FDM 9-40-1 When Used
October 28, 1994

The scope of an improvement project will determine the need for a vertical control survey. As a general rule of thumb most improvement projects will require vertical control. The need for vertical control is becoming increasingly important for both design and construction applications. Vertical control provides a foundation for all aspects of engineering surveys such as drainage information, subgrade preparation, environmental documentation, etc. It is also vital during the construction phases in that it provides the control necessary for proper layout and quantity computations.

FDM 9-40-5 Classification, Standards and Specifications
March 14, 2016

Federal, state, and local governments, as well as private agencies make surveys, maps, and charts of various kinds that are referenced to national horizontal and vertical datums. In surveying it is necessary to establish frameworks of horizontal and vertical control so as to provide a uniform reference system with a certain stated degree of accuracy. To achieve uniformity among different agencies, certain classifications, standards and specifications must be defined and followed.

5.1 Reasons for Classification, Standards and Specifications

The primary reason for detailed classification, standards and specifications is to ensure that a desired accuracy is attained throughout a survey. This means that the accuracy is not only attained at the points of closures, but at all points in the survey. The accuracy is not accidental but is a true indication of the surveys precision. Standards and specifications will also create uniformity among surveys of the same classification. It would be impossible to achieve uniformity if surveyors use different standards and procedures for surveys of the same classification. In some instances standards and procedures may also help to prevent or minimize over-surveying. Under normal conditions, the procedures specified in this procedure will provide the closing and positional accuracies well within the standards specified.

5.2 Classification

Vertical control established by geodetic leveling methods by the Wisconsin Department of Transportation adheres to the classifications as set forth in this procedure. Attachment 5.1 details the recommended minimum classification requirements for vertical control established by geodetic leveling methods.

5.3 Standards and Specifications

Vertical control established by geodetic leveling methods by the Wisconsin Department of Transportation adheres to the standards and specifications as set forth in this procedure. Attachment 5.2 details the recommended standards and specifications for vertical control established by geodetic leveling methods.

LIST OF ATTACHMENTS

Attachment 5.1 Recommended Minimum Classification Requirements

Attachment 5.2 Standards and Specifications for Vertical Control

FDM 9-40-10 Vertical Control Data Base
March 14, 2016

The present vertical control network consists of a hierarchy of interrelated networks throughout the state. Adjusted vertical NGRS data for Wisconsin is published for the NGVD 29 and NAVD 88 datums. The hierarchy is broken down into First, Second and Third Order geodetic quality benchmarks. The vertical datum to which the project will be tied should first be determined. Specifications and procedures for First, Second and Third Order leveling projects are detailed in Federal Geodetic Control Committee publication entitled "Standards and Specifications for Geodetic Control Networks" (1984) and is available at:

http://www.ngs.noaa.gov/FGCS/tech_pub/1984-stds-specs-geodetic-control-networks.htm

10.1 First-Order (Primary Network)

This class of benchmarks consists of benchmarks established approximately 2 km apart along lines of leveling throughout some parts of Wisconsin. The level lines generally follow railroad alignments and provide the most accurate base for further densification of vertical control.

10.2 Second-Order (Secondary Network)

This class of benchmarks consists of benchmarks established approximately 2 km apart along lines of leveling spaced 10 to 50 km apart throughout Wisconsin. The level lines generally follow railroad alignments and provide an accurate base for further densification of vertical control.

10.3 Third-Order (Local Vertical Control)

This class of benchmarks was established to meet local needs for engineering and mapping projects. It is currently the densest network of benchmarks and is documented by level lines contained within the 15-minute quadrangles throughout Wisconsin.

The current database for most vertical control throughout the state is derived from hard copy format obtained from sources such as the NGS, State Cartographer's Office, United States Geological Survey (USGS) and various local agencies.

10.4 Project Order (Project Specific Vertical Control)

This class of benchmarks is established to meet the project specific needs where the region survey coordinator has determined that a transportation improvement project requires additional vertical control where the additional control does not have to meet the specifications for Third Order vertical control or above.

Project Order leveling projects for Wisconsin Department of Transportation (WisDOT) transportation improvement projects shall be tied to the Wisconsin height modernization program (HMP) network of geodetic survey control stations. The HMP stations are surveyed to Second Order Class I specifications.

