>
<td>SPC MI S</td>
<td>255,644.660</td>
<td>3,835,480.807</td>
<td>M</td>
<td>1.00002997</td>
<td>1.00000510</td>
</tr>
</tbody>
</table>

- Elev Factor x Scale Factor = Combined Factor
- Elev Factor = 0.9997514 x 1.00011559 = 1.00009072
- Elev Factor = 0.9997514 x 1.00002997 = 1.00000510
54.233 Use of coordinates, Sec. 3.

- The coordinates for a point on or near the earth’s surface that are used to express the geographic position of that point in the appropriate zone of this system shall consist of 2 distances.

- Each distance shall be expressed in United States survey feet (1 foot = 12/39.37 meters) and decimals of a survey foot if using the Michigan coordinate system of 1927,

- or shall be expressed in meters and decimals of a meter or in international feet (1 foot = 0.3048 meter) and decimals of an international foot if using the Michigan coordinate system of 1983.

Scale Factor is directional

Convert ground to grid

Ground distance × combined factor = Grid distance
Finding the Elevation Factor

\[ F_{\text{elevation}} = \frac{D_{\text{ellipsoid}}}{D_{\text{surface}}} = \frac{R}{h + R} \]

Elevation Factor Rule of Thumb

- For each 1000 foot change in ellipsoidal height, a 1.0 mile distance will change by 0.25 feet.

Elevation Factor Impacts

- 0.1-0.3 ft
- 0.5-0.7 ft
- 0.3-0.5 ft
- 0.1-0.3 ft
- 0.5-0.7 ft
Finding the Combined Factor

<table>
<thead>
<tr>
<th>North</th>
<th>East</th>
<th>Units</th>
<th>Scale Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPC IL E</td>
<td>380,997.666</td>
<td>MT</td>
<td>0.99997614</td>
</tr>
<tr>
<td>SPC IL E</td>
<td>1,249,989.84</td>
<td>sFT</td>
<td>0.99997614</td>
</tr>
</tbody>
</table>

Elev Factor x Scale Factor = Combined Factor

Combined factor possibilities

- EF < 1
- SF > 1

Ellipsoid below ground

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Combined factor possibilities

Coordinate Transformation

- Coordinate transformations give formulas for the coordinates of one system in terms of the coordinates in another system.
Transformation Terminology

Trimble

Site Calibration

Leica Geosystems

Determine Coordinate System

TOPCON

Localization

Transformations using GPS

GPS transformation defined

- Observed GPS positions (stored in WGS84) are translated, rotated and scaled to best fit the given control positions.

- The best fit process is an unweighted least squares adjustment of the observed GPS positions to the given control positions.
Transformation 1:
Adopt existing datum.

- Accept coordinates provided by others
  - Local surface datum
  - Previous adjustment of NAD83

Transformation Steps

1. Observe control positions with GPS using given control point numbers.
2. Enter the given control positions into data collector or computer.
3. Allow software to compute transformation parameters.
4. Evaluate residuals and accept/reject results.
1. Observe control positions with GPS.

2. Enter the given control positions.

<table>
<thead>
<tr>
<th>OBSERVED</th>
<th>GIVEN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point</td>
<td>WGS84 Latitude</td>
</tr>
<tr>
<td></td>
<td>N 40° 13' 16.60900&quot;</td>
</tr>
<tr>
<td>LC0480</td>
<td>LC1913</td>
</tr>
<tr>
<td></td>
<td>N 40° 10' 52.30172&quot;</td>
</tr>
<tr>
<td></td>
<td>LC1632</td>
</tr>
<tr>
<td></td>
<td>N 40° 15' 53.33127&quot;</td>
</tr>
<tr>
<td></td>
<td>LC1051</td>
</tr>
<tr>
<td></td>
<td>N 40° 18' 33.47591&quot;</td>
</tr>
<tr>
<td></td>
<td>LC1036</td>
</tr>
<tr>
<td></td>
<td>N 40° 20' 09.40967&quot;</td>
</tr>
<tr>
<td></td>
<td>DF4293</td>
</tr>
<tr>
<td></td>
<td>N 40° 21' 48.53561&quot;</td>
</tr>
<tr>
<td></td>
<td>LC0470</td>
</tr>
<tr>
<td></td>
<td>N 40° 18' 50.75440&quot;</td>
</tr>
</tbody>
</table>

3. Compute transformation parameters.

- $\Delta_x$, $\Delta_y$, $\Delta_z$: Translation
- $R_x$, $R_y$, $R_z$: Rotation
- $S$: Scale
3D Translation

ΔZ

ΔX

ΔY

Scaling with Z translation

Rotating about Z axis

Vertical translation

SPCS surface

Ground

Ellipsoid
4. Evaluate residuals.

