Recommended RTK GPS Configuration Parameters for the City of Madison, WI Base Station

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For base station information see web site: http://gis.cityofmadison.com/Madison_GPS/

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INTRODUCTION & DISCLAIMER: These are suggested parameters for producing Dane County Coordinates and NAVD 88 elevations (1991, 2007 or 2012) using Real-Time Kinematic (RTK) positioning, in the Madison area, from the City of Madison Global Positioning System (GPS) base station or the Wisconsin Continuously Operating Reference Stations (WISCORS) network. Users of this document are solely responsible for their own spatial measurements, computations and related work, as well as for compliance with applicable standards and specifications, including documentation of datum, bench marks, elevations and dates. The author and the City of Madison make no representation about the accuracy or completeness of this document, and in no event shall the author or the City be liable for any damages whatsoever resulting from its use.

The vertical calibration parameters (geoid model shift & tilt) are computed using 34 National Geodetic Survey (NGS) stations within about 12.5 miles (~20 km) of central Madison. The parameters are not appropriate for work outside that range. Elevation data for the 34 stations was originally obtained from NGS data sheets retrieved Jul. 30, 2007 and Dec. 2007. NAD 83(2011)(Epoch 2010.00) and NAVD 88(2012) data were obtained initially from Aug 14, 2012 data sheets, but NAVD 88(2012) elevations were not found for non-leveled stations until Jan 11 2014 data sheets (other data used from Aug 14 2012 data sheets had not changed). Station MADISON S GPS (DF9799) was destroyed in 2010, but has 2011/2012 adjustment values so remains in the analysis.

NAD 83(2011)(EPOCH 2010.00) is called NAD 83(2011) here for brevity. The 3 adjustments of NAVD 88 are called NAVD 88(1991) (the original), NAVD 88(2007) and NAVD 88(2012).

Users should also be aware of the inherent accuracy limits of RTK GPS. For shorter-duration observations, many manufacturers report single-base RTK vertical accuracy under ideal conditions of about 0.07 ft + 1 part per million (ppm) RMS, or about 0.14 ft + 2 ppm at 95% confidence. At 10 miles from the base, that is +/- 0.24 ft @ 95%. Multiple base networks like WISCORS are said to remove the ppm component. Generally, RTK accuracy is only significantly improved by averaging longer observations from different times of day on different days. Users are responsible for using appropriate methods and checks, and following applicable standards and specifications.

"The Rodman's Guide to Madison Vertical Datums" contains detailed information about the development of the vertical calibration parameters. It can be found on the web at: http://danrodman.tripod.com.

The previous (Feb. 26, 2011) version of this document used the NAD 83(2007) base coordinates and GEOID03 geoid model for the development of configuration parameters.

HORIZONTAL PROJECTION PARAMETERS: DANE COUNTY COORDINATES

Projection Type:	Lambert Conformal Conic One-Parallel (Non-Intersecting)
False Northing:	480943.886 US ft *(146591.9896 m)*
False Easting:	811000.000 US ft *(247193.2944 m)*
Origin Latitude:	43°04'10.25774"N *(central parallel)*
Origin Longitude:	89°25'20.00000"W
Scale Factor:	1.0000384786

Dane County Coordinate parameters shown are the new Wisconsin Coordinate Reference Systems (WISCRS) parameters, rather than the old Wisconsin County Coordinate System (WCCS) parameters which required a raised ellipsoid and made datum and ellipsoid height issues confusing. Within the same datum adjustment, The WISCRS and WCCS parameters produce Dane County Coordinates that differ by no more than 0.01 foot. See www.sco.wisc.edu/coordsys/

Dane County Coordinates are recommended to match the city's Public Land Survey section corner coordinates and avoid significant grid-to-ground distance scale factors associated with other projections, such as State Plane (~ 1 part in 10,000).