Every project order level loop shall begin and end on a height modernization program station. It is desirable that the leveling crew level to other HMP stations that are along the level loop routes of a project to provide additional data checks. It is good surveying practice to observe any non HMP bench marks that are easily recoverable along a level loop route to provide additional usable bench marks and data checks.

Additional project order leveling specifications can be found in Attachment 5.1 and 5.2. Other questions not covered by these procedures can be answered by the region survey coordinator in consultation with the central office surveying and mapping section.

FDM 9-40-15 Field Reconnaissance

March 14, 2016

Elevations for WisDOT improvement projects shall be referenced to the Wisconsin Height Modernization Program (HMP) passive network bench marks. The elevations for HMP bench marks are found in the National Spatial Reference System (NSRS) database of the National Geodetic Survey (NGS). On line access to this information is found at:

http://www.ngs.noaa.gov

The NGS database provides elevation data in the most current vertical datum and adjustment as well as any superseded values for bench marks nationwide.

The Wisconsin State Cartographer’s Office (SCO) website has a control finder application that will help the user to identify vertical bench marks that are in a given project area. Control finder can be found at:

http://www.sco.wisc.edu/controlfinder/controlfinder.html

The user should be cautious when using the control finder application because elevations for some non NGS station (e.g. USGS or County Control Stations) are not automatically updated to the latest NGS datum and adjustment.

The first step when performing the field reconnaissance is recovery of geodetic control survey stations for the project. A visual inspection of the station should be made in order to verify the monument description and whether it may have been disturbed. Any discrepancies or disturbances should be noted. Stations in the NGS database that are discovered to be destroyed or unusable should be reported to the appropriate NGS regional advisor. The advisor will take the necessary steps to confirm the station information and if necessary, remove it from the NSRS database.

As a part of the field reconnaissance, prepare field sketches that accurately depict the positions of existing First, Second or Third Order vertical control and the planned location of the Third Order or Project Order stations to be established. These sketches should show the lines, point numbering sequence and interconnections that are to be measured on all primary, secondary and supplemental control points. USGS quadrangle maps, aerial base documents or rough scaled hand sketches are useful for this purpose. Sketches or digital images of all elevation stations set or used in the course of a leveling project should be documented.

FDM 9-40-20 Field Procedures *March 14, 2016*

Leveling is the term applied to any of the various processes by which elevations of points or differences in elevation are determined. It is a vital operation in producing necessary data for planning, mapping, design and construction. The most common method used in leveling is differential leveling. Some differential leveling techniques are as follows:

20.1 Single Run Double Simultaneous Leveling

This technique uses two parallel, independent foresight and backsight turn points for each IH. Each pair of turn points is set, if possible, at an appreciably different elevation (0.5 foot (150 mm) or more). They are also set a few feet apart so the level will have to be rotated slightly between the two rod readings. This provides a check on the instrument setup if each Instrument Height (IH) elevation agrees for the two lines. From each setup, single wire rod readings are recorded on both backsight and foresight turn points. The adjusted elevations for benchmarks from the two lines are then averaged.

20.2 Double Run Leveling

With this technique a double line of levels is run through a single line of turn points. At each setup site, two independent IH's are established at approximately 0.5 foot (150 mm) difference. From each IH a single wire rod reading is obtained on the single backsight and foresight turn point. The average adjusted elevations from the two lines are then used.

20.3 Three Wire Leveling

This technique utilizes the stadia cross hairs located within the optics of most leveling instruments. Each backsight and foresight is recorded by reading the upper and lower stadia hairs in addition to the horizontal cross hair. The three readings thus obtained are averaged to obtain the desired value. The stadia hairs are positioned an equal distance above and below the horizontal cross hair and are usually spaced to give 1.00 units of interval for each 100 units of horizontal distance between the rod and the level. This method is self checking and the accuracy of a three wire level run is equal to the mean of three lines of single wire levels through the same turn points.

20.4 Single Wire Leveling

A single line of levels is run through a single line of turn points with this method. This method provides no redundancy in observations and does not allow for discovery of errors before moving forward during the leveling procedure. This method should be used only for WisDOT project order vertical control surveys.