Least squares adjustment exposes misfit between observed and given positions.
4. Accept and/or reject results.

Transformations Quality

- Ideal results show small equal residuals.
- Review rotations and scale factor.
  - Projection surface slope should be minimal. (< 30 seconds)
  - Scale factor should be very close to 1.

Transformation rules of thumb

- Build your transformation upon trusted points outside the project footprint.
  - Use minimum of 4 accepted points for horizontal transformations.
  - Use minimum of 5 accepted points for vertical transformations.
- Record your calibration results in the project record.
No redundancy

Plane can tilt and rotate in all directions.

Monument fixes plane vertically at one point.

No redundancy

Plane can rotate about line.

Monuments fix plane vertically at two points.

No redundancy

Plane is fixed in space.

Monuments fix plane vertically at three points.
Horizontal positions checked by diagonals.

4 monuments inadequate for vertical stability.

Redundant in H
Not Redundant in V

Horizontal positions checked by diagonals.

5 monuments needed for vertical stability.

Redundant in H
Redundant in V

Transformation 2: Adopt existing datum.

- Match existing geometry (boundary directions and distances).
  - Adopt the basis of bearing on a plat.
  - Use GPS to recover corners.
Transformation Steps

1. Compute surface coordinates of plat positions.
2. Collect GPS positions of computed points.
3. Allow software to compute transformation parameters.
4. Navigate to remaining points using local grid.
5. Evaluate residuals and accept/reject results.

1. Compute surface coordinates

Assumed
N 5000.00
E 5000.00

2. Collect GPS positions.

Lot 12
6.67 acres

FOUND

NOT FOUND

Lot 12
6.67 acres

FOUND

Not Found

FOUND
3. Compute transformation.

<table>
<thead>
<tr>
<th>Observed WGS84 positions</th>
<th>Local Grid positions</th>
<th>Nothing</th>
<th>Easting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>Longitude</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 40 8 12.733892 N</td>
<td>88 17 12 209471 W</td>
<td>15 4006.53</td>
<td>6595.14</td>
</tr>
<tr>
<td>16 40 8 17.754982 N</td>
<td>88 17 18 270518 W</td>
<td>16 5417.41</td>
<td>5420.13</td>
</tr>
<tr>
<td>17 5000.00</td>
<td>5000.00</td>
<td>17 5000.00</td>
<td>5000.00</td>
</tr>
<tr>
<td>18 5310.00</td>
<td>4736.20</td>
<td>18 5310.00</td>
<td>4736.20</td>
</tr>
<tr>
<td>19 3113.44</td>
<td>3707.20</td>
<td>19 3113.44</td>
<td>3707.20</td>
</tr>
<tr>
<td>20 4736.20</td>
<td>3707.20</td>
<td>20 4736.20</td>
<td>3707.20</td>
</tr>
<tr>
<td>21 5310.00</td>
<td>4736.20</td>
<td>21 5310.00</td>
<td>4736.20</td>
</tr>
</tbody>
</table>

Line 15-16: S42°50'37"E


5. Evaluate and revise.

- Computed position
- Found position
- Recompute using trusted monuments.
- Apparent rotation
- ?
Transformation 3: Create new datum.

- Create a surface datum related to SPCS.
  - Commonly known as Modified SPCS.

Transformation Steps

1. Collect SPCS positions on control monuments.
2. Compute project scale and elevation factors.
3. Apply project combined factor to GPS positions.
4. Translate positions to distinguish from SPCS.
5. Perform transformation to new ground datum.
2. Compute Project Scale Factor.