HORIZONTAL DATUM: NAD 83 = WGS 84

Ellipsoid Semi-Major Axis: 20925604.474 US ft (*6378137.000 m) (Note 1)*
Ellipsoid 1/flattening (1/f): 298.257222101 *(Note 1)*
Transformation from WGS 84: None *Assume same ellipsoid parameters, and zero shift, rotation & scale. (Note 2 & 3)*

1. The ellipsoid parameters (semi-major axis & flattening) are for the GRS80 ellipsoid, which is used by the NAD 83 datum. The WGS 84 datum uses the same semi-major axis value. The WGS 84 1/f = 298.257223563 is slightly different than GRS80, but any 1/f to 298.25722… gives positions and heights differing by well under 0.01 ft. Use either flattening value.
2. Consider NAD 83 and WGS 84 to be identical. The recent adjustments of NAD 83 and WGS 84 actually differ by about a ~2m shift, ~0.1 ppm rotation, and ~0.001 ppm scale. See www.ngs.noaa.gov. However, for single-base relative positions over shorter distances (<30 km), the datums are interchangeable. That is, NAD 83 base station coordinates are entered as WGS 84 coordinates, the baseline is solved in WGS 84 (with slight distortions), and since this baseline is virtually parallel to NAD 83, the "WGS 84" coordinates computed at the rover are actually NAD 83 coordinates, in the same NAD 83 adjustment as the base station. The relative error caused by the WGS 84 = NAD 83 assumption is approximately 0.1 ppm (~ 0.01 foot in 20 miles). See Chapter 5.3.5, GPS Satellite Surveying 3rd ed. by Alfred Leick.
3. WISCORS: The coordinates and baselines computed for end-users are in the NAD 83 datum. If the user's data collector considers them to be WGS 84 (as does the author's) then no transformation should be applied from WGS 84 to NAD 83. See https://wiscors.dot.wi.gov/

HORIZONTAL ADJUSTMENT

With both WISCORS and the city's single base broadcast position being in NAD 83(2011), the rover will be solved in NAD 83(2011) as well. In the Madison area, a simple shift of –0.07 ft east shift (= 0.07 ft west) converts back to NAD 83(2007) if needed. No rotation or scale is necessary, thus the origin of rotation and scaling can be N,E=0,0. There is some information on horizontal shifts to earlier (1991, 1997) adjustments of NAD 83 in the "Rodman's Guide" listed above.

VERTICAL ADJUSTMENT USING GEOID12A

The City of Madison's Public Land Survey System monument records have NAVD 88(1991) elevations, so those are the suggested parameters. Parameters are shown for the 2007 and 2012 adjustments as well. Also note that NGVD 29 elevations are about 0.2 ft larger than NAVD 88(1991) elevations in the Madison area.

Tilts that were necessary to adjust the old GEOID03 to produce NAVD 88 elevations are not significant for GEOID12A in the Madison area for RTK GPS, so north & east tilt (slope) parameters are zero and a vertical adjustment origin (pivot) point is irrelevant; use N,E=0,0 if an origin is required. Only a vertical shift (constant) parameter is suggested here.

NAVD 88 Desired	Base Ellipsoid Height	Geoid Model	Vertical Shift Parameter (note 1 & 2)
NAVD 88(2012)	NAD 83(2011)	GEOID12A	0 (note 3)
NAVD 88(2007)	NAD 83(2011)	GEOID12A	-0.06 ft (note 4)
NAVD 88(1991)	NAD 83(2011)	GEOID12A	**–0.167 ft** (note 5)