20.5 Reciprocal Leveling

The surveyor should always try to keep backsight and foresight distances equal during differential leveling so that instrument and natural errors cancel out. In some situations, such as river or valley crossings, this is not always possible. The reciprocal leveling technique should then be utilized; this technique is illustrated in Figure 20.1 below. The level is set up and readings are taken on TP3 and TP4. (Precision can be improved if multiple readings are taken on the turn points and then averaged.) The instrument is then moved to the other side and the process is repeated. The differences in elevation thus obtained are averaged to obtain the final result. The averaging process should eliminate instrumental and natural errors such as curvature and refraction.

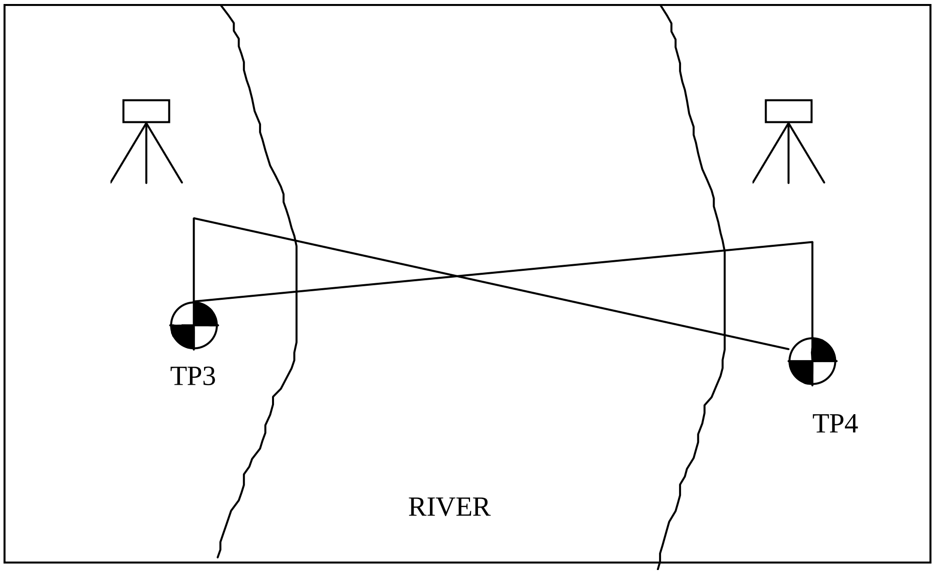

Figure 20.1. Illustration of Reciprocal Leveling Technique

20.6 Trigonometric Leveling

The use of a total station as a level increases acceptable distances on sight lines and can increase production in many situations. The difference in elevation between any two points can be determined if the vertical angle (VT) and slope distance (DS) of the line from one point to the other are measured. With modern total stations, the elevation difference can be calculated automatically but an understanding of the formulas used and what the different combinations of Instrument Height (IH) and Staff Height (SH) will produce in the form of displayed or recorded results is necessary. Figure 20.2 below shows a total station measuring a slope distance and vertical angle.

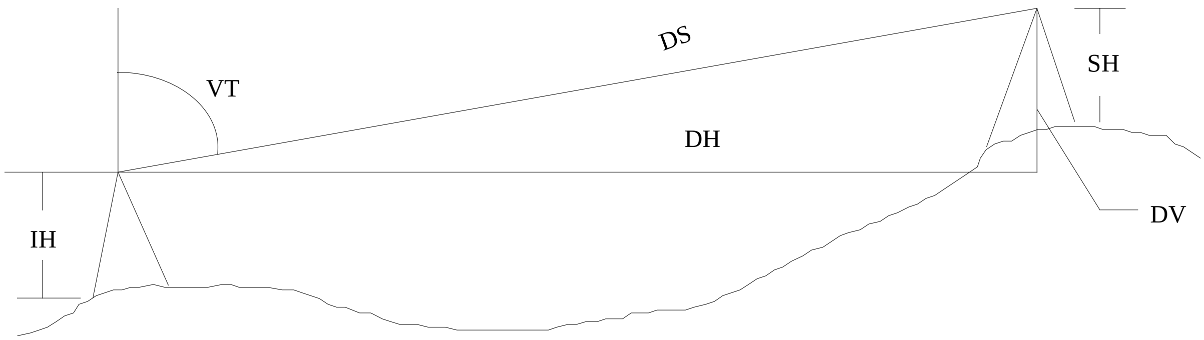

Figure 20.2. Illustration of Slope Distance & Vertical Angle

The vertical distance, (DV), can be determined by the equation:

