CONNECTICUT DEPARTMENT OF TRANSPORTATION

GNSS SURVEY STANDARDS MANUAL

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GNSS Utilization for Horizontal and Vertical Control and Survey

The purpose of the following sections is to provide guidelines and specifications to Connecticut Department of Transportation Surveys in performing land surveys using Global Navigation Satellite System (GNSS) positioning, that in whole or in part, that comply with minimum accuracy standards, classifications and content requirements of land surveys set forth in the Regulations of Connecticut State Agencies, Sections 20-300b-1 through 20-300b-20, as well as those set forth in the NGS User Guidelines for Single Base Real Time GNSS Positioning (v. 3.1, April, 2014) and described in the ASPRS Positional Accuracy Standards for Digital Geospatial Data Edition 2 (v 2.0, 2024). In addition, NOAA Technical Memorandum NOS NGS 92, Classifications, Standards and Specifications for GNSS Geodetic Control Surveys using OPUS Projects, published October 23, 2024, was used for guidance.

It is recognized that with the current momentum of development in GNSS technology, GNSS equipment, software and processing algorithms will continue to improve and as such, these guidelines will face ongoing revision.

Although ASPRS now recommends reporting Root Mean Square error (RMSe), Connecticut Department of Transportation (CTDOT) will continue to report error at the 95% confidence interval due to its use by the National Geodetic Survey and the accuracy standards laid out by the Federal Geographic Data Committee (FGDC).

A. Observations and Equipment

- Carrier phase shall be observed. Doppler and timing codes (e.g. GPS C/A and P-Codes) may be observed.
- Fixed height tripods are recommended. All measure-ups should be in feet and meters if fixed height tripod not used, and measurement type and location (slant, vertical, bottom of mount, notch, etc.) should be noted.
- Survey-grade antennas shall be used.
    - Recommended to receive at least 240 channels with 3 constellations (e.g. GPS, GLONASS, Galileo, etc.) and all current signal frequencies (e.g. L1, L2, L5)

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B. Procedures

There shall be favorable ionospheric, tropospheric, and multipath conditions. Ionospheric conditions can be assessed by consulting the National Space Weather Service (http://www.swpc.noaa.gov/) and poor conditions avoided by not observing during severe space weather. Poor tropospheric conditions can also be avoided by not positioning while weather fronts pass through.

Sites that are partially obscured by nearby objects such as vegetation, signs, buildings and hills are prone to producing multipath or occluded space vehicle transmissions. These sites may be suitable for land surveys if proper session planning efforts are undertaken. Mission planning (https://www.gnssplanning.com/) can inform the surveyor when the best conditions (e.g. low DOP, maximum satellite availability) will occur and aid in effective time management. Mission planning is especially important for suboptimal conditions, to ensure quality measurements can be made efficiently.

For GNSS use in surveys, field notes or a log sheet should minimally include a description of markers with sketches and/or photographs, date of occupation, start and stop times, point ranges of sessions, antenna type and height (noted as slant or vertical), equipment serial numbers, weather conditions, and observer name. Alternatively, GNSS Logging apps, such as GNSS Log App may be used.

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C. Redundancy

Accuracy in GNSS surveys is assessed through redundancy. Redundancy occurs in several ways including occupation duration, use of multi frequency/multi constellation receivers and reoccupation:

- Occupation duration: For static or rapid-static occupations, the longer the time between the epochs the better the results in those data sets. For example, 60 epochs collected over 600 seconds will result in higher accuracy than 60 epochs collected over 60 seconds.
- Multi-constellation receivers: Observables from six or more NAVSTAR GPS, GLONASS, and/or GALILEO space vehicles (SVs), observed simultaneously, shall be used to process a baseline. Additional data from other constellations, such as BEIDOU, may be beneficial, but not required.
- Multi-frequency receivers: Observables from two or more frequencies (L1, L2C, L5, etc.) provide redundant information generally resulting in better differencing results and ionospheric delay removal. In addition, outliers may be more appropriately filtered.
- Reoccupation: The geometry of the SVs in view directly affects position quality. Reoccupation is necessary to guarantee independent observations. Reoccupied sessions are preferred to be not less than three hours apart nor multiples of twenty four hours apart[1].

[1] Minus four minutes per day because of sidereal vs solar time.