- Project Scale Factor SF 0.99997586
- Project Scale Factor SF 0.99997627
- Project Scale Factor SF 0.99997674
- Project Scale Factor SF 0.99997745

2. Compute Project Elevation Factor.

- Build elevation factor using ellipsoidal height that represents overall site.

2. Compute project elevation factor.

- Project Elevation Factor SF 0.99997031

3. Apply Project Combined Factor.

- Project Scale Factor × Project Elevation Factor = Project Combined Factor (PCF)

- Grid distance + PCF = Modified distance
3. Apply Project Combined Factor.

GRID DISTANCE ÷ PCF = MODIFIED DISTANCE

**Modified Grid Surfaces**

- Central Meridian (Common to all three grid systems)
- Modified Grid System (Scale increased)
- Original Grid System
- Modified Grid System (Scale decreased)


**3. Apply Project Combined Factor.**

- Modified distance
- SPCS grid distance
- Grid distance × PCF = Modified distance
3. Apply Project Combined Factor.

<table>
<thead>
<tr>
<th>Original SPCS</th>
<th>Modified SPCS</th>
<th>Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northing</td>
<td>Northing</td>
<td>ΔN</td>
</tr>
<tr>
<td>Easting</td>
<td>Easting</td>
<td>ΔE</td>
</tr>
<tr>
<td>1288808.30</td>
<td>1288876.75</td>
<td>68.45</td>
</tr>
<tr>
<td>945222.74</td>
<td>945272.94</td>
<td>50.20</td>
</tr>
<tr>
<td>1295617.92</td>
<td>1295686.73</td>
<td>68.81</td>
</tr>
<tr>
<td>937955.33</td>
<td>938005.15</td>
<td>49.82</td>
</tr>
<tr>
<td>1293343.62</td>
<td>1293412.31</td>
<td>68.60</td>
</tr>
<tr>
<td>95094.08</td>
<td>950993.59</td>
<td>50.51</td>
</tr>
<tr>
<td>1289405.41</td>
<td>1289473.80</td>
<td>68.48</td>
</tr>
<tr>
<td>943704.92</td>
<td>943755.04</td>
<td>50.12</td>
</tr>
</tbody>
</table>

Project Combined Factor (PCF) = 0.99994689

Original N ÷ PCF = Modified N
Original E ÷ PCF = Modified E

4. Translate positions.

<table>
<thead>
<tr>
<th>Modified SPCS</th>
<th>Ground Coordinates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northing</td>
<td>Northing</td>
</tr>
<tr>
<td>Easting</td>
<td>Easting</td>
</tr>
<tr>
<td>1288876.75</td>
<td>88876.75</td>
</tr>
<tr>
<td>945222.74</td>
<td>45272.94</td>
</tr>
<tr>
<td>1295686.73</td>
<td>95686.73</td>
</tr>
<tr>
<td>937955.33</td>
<td>38005.15</td>
</tr>
<tr>
<td>1293412.31</td>
<td>93412.31</td>
</tr>
<tr>
<td>95094.08</td>
<td>50993.59</td>
</tr>
<tr>
<td>1289473.89</td>
<td>89473.89</td>
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<td>943704.92</td>
<td>43755.04</td>
</tr>
<tr>
<td>1291912.57</td>
<td>91912.57</td>
</tr>
<tr>
<td>956892.28</td>
<td>56892.28</td>
</tr>
</tbody>
</table>

New positions don’t resemble SPCS.
5. Transform to new ground datum.

Principal Vertical Datums

- National Geodetic Vertical Datum of 1929 (NGVD 29)
  - Superseded by NAVD 88
  - Normal Orthometric Heights

- North American Vertical Datum of 1988 (NAVD 88)
  - Principal vertical datum for CONUS/Alaska
  - Helmert Orthometric Heights
Ellipsoidal Height ≠ Elevation

- Ellipsoidal Height is the vertical distance from a geometric surface.
- Elevation is the vertical distance from a gravitational surface.
- Geometry ≠ Gravity

What is the geoid?