1. The sign of the vertical shift parameter is the same as the geoid residual (ΔN) in The Rodman's Guide. A negative shift makes the geoid separation (N) less negative, and the NAVD 88 elevation (H) less positive.
2. GEOID12A, like previous geoid models, cannot be adjusted with shift, or even shift & tilts, to *exactly* match published ellipsoid heights and NAVD 88 elevations at the 34 NGS stations used. Thus even with perfect GPS measurements, computed elevations would be off slightly from published NAVD 88 elevations. Some values are shown to 0.001 ft precision only to reduce rounding error when duplicating calculations from The Rodman's Guide.
3. GEOID12A is designed to convert NAD 83(2011) ellipsoid heights to NAVD 88(2012) elevations, and does so to within +/-0.04 ft (average -0.001 ft) at the 15 of 34 Madison-area NGS stations that have leveled elevations. A zero shift is suggested.
4. The -0.06 ft shift is the average difference between NAVD 88(2007) and NAVD 88(2012) elevations for leveled NGS stations in the Madison area. No specific calibration was computed in "The Rodman's Guide" for GEOID12A using NAVD 88(2007), but the difference in calibrated shifts for NAVD 88(1991) & NAVD 88(2007) was -0.103 ft for GEOID09 and -0.114 ft for GEOID03. Subtracting these from the -0.167 ft shift for NAVD 88(1991) gives -0.064 ft & -0.053 ft, which are very similar.
5. The -0.167 ft shift is from a best-fit calibration of GEOID12A to NAD 83(2011) ellipsoid heights and NAVD 88(1991) elevations for the 34 NGS stations. Using the -0.167 ft shift, 27 of the 34 NGS stations are within 0.03 ft of their published NAVD 88(1991) elevations, and 32 of 34 are within 0.05 ft (SPRINGFIELD GPS = 0.07 ft, ARP 2 MSN = 0.10 ft). The -0.167 ft shift matches the average -0.17 ft shift = NAVD 88(1991) minus NAVD 88(2012) at a larger set of leveled NGS stations in the Madison area.

EMIL STREET BASE STATION (MAON) AS OF MARCH 2013

Point Name:	MAON *(note 1)*
Antenna:	Trimble Zephyr Geodetic Model 2 (model 55971-00) *(note 5)*
Latitude:	43°02'12.78285"N *NAD 83(2011) (note 2, 3)*
Longitude:	89°24'34.27002"W *NAD 83(2011) (note 2, 3)*
Ellipsoid Height:	Bottom of antenna mount (Antenna Ref Point) = 248.669 m / 815.84 US ft *NAD 83(2011) (note 2, 4, 5)*
	Mechanical Phase Center = 248.754 m = 816.12 US ft *NAD 83(2011) (note 2, 4, 5)*

Dane County Coordinates:	N=469050.00	E= 814396.37	*NAD 83(2011), US Survey foot*
WI State Plane Coordinates NAD83, South Zone:	N=378471.26	E=2126363.41	*NAD 83(2011), US Survey foot*

1) MAON is the base name in the WI DOT's WISCORS network. The same name is also used for the single-base correction signal broadcast by the City of Madison. See https://wiscors.wi.gov/ and http://gis.cityofmadison.com/Madison_GPS/

2) The NAD 83(2011) latitude, longitude and ellipsoid height are the WISCORS values determined by the WDOT in March 2013. RTK users may see a slightly different latitude/longitude in their GPS controllers due to rounding in coordinate conversions (0.01 ft = approx. 0.0001"). The position is 0.01 ft north and 0.07 ft west, and the ellipsoid height is 0.08 ft smaller, than the DOT's original Jan. 2009 position in NAD 83(2007) = 43°02'12.78277"N, 89°24'34.27099"W, Ellip Ht ARP 248.694 m / 815.92 US ft, WISCRS-Dane N=469049.99, E= 814396.30 US ft. The DOT's shifts match within 0.02 ft the datum shifts at Madison-area NGS stations (average 0.00 ft north, 0.07 ft west, ellip ht 0.09 to 0.10 ft smaller).

3) Static GPS checks from 2008 to 2013 from NGS stations MADISON S GPS, WESTPORT N GPS, MIDDLETON GPS and FITCHBURG N GPS show horizontal position in the corresponding datum (2007 or 2011) to be 0.02 to 0.04 ft north and 0.00 to 0.03 ft west of the DOT's (within RTK GPS accuracy).

4) Differential leveling by the city in 2008 put the base ARP 60.22 ft above MADISON S GPS (destroyed in 2010), giving a NAVD 88(2012) elevation of 868.07+60.22 = 928.29 ft. Adding the GEOID12A geoid separation (unadjusted) of -112.46 ft at the base gives a NAD 83(2011) ellipsoid height of 815.83 ft for the ARP, only 0.01 ft lower than the DOT's. A Sept. 2012 city check using trigonometric leveling from 2008 on-site bench marks to the base ARP matched 2008 values to 0.01 ft (within accuracy of 2012 measurements).