DV = DS * cos (VT)

If the ground elevation at the instrument is known,

Ground Elev @ Target = Ground Elev @ Instr + IH = DV – SH

In order to get elevation difference from ground-point to ground-point, the IH must be added and the SH subtracted from the DV. The keys to success in running trigonometric elevations is to take the mean direct and reverse readings of the vertical circle, limit sight distances to less than 1000 ft (300 m), and use proper targeting. Deviations from these procedures can result in large errors due to the effects of earth curvature and refraction.

20.7 Digital Leveling

Advances in electronics now enable surveyors to perform differential leveling with an electronic digital level. The digital level processes an electronic image of a bar coded staff for determination of heights and distances with automatic recording of the data for future processing on a computer. The digital level is an automatic level (pendulum compensator) capable of normal optical leveling with normal graduated staffs. The level can also be used with the bar coded staff and rod readings obtained digitally with output units in either metric or Standard English units.

20.8 Curvature and Refraction

All rod readings taken with a level will contain small amounts of error due to earth curvature (c) and refraction (r). The curvature of the Earth appears to make the rod 'fall away' as one gets farther from the instrument and causes the surveyor to read higher on the rod than intended. Refraction is created when sight lines are curved downward by the earth's atmosphere and temperature gradients and causes the surveyor to read lower on the rod than intended. Normally, the effects of earth curvature (c) and refraction (r) partially offset each other with curvature being the larger value. Curvature and refraction errors can be negated by balancing backsight (BS) and foresight (FS) distances, causing the errors to cancel out or by taking short site distances (less than 1000'). For the most part this error is small but it could be a problem on long level lines where BS and FS distances are not balanced.

Figure 20.3 below depicts the effects of curvature and refraction:

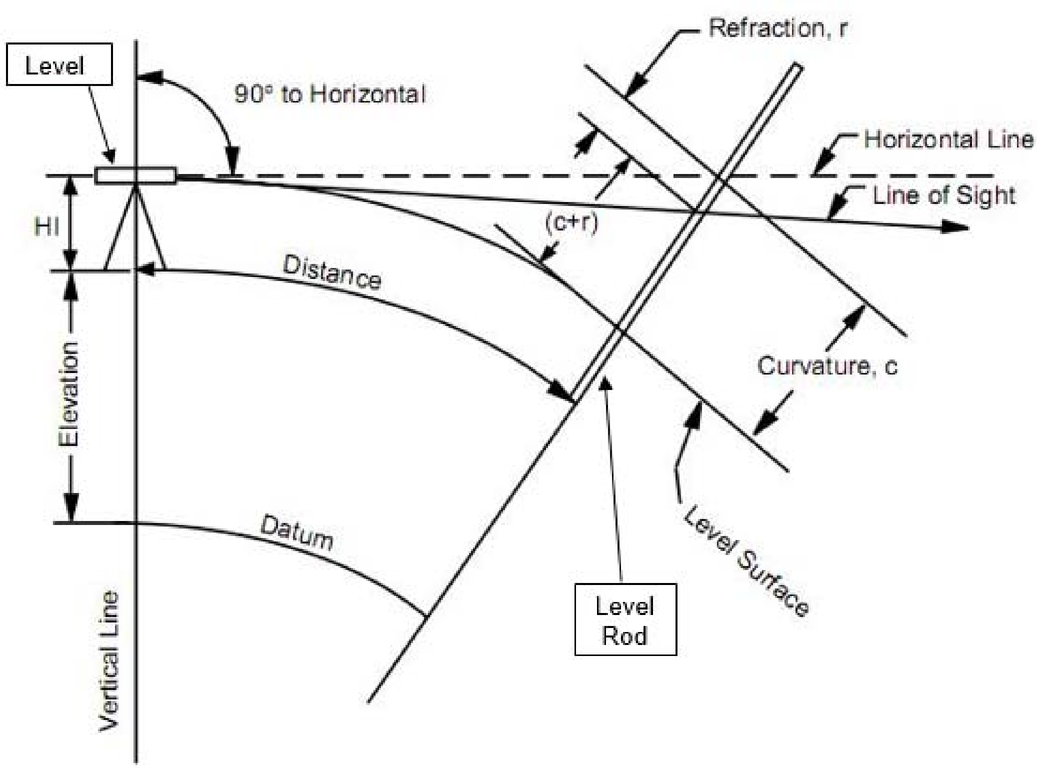

Figure 20.3 Effects of Curvature and Refraction

20.9 Peg Test

In order to measure precise elevation differences with a geodetic level it is important that the axis of sight be perpendicular to the vertical axis. A simple procedure to test and adjust for this error is termed the peg test and should be performed frequently on geodetic levels.