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D. Processing

Positions shall be determined from phase differenced relative positioning. The resulting vectors shall be referenced to an appropriate datum or coordinate system even if only through localization. Users may localize to project control where necessary, even though this may reduce precision but improve accuracy. Epochs or observables failing the following quality checks shall be excluded from position computations either by receiver settings or by filters in the least squares processing software:

- any observable from an SV closer than 10° to the local horizon; (recommended collect at 10° and process at 15°)
- any epoch with less than 6 GNSS (outlined above) SVs in common for stations being differenced
- any epoch with a PDOP greater than 1.5 and
- for vertical positions, any epoch with a VDOP greater than 1.5.

In addition to the above criteria:

- control surveys shall not incorporate floating solutions
- antenna calibration information (phase center variation, PCV) for all GNSS antennas used in the survey, including any CORS stations, shall be entered correctly into the post-processing software. Calibration data shall be obtained from a reliable source, such as the NGS (http://www.ngs.noaa.gov/ANTCAL/) or an antenna's manufacturer;
- for vertical control surveys, precise ephemerides are required. For other surveys, precise ephemerides shall be used whenever practical; even ultra-rapid is better than broadcast ephemerides. Further information concerning precise ephemerides is available at the IGS website (https://igs.org/products/#precise_orbits)
- for all types of surveys involving elevations (vertical control, topography, construction), orthometric heights shall be determined from ellipsoid heights transformed using the latest national geoid model (currently GEOID18).
- OPUS solutions may be used for static and rapid-static GNSS post-processing or utilized along with other least-squares solutions for blunder check

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E. GNSS Positioning Methods

Listed below are the various GNSS positioning methods that are suggested to achieve the standards that are defined within this document. Although other GNSS positioning methods could be used, these are the more common methods that are used at CTDOT with proven and achievable results utilizing the current GNSS receivers and processing software that are available today.

Static

Static GNSS surveying is used to produce relative baseline vectors between two or more stationary GNSS units by simultaneously observing and recording data over an extended period of time (typically 30 to 120 minutes) depending on the baseline length, during which the satellite geometry changes. The observation duration should be long enough for the post processing software to resolve the integer ambiguity. This method allows various systematic errors such as delays caused by atmospheric refraction to be resolved. This method provides the highest accuracy achievable and requires the longest observation times.

Rapid Static

Fast Static GNSS surveying also known as Rapid Static, is similar to Static GNSS surveying, but with shorter observation and recording periods (typically 5 to 10 minutes, or if using OPUS a minimum of 15 minutes is required). A minimum of 15 minutes is required to upload to OPUS Rapid-Static (see below).

RTK (Real Time Kinematic)

RTK surveying provides the position of the rover unit computed relative to the fixed stationary base unit in real time. In this method, a communication link is maintained between the base unit and the rover unit, and the base unit streams via the communication link the pseudo-range and carrier phase measurements to the rover unit, which in turn computes its position relative to the base unit. Redundant observations are a must to produce reliable positions by averaging multiple observations preferably obtained at different sidereal times and/or with different base locations, during which the satellite geometry changes. This method is generally limited to baseline lengths no greater than 3 miles due to radio antenna signal strength.

RTN (Real Time Network)

RTN surveying is the same method as RTK but includes corrections to minimize the PPM distance related errors (atmospheric and satellite orbits) that degrade the precision of RTK, thus baseline lengths can be increased more than 30 miles. These corrections are computed from a network of GNSS base stations that computes a network solution. From this network solution, the observation errors and their corrections are computed and broadcasted to the GNSS rover units located within the bounds on the Real Time Network (RTN). The quality of these corrections depends on the ability of the network to estimate the errors at individual base stations, as well as the capability to spatially model the errors. Where RTN exists, it is important for users to be aware of the extent of the RTN and where their project lies within that network. Accuracy rapidly declines the further a survey project lies outside the umbrella of the RTN (Henning 2011a).

OPUS and OPUS Projects

OPUS is an online positioning users service provided by the National Geodetic Survey (NGS) that allows you to upload GNSS Static data and uses software to compute coordinates relative to the NGS Continuously Operating Reference Station (CORS) network. These resulting positions are accurate and based on the National Spatial Reference System (NSRS). *OPUS requires that the antenna must remain static throughout the session, 15-minutes of data or more*, antenna type, and antenna height. The final solution is delivered via email in the datum and epoch date of the CORS network. The final solution (a single point solution) must therefore be transformed to the target geodetic datum and epoch date if different than CORS.