5) The Emil St antenna has its mechanical and nominal electrical phase centers both 85 mm (0.28 ft) above the base of the antenna mount (Antenna Referecen Point = ARP), so potential discrepancies with NGS antenna calibrations due to confusion of mechanical and electrical phase centers should not be a problem. The ellipsoid height is a NAD 83(2011) value, appropriate for GEOID12A and the vertical calibration parameters given above. Note that in the author's Trimble Survey Controller, if the coordinates of a WISCORS base are automatically uploaded (e.g. when raw positions are stored as vectors rather than positions), the ellipsoid height for the base's ARP (bottom of antenna mount) is assigned to the phase center of an "unknown external" antenna. This base antenna mismatch does not introduce an error however, because no phase center offset is applied to an unknown antenna. Heights computed at the rover should be correct, assuming that the user has properly specified the rover antenna type and other parameters.

TEST POINTS: The NGS stations below are provided to test the parameters given above. The "input" latitude, longitude and ellipsoid height are NGS published values (as of Jan 11 2014) in the NAD 83(2011) Datum. The "output" Northing and Easting are Dane County Coordinates, in both NAD 83(2007) and NAD 83(2011), using the WISCRS parameters. The "output" NAVD 88 elevations are given in 1991, 2007 and 2012. The Emil Street base (MAON) is included below, but manually entering it in your data collector with point name "MAON" may cause confusion with the broadcast base position. Remember the difference between bottom of antenna mount (Antenna Reference Point - ARP) & phase center height.

Note that the computed NAVD 88 elevations do not exactly equal NGS-published values. This is because GEOID12A cannot be shifted (or even shifted and tilted) to exactly match published NAD 83 ellipsoid heights and NAVD 88 elevations at all of these stations. Moreover, users may see their own computed values differ by about 0.01 foot from those here, due to rounding of the vertical adjustment parameters or unit conversions. Keep in mind that these rounding errors, and even the computed vs. published discrepancies, are well within RTK GPS accuracy.

Also, keep in mind that matching these results in your data collector only shows that the coordinate system parameters have been correctly entered. Producing correct positions when using GPS also depends on other factors (correct base station coordinates, antenna height & model, rod leveling, good conditions, etc.)

Test Input: NAD 83(2011)

Station	Latitude (dms)	Longitude (dms)	Ellipsoid Height, ft
FITCHBURG N GPS (PID# DG4870)	43 00 55.83685	089 26 04.07150	824.10
VERONA GPS (PID# DF9766)	42 55 44.89369	089 30 40.73981	841.08
ROCK (PID# OM0651)	43 12 01.93289	089 30 05.36550	946.38
SUN PRAIRIE W GPS (PID# DF9946)	43 10 27.50394	089 12 25.50203	847.43
STOUGHTON GPS (PID# DF9920)	42 56 26.87393	089 11 38.49587	776.50
MAON ARP (Emil St base)	43 02 12.78285	089 24 34.27002	815.84 *(ARP)*

Horizontal Test Output – Dane County Coordinates (WISCRS, US ft)
Discrepancies for NAD 83(2007) = Computed (using 0.07 ft west shift) minus Published (NGS NAD 83(2007) lat/lon projected to WISCRS). There is no discrepancy here for NAD 83(2011) since NGS NAD 83(2011) lat/lon were used to project to WISCRS.

	NAD 83(2011) No horizontal shift		NAD 83(2007) Computed using 0.07 ft west shift		NAD 83(2007) Discrepancy	
Station	Northing	Easting	Northing	Easting	Northing	Easting
FITCHBURG N GPS (PID# DG4870)	461259.36	807725.67	461259.36	807725.60	+0.01	0.00
VERONA GPS (PID# DF9766)	429789.70	787136.90	429789.70	787136.83	0.00	0.00
ROCK (#OM0651)	528710.95	789862.22	528710.95	789862.15	+0.01	-0.01
SUN PRAIRIE W GPS (PID# DF9946)	519213.52	868393.59	519213.52	868393.52	0.00	0.00
STOUGHTON GPS (PID# DF9920)	434110.48	872108.42	434110.48	872108.35	0.00	0.00
MAON ARP (Emil St base)	469050.00	814396.37	469050.00	814396.30	+0.01	0.00