To perform the peg test, the surveyor first places two stakes at a distance of 200 to 300 ft (60 to 90 m) apart. The level is set up midway between the two stakes and rod readings are taken at both locations (see Figure 20.4).

If the line of sight through the level is not horizontal, the error in rod reading (E1) at both points A and B will be identical as the level is halfway between the points. Since the errors are identical, the calculated difference in elevation between points A and B will be the true difference in elevation.

The level is then moved to one of the points (A) and set up so that the eyepiece of the telescope just touches the rod as it is being held plumb at A. The rod reading at A can then be determined by sighting backward through the objective lens at a pencil point that is being slowly moved up and down the rod. The reverse rod reading at A is then recorded and a normal rod reading at B is obtained. This computed elevation difference is then compared to the true elevation difference obtained from the first set up. The difference, if any, between the computed and the true elevation difference is the error to be corrected by adjustment. Refer to the instrument's user manual for proper adjustment procedures.

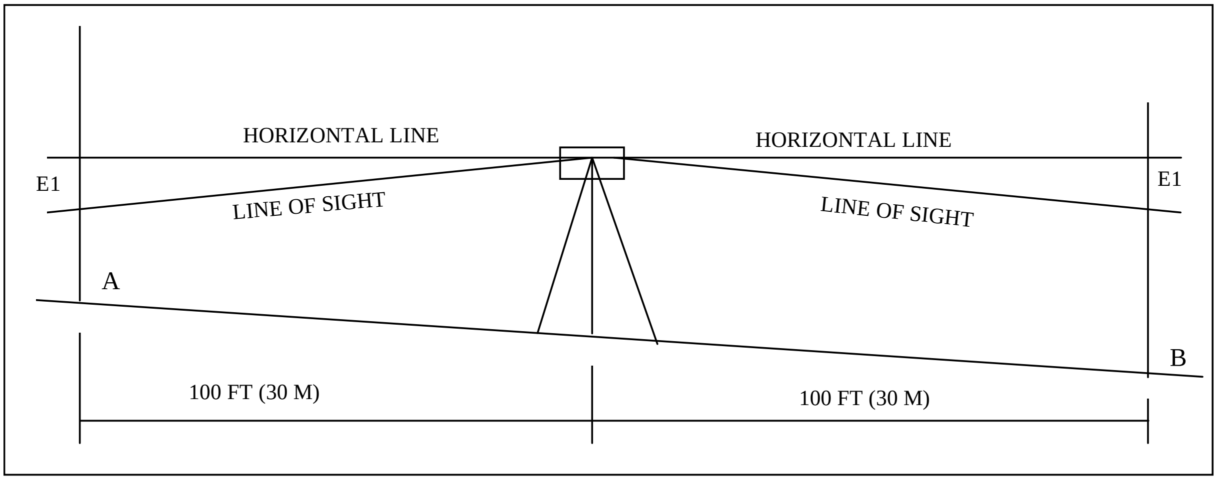

Figure 20.4. Peg Test Demonstration

20.10 Data Collection

The following items should be noted and recorded as project metadata while performing vertical control survey work for the department:

1. Project Header Information
   - Task (type of leveling, e.g. single-wire leveling, 3-wire leveling, trig, etc.)
   - Project ID
   - Project description
   - Time, date and crew
   - Weather conditions, temperature and barometric pressure
   - Units of angles, length, temperature and pressure
   - Instrument type and serial number
   - Curvature and refraction settings

   Note: The data collector can be designed to prompt or measure the above information. The list above provides some of the necessary information for further computations and can be supplemented with additional information as desired.