- The zero elevation gravity surface.
- The equipotential surface of the Earth's gravity field which best fits, in the least squares sense, (global) mean sea level. (Geodetic Glossary, September 1986)
- Geoid is mathematically related to and modeled from gravity data.
- A geoid height (N) is the ellipsoidal height from an ellipsoidal datum to a geoid.

http://www.csr.utexas.edu/grace/gravity/
Geoid is a DTM of gravity

Geoid – Ellipsoid – Ground

\[ H = h - N \]

H = Orthometric Height (NAVD 88)
\( h \) = Ellipsoidal Height (NAD 83)
N = Geoid Height (GEOIDXX)

Topographic surface

GeoidXX (NAVD88) Geoid Height (GEOIDXX) Ellipsoid (NAD83)

N is negative throughout CONUS.

-45m
-10m
-34m

Michigan Society of Professional Surveyors
The GEOID12B Model

- GEOID12B is a hybrid geoid model. The gravimetric model was modified to fit GPS ellipsoid heights on leveled bench marks.
- The GEOID12B model is anchored to the NAD83 datum.
- It allows direct conversion between NAD83 ellipsoidal heights and NAVD88.

Gravimetric vs Hybrid Geoid

- Earth surface
- NAVD 88 elevation
- hybrid geoid
- Gravimetric geoid
- 50 cm average difference
- 100 cm tilt across CONUS
- 1-2 meters average in Alaska

NAVD88 vs GPS Derived Height

<table>
<thead>
<tr>
<th>Year</th>
<th>Ellipsoidal Height (h)</th>
<th>Geoid Height (N)</th>
<th>Hrh-N</th>
<th>NAVD88 elevation</th>
<th>Δ=NAVD88 - H</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>69.76m NAD83(92)</td>
<td>-32.64m Geoid96</td>
<td>102.46m</td>
<td>102.431m</td>
<td>0.029m</td>
</tr>
<tr>
<td>2000</td>
<td>69.79m NAD83(92)</td>
<td>-32.543m Geoid99</td>
<td>102.32m</td>
<td>102.431m</td>
<td>0.11m</td>
</tr>
<tr>
<td>2004</td>
<td>69.77m NAD83(92)</td>
<td>-32.601m Geoid03</td>
<td>102.38m</td>
<td>102.431m</td>
<td>0.05m</td>
</tr>
<tr>
<td>2010</td>
<td>69.764m NAD83(07)</td>
<td>-32.650m Geoid09</td>
<td>102.414m</td>
<td>102.431m</td>
<td>0.017m</td>
</tr>
<tr>
<td>2012</td>
<td>69.768m NAD83(11)</td>
<td>-32.641m Geoid09</td>
<td>102.409m</td>
<td>102.431m</td>
<td>0.022m</td>
</tr>
</tbody>
</table>
Strengthening Field Practices

DOP is always changing

PDOP < 3 gives best results

www.trimble.com/GNSSPlanningOnline

Satellite geometry changes.

9:00 AM

11:00 AM
Adding Redundancy

- Repeat the observation with different satellite geometry.
  - Re-measure control points before, during, and after survey session.

### Importance of Redundancy

<table>
<thead>
<tr>
<th>MOLA to RV22</th>
<th>10.8 Km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 264</td>
<td>dh (m)</td>
</tr>
<tr>
<td>14:00-14:30</td>
<td>-10.274</td>
</tr>
<tr>
<td>15:00-15:30</td>
<td>-10.277</td>
</tr>
<tr>
<td>16:00-16:30</td>
<td>-10.278</td>
</tr>
<tr>
<td>17:00-17:30</td>
<td>-10.279</td>
</tr>
<tr>
<td>18:00-18:30</td>
<td>-10.270</td>
</tr>
<tr>
<td>19:00-19:30</td>
<td>-10.271</td>
</tr>
<tr>
<td>20:00-20:30</td>
<td>-10.272</td>
</tr>
<tr>
<td>21:00-21:30</td>
<td>-10.273</td>
</tr>
</tbody>
</table>

**Two Days / Same Time**
-10.254 > -10.253
Spread = 0.003 m
Mean = -10.256

**Two Days / Different Times**
-10.254 > -10.275
Spread = 0.021 m
Mean = -10.265

Mean dh (m) = -10.275

**Difference = 0.023 m**

**Difference = 0.001 m**

Spread = 0.044 m
Mean = -10.276

Two Days / Same Time

Two Days / Different Times

Mean dh (m) = -10.276

**Spread = 0.044 m**

**Mean = -10.276**
Repeat with a new base location

Measuring points in the network that have already been located creates redundancy.