Vertical Test Output – NAVD 88(1991) (ft) *NGS-published elevations are dated 2004*

Station	Computed	NGS-Published	Discrepancy
FITCHBURG N GPS (PID# DG4870)	936.26	936.25	+0.01
VERONA GPS (PID# DF9766)	952.68	952.66	+0.02
ROCK (#OM0651)	1059.50	1059.48	+0.02
SUN PRAIRIE W GPS (PID# DF9946)	961.03	961.02	+0.01
STOUGHTON GPS (PID# DF9920)	888.73	888.72	+0.01
MAON ARP (Emil St base)	928.13	928.13 (city leveled)	0.00

Vertical Test Output – NAVD 88(2007) (ft) *NGS-published elevations are dated 2007*

Station	Computed	NGS-Published	Discrepancy
FITCHBURG N GPS (PID# DG4870)	936.37	936.38	-0.01
VERONA GPS (PID# DF9766)	952.79	952.80	-0.01
ROCK (#OM0651)	1059.61	1059.60	+0.01
SUN PRAIRIE W GPS (PID# DF9946)	961.14	961.14	0.00
STOUGHTON GPS (PID# DF9920)	888.84	888.81	+0.03
MAON ARP (Emil St base)	928.24	928.23 (city leveled)	+0.01

Vertical Test Output – NAVD 88(2012) (ft) *NGS-published elevations are dated 2012*

Station	Computed	NGS-Published	Discrepancy
FITCHBURG N GPS (PID# DG4870)	936.43	n/a	n/a
VERONA GPS (PID# DF9766)	952.85	952.86	-0.01
ROCK (#OM0651)	1059.67	1059.66	+0.01
SUN PRAIRIE W GPS (PID# DF9946)	961.20	961.22	-0.02
STOUGHTON GPS (PID# DF9920)	888.90	888.88	+0.02
MAON ARP (Emil St base)	928.30	928.29 (city leveled)	+0.01

GEOID12A VS. GEOID03 Comparing GEOID12A to previous geoid models is difficult because it is based on new adjustments of both NAD 83 and NAVD 88. Since the Emil Street base station (MAON) was established in 2009, City of Madison surveyors had been using GEOID03 adjusted to fit 2007 NAD 83 ellipsoid heights and NAVD 88(1991) elevations, so a comparison is shown to that.