OPUS Projects is a web-based access to simple management and processing tools for projects involving multiple sites and multiple occupations. *OPUS Projects requires that the antenna must remain static for no less than 120 minutes.*

CORS and the NSRS

There are a variety of Continuously Operating Reference Stations (CORS) that provide coverage of the entire State. These include CORS networks of the CT DOT, MASS DOT and NY DOT, as well as Cooperative CORS in these states and RI. These CORS are components of the National Spatial Reference System (NSRS).

GNSS facilitates connecting boundary and engineering surveys to the NSRS. When a survey is tied to the NSRS, the NSRS effectively becomes a monument of the survey. The CORS can be used to accurately resurvey the site, should local control be destroyed.

GNSS can also be used in strictly local control surveys without connecting to the NSRS. However, doing this forsakes the permanence and repeatability imparted by the NSRS.

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F. Metadata

Metadata is an essential element for all manners of land surveying (typically surveyors' field book). Because coordinates and little else are the typical output of Real Time positioning, it is imperative that the user record in any manner the associated metadata of each session (typically observation log or surveyors field book as noted previously).

Certain metadata to keep on record might be:

- Datum, adjustment and epoch used by the Real Time Network. (When were the reference station coordinates last changed?).
- If and how well, the RTN is in alignment with the National Spatial Reference System (NSRS).
- Was a project localization to passive marks performed? If so, what passive monuments were constrained? What are the quality, source, reliability and general usefulness of these coordinates as a constrained point? What were the best fit residuals on the monuments?
- What hardware (especially antenna model), firmware and software were used? What versions of the firmware were used in the data collector?
- Were any guidelines or standards adhered to for collection? How many data collection epochs were collected to produce the coordinates? What collection interval was used? Were important points observed redundantly at staggered times, etc.?
- What were the field conditions during data collection? This would include PDOP (or GDOP, RDOP, etc.), number of satellites, satellite constellation(s) used, local weather, space weather, RMS of the solution(s), horizontal and vertical precisions (give at 95% confidence).
- What were the multipath conditions? (benign or list potential problem conditions – sky plots & elevation mask).
- Note any communication issues and possible interference conditions (high tension wires nearby, intermittent or problem communication, traffic

conditions, vibration on bridge platform, battery failure, etc.).

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G. Accuracy Standards and Recommended Practices

It is the Surveyor's or user's responsibility to ensure appropriate accuracy of the results of their use of GNSS methods. Primarily, it is imperative that they understand potential sources of error, equipment limitations, GNSS conditions, and other factors in determining the appropriate use of GNSS methods, and as such, the following tables are CTDOT guidelines and shall not replace the judgment of the Surveyor. Dilution of Precision (DOP), satellite geometry, signal strength, environmental factors (atmospheric conditions), multi-path obstructions, receiver specifications, and data on other sources like ionospheric and tropospheric delays, as well as sources of random and systemic error must be considered in determining adherence to allowable error for each application. Particularly with real-time GNSS methods, it is understood that residuals will often be utilized to assess potential error, but these residuals alone cannot substitute for experience based on the redundant use of GNSS technologies alongside other methods of measurement, calculations of error, and proper post-processing and assessment.

SPATIAL ACCURACY	**Level I**	**Level I I**	**Level I I I**	**Level** IV
Application	Geodetic Control Primary Project Control Densification	Primary Project Control Aerial and LiDAR Control	Secondary Project Control Aerial and LiDAR Control ROW Bounds Property Corners	Topography Non-critical stakeout
Minimum Method	Static	Fast Static RTK A ***	Fast Static RTK A RTK B	RTK C
Maximum allowable horizontal error at 95% confidence interval	0.03’	0.05’	0.07’	0.10’
Maximum allowable vertical error at 95% confidence interval	0.06’	0.10’	0.10’	0.15’
Repeat Station Observations percent of number of stations	100%	100%	100%	Only critical stations

GNSS Method	Static	Fast Static	RTK A	RTK B	RTK C
Min. No. of Sessions *	2	2	4 (2 before and after sidereal displacement)	2	1
Min. time between occupations (start time to next start)	3 hrs.	2 hrs.	2 hrs. or utilize a different base station **	None **	None
Min. Occupation Length	2 hrs.	20 mins.	180 sec.	180 sec.	5 sec.
Minimum. Satellite Elevation Mask for processing	15°	15°	15°	15°	15°
Minimum number of satellites utilized per epoch	6	6	6	6	6
Epoch Interval for data sampling during observation session	10 sec.	5 sec.	5 sec.	5 sec.	1 sec.
Maximum baseline length error at 95% confidence interval	0.025’ + 1ppm	0.025’ + 1ppm	0.025’ + 1ppm (base to rover)	0.04’ + 1ppm (base to rover)	0.05’ + 2ppm (base to rover)
Maximum setup error	0.005’	0.005’	0.007’	0.007’	0.01’

*Session for each station should have rotational difference of n degrees according to formula n = 360 / s where s is the number of sessions.