Avoiding Multi-Path Error

- Set the base at a wide open site.
- Expect multi-path near buildings.
- Chain link fences reflect GPS signals.
  - Mesh openings are too small to allow signals to pass.
  - Set offset points with GPS from which to measure by other means.
  - Raise antenna.
Using Online Positioning User Service (OPUS)

- OPUS provides simplified access to high-accuracy National Spatial Reference System (NSRS) coordinates.
- Upload a GPS data file collected with a survey-grade receiver and obtain an NSRS position via email.

www.ngs.noaa.gov/OPUS/about.jsp

- OPUS requires minimal user input.
- It uses software which computes coordinates for the CORS network.
- The resulting positions are accurate and consistent with other National Spatial Reference System users.

www.ngs.noaa.gov/OPUS/about.jsp
CORS sites collect simultaneous data.

OPUS Concept

Your receiver

CORS
CORS baseline 1
Baseline 2
CORS
Baseline 3
CORS

OPUS workflow

Data Upload
Data Preparation
OPUS Processing
Data Download
Field Observation
Data Delivery

OPUS: Online Positioning User Service

Enter your email address.

Browse to and select your data file.

Enter the antenna height.

Identify your antenna.
OPUS Processing Options

- **Static**
  - For data over 2 hours in duration.
  - Coordinates are averaged from three independent, single-baseline solutions.

- **Rapid-static**
  - For data from 15 to 120 minutes in duration.
  - Uses more aggressive algorithms but has stricter data continuity and geometry requirements.
  - There are some remote areas of the country in which it will not work.

This is a Rapid Static solution.
(less than 2 hours data)
Rapid Static baselines

My nearest CORS weren't used. Why not?

- OPUS tries to use the nearest CORS, but tests the integrity of each dataset, and will expand the search area until it finds enough quality data.
- Some CORS data are not available until the next day.

FILE: 5326078C.160 OP1456665900027
NGS OPUS SOLUTION REPORT

All computed coordinate accuracies are listed as peak-to-peak values.
For additional information: http://www.ngs.noaa.gov/OPUS/about/accuracy

USER: thorton@parkland.edu
DATE: March 22, 2016
TIME: 16:59:30 UTC

SOFTWARE: pegasus 129,24 master122.pl 023914
EPMERIES: gsp18855.spk [rapid]
NAV FILE: bmd0790.16n
ANT NAME: T36864 None
ARP HEIGHT: 2.000

REF FRAME: NAD_83(2011) (EPH 2010.0000)

X: 145634.808(m) 0.004(m)
Y: -4881013.433(m) 0.004(m)
Z: 4098624.237(m) 0.002(m)

LAT: 40 8 7.49257 0.003(m)
E LON: 271.42 32.49814 0.004(m)
W LON: 68 17 27.50186 0.004(m)
EL HDG: 204.685(m) 0.003(m)
ORTH HDG: 226.785(m) 0.012(m)

This is a Static solution, (more than 2 hours data)

Peak-to-Peak Errors

Peak to Peak:
- X: ±0.003
- Y: ±0.004
- Z: ±0.002
- LAT: ±0.003
- LON: ±0.004
- EL: ±0.003
- HDG: ±0.012
Peak-to-Peak Error

Position: Averaged from 3 best solutions.

Peak-to-Peak Errors: Dimensions of a bounding box enclosing 3 best solutions.