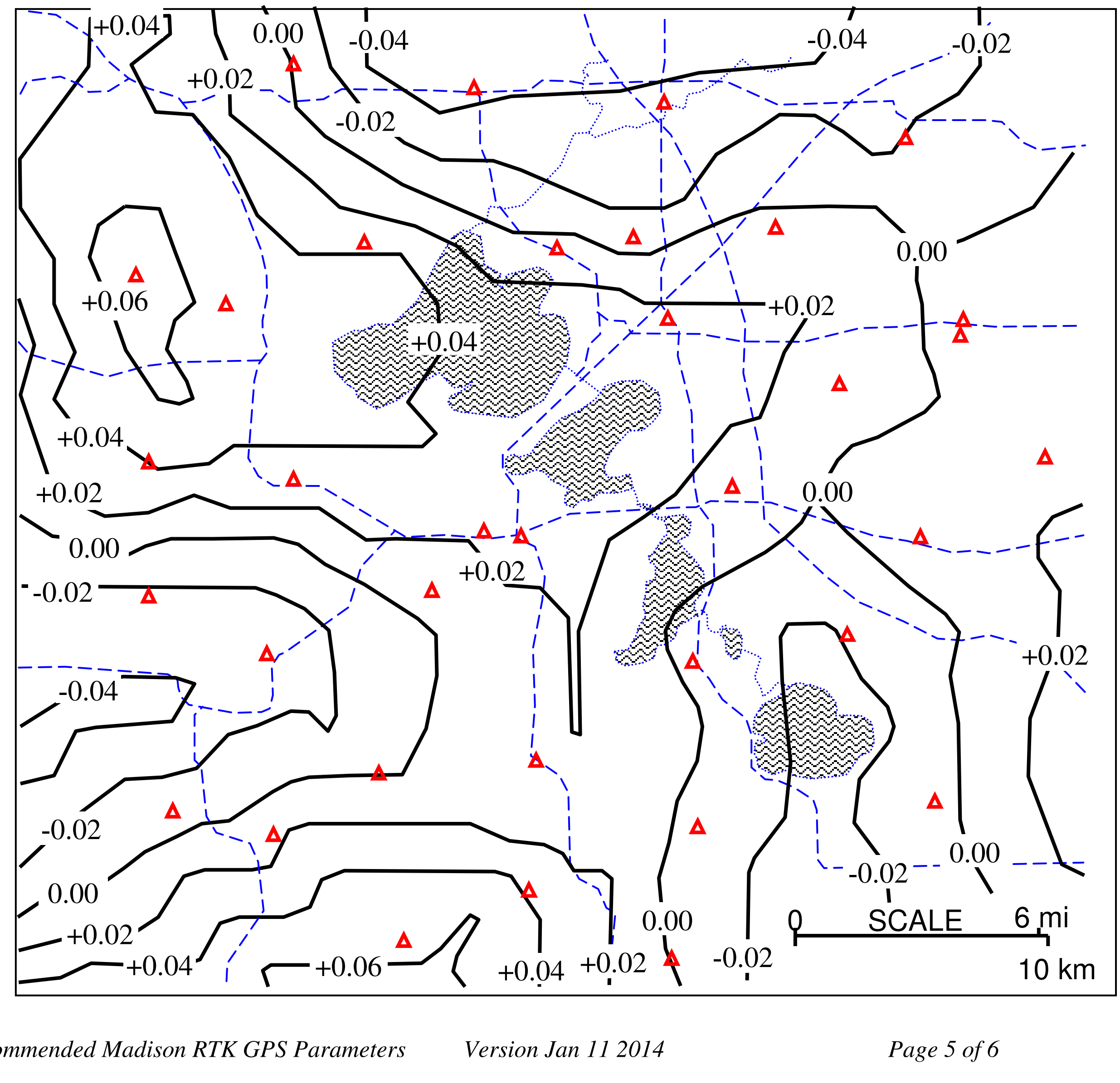
Adjusted GEOID03: Origin (pivot point) N, E = 469050, 814396 US ft, East tilt = +1.70 ppm North tilt = -0.90 ppm, Shift (constant) = -0.087 ft. (see Rodman's Guide)

Adjusted GEOID12A: Added 0.27 ft (making geoid separation less negative). Computed from -0.10 ft average change in ellipsoid heights from 2007 to 2011, and +0.17 ft average change in NAVD 88 elevations from 1991 to 2012 for Madison-area NGS stations.

Geoid separation values were generated from each using a 1-minute grid (0°01' latitude, 0°01'longitude), and 0.01-foot contours were interpolated from the difference values (= GEOID12A + 0.27 ft - modified GEOID03). The contours show the change in *curvature* of GEOID12A from GEOID03, resulting from the updated gravity data and bench mark data used for GEOID12A. Where the difference contours are *positive* (i.e. +0.07 ft at SPRINGFIELD S GPS west of Madison), the adjusted GEOID12A geoid separation is *less negative* than that from the adjusted GEOID03. When the (negative) geoid separation is subtracted from a GPS-measured ellipsoid height, the resulting NAVD 88 elevation is *less positive* (lower) using GEOID12A than using the adjusted GEOID03.

Changes in Madison are within 0.05 feet, within RTK GPS accuracy. Thus for RTK GPS, using GEOID12A (with the -0.167 ft shift) to convert NAD 83(2011) ellipsoid heights to NAVD 88(1991) elevations will not result in significantly different NAVD 88(1991) elevations than what the City of Madison has been using previously.

Adjusted GEOID12A minus Adjusted GEOID03 (feet)



HOW VERTICAL ADJUSTMENT PARAMETERS WORK:

The Vertical Adjustment parameters are designed to reduce the "geoid residual" between:

1) geoid separations computed from the difference between published ellipsoid heights (h) and elevations (H): ("h-H")
2) geoid separations predicted by a geoid model, like GEOID12A ("N").