**Sidereal time recommended for RTK sessions. However, independent initializations may be substituted if deemed appropriate by the Surveyor, and unit should be re-initialized 15 ft. horizontally from station. Independent measurements should be averaged or weighted, with additional measurements added as needed. Outliers should be assessed/removed.

***Each project should have *at least* two Primary Control (Level II or better) points established via static method. Subsequent Level II control may be established via an RTK rover if either recommended sidereal time (two sessions with rotation and 15 ft. reinitialization**, then repeated following sidereal displacement) or a second base occupation (of another Level II point) is utilized. Both sidereal displacement and a second base occupation are recommended to be used in conjunction.

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RTK Note

The project surveyor should be aware of PDOP and baseline length as necessary according to equipment utilized and accuracy desired. With additional satellites tracked at the base and rover, lower quality signals and outliers are typically removed by software in the latest data collectors. Check shots must be observed and recorded by rover following base station setup and before base station is shut down. Control points for the purpose of RTK check shots may be set close to the base, and typical projects shall have an alternative control point to be used as a base.

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Use of RTN

Single-base and network-solution RTN may be substituted for single-base RTK methods, but baseline length, PDOP, RMS, and other factors must be factored into procedures to ensure adherence to accuracy standards. Three sessions or more are preferred per station, and additional checks, redundancies, and observation times must be implemented, especially for baseline lengths over 25 kilometers. In addition, the tracking of specific satellite constellations by the network and rover should be considered in either method.

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Vertical Note

Vertical maximum accuracies derived from GNSS, especially for CTDOT Level I, II, and III GNSS surveys, do not typically meet CTDOT vertical control standards. Therefore, digital leveling, or other leveling techniques, are generally required to produce relative elevations accurate to project control (See Location Manual Sec. 3.3 – Vertical Control Survey).

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H. Recommended GNSS Survey Field Procedures

CTDOT Level I GNSS Surveys

1. Static
2. Multiple control points – network
3. For corridor type control surveys, it is recommended to include single “drift” points approximately every 2500 feet.
4. Trimble Business Center (or a pre-approved alternative) is used to post process static data, providing X, Y and Z values for each control point.
5. All Z values are checked to bench marks set from fixed published bench marks local to the project area or to project through digital leveling
6. Additional checks and cross ties with RTN are preformed utilizing fixed local control.
7. OPUS Rapid-Static, OPUS Static or OPUS Projects utilized for additional independent/redundant verifications and checks to final values.
8. Final ephemeris should be used for post processing.

CTDOT Level II GNSS Surveys

1. Fast Static, Real-Time Kinematic (RTK).
2. Two or more control points per location.
3. *IF* there are no fixed published bench marks local to the project area, then the elevation of just one control point is held and additional bench marks are derived from it.
4. Additional checks with RTN are performed utilizing fixed local bench marks, horizontal (X, Y) and vertical (Z) local control.
5. Rapid ephemeris can be used for post processing.

CTDOT Level III GNSS Surveys

1. RTK, Real-Time Network (RTN).
2. Three control points per location.
3. The mean of the two sessions with their two rotations provide the final X, Y and Z values for each control point.
4. *IF* there are no fixed published bench marks local to the project area, then the elevation of just one control point is held and additional bench marks are derived from it.

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Short Baselines

Intervisible pairs of GNSS control points may be checked with an EDM, taking care to properly reduce field measurements for compatibility with inversed GNSS coordinates.

For extremely short baselines measured with static GNSS (less than 1 km [0.6 mi]), horizontal accuracies of 1 to 2 mm and vertical accuracies of 5 to 10 mm are possible. The surveyor should also be concerned with centering errors and antenna height measurement errors, as they will degrade accuracy. This will be especially apparent over very short baselines or between closely spaced points that are positioned radially, where the combined errors could exceed the relative accuracy requirements of the State standards.