<table>
<thead>
<tr>
<th>UTM COORDINATES</th>
<th>STATE PLANE COORDINATES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northing (Y) [meters]</td>
<td>UTM (Zone 16)</td>
</tr>
<tr>
<td>4443565.837</td>
<td>365096.684</td>
</tr>
<tr>
<td>Easting (X) [meters]</td>
<td>SPC (1201) IL E</td>
</tr>
<tr>
<td>300019.347</td>
<td>303610.069</td>
</tr>
<tr>
<td>Convergence [degrees]</td>
<td>-0.03232555</td>
</tr>
<tr>
<td>0.02730549</td>
<td></td>
</tr>
<tr>
<td>Point Scale</td>
<td>0.99974860</td>
</tr>
<tr>
<td>Combined Factor</td>
<td>0.99991680</td>
</tr>
<tr>
<td>0.99994305</td>
<td></td>
</tr>
</tbody>
</table>

US NATIONAL GRID DESIGNATOR: 16700001943580(NAD 83)

BASE STATIONS USED:

<table>
<thead>
<tr>
<th>PID</th>
<th>DESIGNATION</th>
<th>LATITUDE</th>
<th>LONGITUDE</th>
<th>DISTANCE (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DL795</td>
<td>HDL MACKINAW/WAL2006 CORS ARP</td>
<td>N40°33′21.161″</td>
<td>W089°17′38.330″</td>
<td>97170.3</td>
</tr>
<tr>
<td>DL6165</td>
<td>BLOM CITY/BLOOMINGTON CORS ARP</td>
<td>N40°39′44.282″</td>
<td>W089°55′59.461″</td>
<td>72337.7</td>
</tr>
<tr>
<td>DM3495</td>
<td>INCR CRAWFORDSVILLE CORS ARP</td>
<td>N40°04′55.782″</td>
<td>W086°54′17.479″</td>
<td>118326.6</td>
</tr>
</tbody>
</table>

NEAREST NGS PUBLISHED CONTROL POINT:

| DOS100 | KARA CO 4 COOP CORS L1 PHASE C | N40°07′53.797″ | W088°17′33.849″ | 431.2 |

This position and the above vector components were computed without any knowledge by the National Geodetic Survey regarding the equipment or field operating procedures used.
OPUS & Precise Ephemeris

- OPUS uses the most precise ephemeris available at the time of processing.
- This solution used the precise IGS ephemeris.

Wait a day

- While most CORS are archived within 30 minutes past the hour, some aren't available until the next day.
- Rapid orbits, available at 17:00 UTC the next day, may offer a slight improvement in your accuracy.
To improve OPUS accuracy

- **Observe longer**: A longer-duration session provides OPUS a better opportunity to accurately fix ambiguities and mitigate multipath error.

Session duration versus accuracy

To improve OPUS accuracy

- **Observe again**: A second, independent observation can increase confidence in your results.
- **Maximize independence by using**
  - a different observer,
  - different equipment,
  - on a different day,
  - at a different time of day.
Ionospheric Disturbance

- OPUS-RS may perform poorly or fail during periods of high ionospheric disturbance.
- Avoid performing any GPS survey during geomagnetic storms that cause large and variable ionospheric refraction.
- Geomagnetic storm alerts are issued online by NOAA's Space Environment Center.

Space Weather Prediction Center

- Solar radiation ionizes the electrons in the ionosphere which leads to errors up to 50 m in GPS observations.
- Variation of electron density in the ionosphere follows the 11 year solar cycle.
- www.swpc.noaa.gov

Space Weather
Tropospheric Delay

- OPUS-RS performs a simple geographic interpolation to predict the tropospheric delay at your GPS location.
- Under normal conditions this works well. However, it may not work well during the passage of a strong weather front, and these situations should be avoided.

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Case Studies

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Project 1: Scenario

- Task:
  - Design survey for remote bridge
  - Set control and collect topo with GPS
- Conditions:
  - CORS coverage is not available
  - RTK base and rover are available
Project 1: Bridge Project Control

1. Set intervisible points A and B.

2. Occupy A with RTK base
   a. Configure to log static data.
   b. Accept an autonomous position (HERE shot) for base position at A.

3. Collect positions of B, panels, and topo points by rover relative to point A.

Project 1: First RTK Occupation
Project 1: Second RTK Occupation

1. Occupy B with RTK base
   a. Configure to log static data.
   b. Accept an autonomous position (HERE shot) for base position at B.

2. Collect positions of A and panels by rover relative to point B.
   a. These observed coordinates of A and panels will differ from those collected in first occupation.