The geoid residual (ΔN) is computed as $\Delta N = N - (h - H)$

The Shift, Tilt North and Tilt East parameters from the Vertical Adjustment compute 3 components of a tilted plane model of the geoid residual. Sample computations are shown below for NGS station STOUGHTON GPS, using the NAVD 88(1991) parameters (see Vertical Adjustment section). Since the tilt components are determined to be insignificant for GEOID12A, the origin (pivot) point is irrelevant and only the Shift component is considered here. See The Rodman's Guide for sample tilt computations.

Shift component = geoid residual (ΔN) = –0.17 ft

Adjusted geoid separation = (GEOID12A @ STOUGHTON GPS – geoid residual) = (–112.40 – (–0.17)) = –112.23 ft

Computed NAVD 88(1991) elevation = NAD 83(2011) ellip ht – adjusted geoid separation = (776.50 – (–112.23) = **888.73 ft**

The result matches the "Computed Elevation" in the "Vertical Test Output – NAVD 88(1991)" table above.

DEALING WITH DISCREPANCIES:

If a GPS receiver configured with the above parameters doesn't produce the published coordinates at a control station, the problem would generally fall into one or more of these categories:

- **Bench marks:** The published coordinates may be wrong, or the station may have moved. This applies to the base station as well, but the WISCORS network does continuously monitor for base movement.
- **GPS Baseline:** The fundamental 3-dimensional GPS measurement from antenna phase center to antenna phase center, or from a network (WISCORS) solution, has unavoidable errors. Multipath and poor satellite geometry can introduce large errors. Remember that accuracy estimates (e.g. RMS values) produced by a GPS controller are occasionally way off. The author has observed "fixed" positions with estimated RMS at 0.05 feet that are actually 4 feet off. High accuracy is usually only achievable by averaging different observations at different times of day and on different days.
- **Antenna Heights & Models:** Antenna heights must be entered correctly, and antenna phase center offset and variation (change with satellite elevation angle) must be accounted for by specifying the correct antenna type in the GPS controller. Users should contact their equipment vendor to make sure antenna models and other necessary information are loaded.
- **Configuration Parameters:** The above coordinate system parameters may have been incorrectly entered. The wrong geoid model may be loaded. A certain GPS controller may have the opposite sign convention for geoid shift and tilt values, or it may be configured to use the height of the base antenna mount instead of the phase center. The controller may have user entered coordinates for the base station which override the broadcast coordinates, and are not in the datum assumed for the calibration parameters given.

LOCAL / SITE CALIBRATION:

RTK GPS systems typically allow the user to adjust results both horizontally and vertically based on observations at one or more control point(s). Typical horizontal calibrations allow either: 1) translation; or 2) translation, rotation and scaling (i.e. 2D conformal transformation) . Typical vertical calibrations allow either: 1) a constant shift (parallel offset); or 2) a shift and two tilts (inclined plane). Calibration can greatly simplify the removal of systematic errors, and is generally the best option for being consistent with pre-established project control. However, keep in mind its limitations:

- **Calibration only removes constant errors.** Calibration does not remove random errors, specifically errors in the GPS observation(s) used to compute the calibration (e.g. multipath errors at obstructed section corners), and in the observations to each subsequently surveyed point. Calibration may give a false sense of higher accuracy, particularly since GPS errors sometimes change gradually over hours or days. The parameters given above are based on published NGS heights, which are computed from extensive static GPS observations and differential leveling, checked and adjusted by the NGS.
- **Calibration trusts control, right or wrong.** Calibration to a single station does not indicate if that station's published coordinates are correct. The monument may have been reset at a different elevation, for example, as sometimes happens with section corners in streets. Checking another station after calibration (or calibrating to 2 or more stations) can at least ensure local consistency, but there still may be a systematic shift relative to datum. Using the above parameters allows the base station (or base network) to be used as a control station itself, and a rover observation on a local bench mark becomes an independent check (within GPS accuracy, of course) rather than a required and unquestioned calibration point.
- **Calibration only applies near the calibration points.** Working outside the calibration area magnifies any errors present in the calibration. The above parameters are computed using NGS stations out to 20 km (~12.5 mi) from central Madison.