When GNSS control surveys are densified with terrestrial surveys, such as traverses and leveling, GNSS and terrestrial measurements should be combined in a properly weighted least squares network adjustment.

In the network adjustment phase, only independent GNSS base lines will be utilized. Each unknown GNSS control point shall be connected to a minimum of two (2) independent base lines. Additionally, every reasonable attempt shall be made to observe two (2) sessions at each station in the network.

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Azimuth Pairs

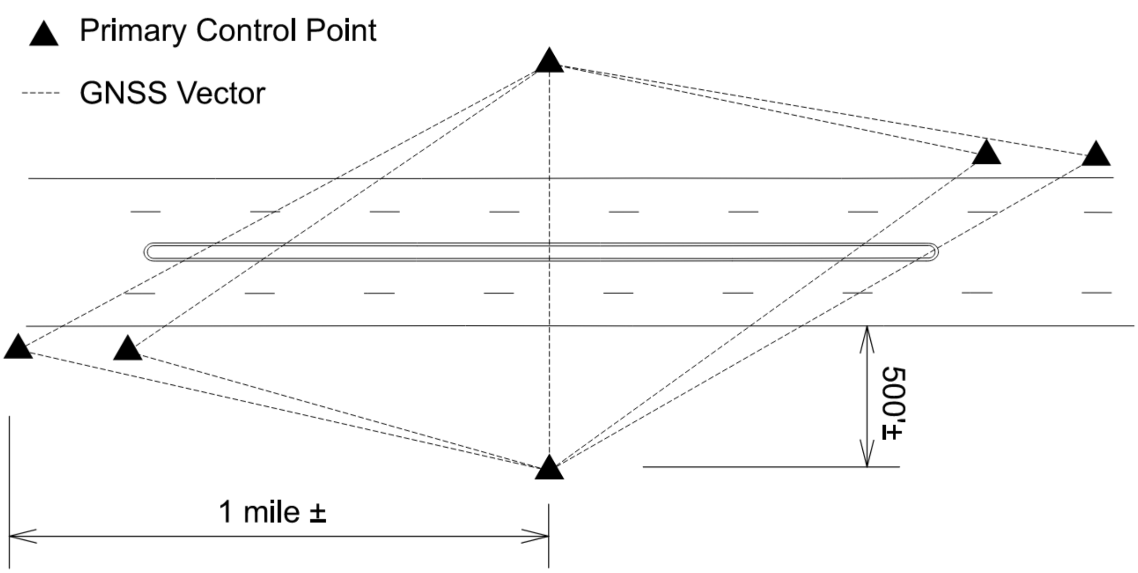
Azimuth pairs consist of a pair of intervisible Primary Project Control points, which allow for the use of Total Station with backsight. They also function as RTK base points with check shots. The control points in each pair shall be spaced at

750 ft. to 1000 ft. depending on field conditions, and they shall be set at a maximum of 2-mile intervals throughout the project area.

Primary Project Control shall be placed on either end of a linear project, intended for RTK GNSS base stations or conventional survey setup. The method of measurement shall be according to CTDOT Level II or better GNSS specifications. Furthermore, the project may be boxed or surrounded by Primary Project Control, especially if RTK or GNSS methods are intended to be utilized to measure Ground Control Targets and Validation Points (see CTDOT Specifications for Photogrammetry and LiDAR), perform additional map checking, or set Secondary Project Control.

A typical network design might include two primary control points set approximately 500' away from (measured approximately perpendicularly) from the linear corridor in either direction for each 2-mile linear project section (Exhibit B).

Exhibit B



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I. GNSS Information to be furnished to the Department for Review

Prior to acceptance by the Department of GNSS survey, the Consultant shall furnish to the Office of Central Surveys, a Control Report including the following information:

a) GNSS observation details, including start and stop times

b) Statistical summary

c) Weighting strategy

d) Observation adjustment with listed “a priori” and “a posteriori” standard deviations

e) Accuracy expressed at the 95% confidence interval

f) ORD drawing file and/or report containing station names/numbers, state plane coordinates with mapping angle and scale factor, ellipsoidal and orthometric elevations, latitude and longitude for all GNSS-surveyed points

g) OPUS report, if applicable, and any Rinex or other raw GNSS files utilized in adjustment

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