Project 1: OPUS Solutions

1. Extract RINEX files for points A and B.

2. Process OPUS solutions for A and B.

3. Replace autonomous positions of A and B (poor position quality) with OPUS-derived positions (good position quality).
   a. RTK vectors will move with base positions.
   b. Repeat observations will agree closely.
   c. Average all repeat observations for increased confidence.
**Project 1: Results after OPUS solutions**

Average all positions with multiple observations. Line AB has been observed twice (higher confidence).

**Project 1: Conclusions**

- Adjacent OPUS solutions can give results sufficient for control.
  - Repeated and averaged OPUS sessions will improve confidence.
- Use of OPUS allows work to proceed without certainty of positions relative to a datum.

**Project 1: Lessons Learned**

- Pay close attention to point names.
  - Depending on your processing sequence, you may need different names for the first and second observations of a point.
- File management is crucial.
  - You may need to create a separate job file in the field for the second occupation.
  - Two job files can be combined in your desktop software.
Project 2: Scenario

• Task:
  – Data management for large boundary survey (approximately 800 corners).
  – Deliverables include SPCS positions on all corners.

• Conditions:
  – GPS and total station used dissimilar controllers.

Project 2: Data Manipulation

• Collected all data in SPCS.
  – Over 4 weeks of field work.
  – Crew chief scaled and translated SPCS positions to local surface grid each day.
  – Surveyors in office computed boundary using surface coordinates.

Project 2: Data Manipulation

• Office staff experienced confusion.
  – Attempted to scale SPCS without translating.
  – Mixed scaled and unscaled coordinates.
Project 2: Data Transfer

- Transferred coordinates between dissimilar controllers.
  - Cumbersome process.
  - Inadvertently applied International Feet to one set of US Survey Feet data.
  - Experienced large bust in the field.

Project 2: Lessons Learned

- Establish local surface grid first.
  - Use for all field work and boundary analysis.
- Transform to SPCS coordinates once at end of project.
- Use one controller for both GPS and total station measurements.

Project 3: Scenario

- Task:
  - Collect 20 miles of channel sections and profile using RTK for drainage district.
- Conditions:
  - Vertical control is available at middle and both ends of project.
Project 3: Field Procedure 1

- First ten miles:
  - RTK leapfrog
  - Base unit elevations dependent on previous rover shots.
  - 1.0 foot closure on vertical control.

Project 3: Field Procedure 2

- Second ten miles:
  - OPUS solution for each RTK base point
  - Rover shots between base points provide checks.
  - 0.2 foot closure on vertical control.

Project 3: Lessons Learned

- RTK leap frog method compounded errors.
- OPUS solutions built checks into process.
  - Antenna height
  - Solution quality
- Post-processing enhances accuracy.
Project 4: Scenario

• Task:
  – Establish control network for design and construction of 20 mile light rail project.

• Conditions:
  – Another company will provide construction layout using your plans.
  – Your control points must have surface coordinates.

Project 4: SPCS Inadequate

Ground to grid distortion too large for error budget

Low Distortion Projections

LDPs are optimized map projections that take into account the combined effect of Earth’s curvature and ground height above the ellipsoid.
Notice general east to west slope.

Distortion increases with vertical separation between the ground and the projection surface.

Central meridian location influences LDP fit.
LDPs minimize the vertical separation between the ground and the projection surface.

Scale factor indicates LDP height above the ellipsoid.

LDPs can limit distortion to 5 ppm or less (5 ppm = 0.026 foot/mile)
Advantages of LDPs

Grid distances very closely match the same distance measured on the ground.

10 ppm = 0.053 feet/mile
8 ppm = 0.042 feet/mile
6 ppm = 0.032 feet/mile
4 ppm = 0.021 feet/mile
2 ppm = 0.011 feet/mile

LDP Surface Options

Lambert Conformal Conic Projection
Oblique Mercator Projection
Transverse Mercator Projection
Oregon Coordinate Reference System

[Image: Michael Dennis, Geodetic Analysis, LLC]

www.oregon.gov/ODOT/HWY/GEOMETRONICS/Pages/ocrs.aspx

Indiana Geospatial Coordinate System


www.in.gov/indot/InGCS.htm

LDPs are optimized map projections

Wrap Up

- What was the most valuable thing you learned today?

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