2. Occupied Station Entries
   - Station/bench mark name and/or number
   - Point description (e.g. RR SPIKE IN 13" DIA OAK, brass WisDOT disk, etc.)
   - Other description information about station, (such as reference ties, bridge number, etc.)
   - Instrument height (applicable during trig leveling)
   - X, Y, and Z coordinates if known (optional)

   Note: The differential leveling tasks always begin with an occupied station activity and a backsight activity to establish an elevation at the first instrument setup. The tasks then proceed to side shot activities to establish or carry forward other elevations. Coordinates may be entered into a system control file for access just before field data reduction and adjustment if desired.

3. Sighted Station Entries (BS, FS, TP etc.)
   - Station/bench mark name and/or number
   - Point description (e.g. CHIS '+' IN CONC STEP, brass WisDOT disk, etc.)
   - Other descriptive information data about station (such as reference ties, fire number or building

address, etc.)
- Staff height of rod or tripod (applicable during trig leveling)
- X, Y, and Z coordinates or fixed azimuth if known (optional)
- Measured data such as rod readings, horizontal and vertical angles and slope distances

Note:The recording of the above information will provide enough information for field data reduction, analysis and adjustment and can be supplemented with additional information as desired.

Once all the necessary data has been collected, the field crew can perform some preliminary calculations to check closure specifications while out in the field. After it has been determined that the field work meets the desired accuracy specifications, all data including any field sketches or supplemental notes should be turned over to the appropriate individual for download to PC, final adjustment, transmittal to others and archival.

FDM 9-40-25 Computations

October 28, 1994

The department currently uses a variety of software packages and computer programs for data reduction and adjustment of vertical control. The correct method of operation of each package or program is described in the appropriate user manual for each. This procedure describes some of the fundamental computations that the above programs accomplish as well as provides some general guidelines for proper vertical control adjustment.

25.1 Single-Wire Adjustment

Single-wire level runs should be adjusted between two consecutive control benchmarks. The misclosure between the control benchmarks is prorated to each turning point or set of turning points. The formula for adjustment of elevations is as follows:

$$\text{Adjustment} = \text{Misclosure} * \frac{\text{Number of T'Ps to a Given TP}}{\text{Total Number of T'Ps}}$$

TP = Turning Point

25.2 Three-Wire Adjustment

The adjustment of elevations of a three-wire level circuit is based on the length of sections. A section is defined as the level run between any two benchmarks (controlling or new). The sections should be arranged in the order that the level line was run, because the computations of a line of levels is a progressive calculation. The length of a section and/or sight in meters or feet is computed by multiplying the total stadia intercept by the stadia constant for the particular instrument used.

The misclosure between the control benchmarks is adjusted proportionately to the section lengths. If the section lengths are accumulated between control benchmarks, the adjustments can be expressed in accumulated values to simplify the calculations. The formula for adjustment of elevations is as follows:

$$\Sigma \ \text{Adjustment} = \text{Misclosure} * \frac{\Sigma \ \text{Section Lengths}}{\text{Length Between Control BM's}}$$

25.3 Least Squares Adjustments

Primary level circuits involving multiple loops and/or redundant observations should be adjusted by the least squares method. In a least squares adjustment, the "best" solution is defined as the solution producing the smallest change to the original field measurements. These changes between the best-fit measurements and the original field measurements are called residuals. This method, based on the theory of probability, simultaneously adjusts the elevation differences of each separate line in the level circuit to make the sum of the squares of the weighted residuals a minimum. The corrections sought are those that produce the highest probability of their simultaneous occurrence in the level circuit.

The ability to weight individual measurements is available in the least squares package. This gives the user the extra control needed to provide the overall best adjustment. Each observation (elevation difference) can be assigned an individual weight, either mathematically derived based on the length of line or number of turn points or could be assigned a constant based on the type of instrument, method of measurement or skill of the field crew. Lower weights can be given to less accurately known field data while higher weights can be given to observations that are more accurately known. During the adjustment, larger changes will be assigned to the less accurate data, minimizing the changes to the more accurate data.

Least squares also provides a complete analysis of the survey, including a statement on the positional accuracy of each computed point, and a list of residuals for all measurements. This analysis can help in the detection of survey blunders and areas in need of improvement. It can also assist in the preplanning of subsequent surveys. In addition, the least squares method provides a number of significant advantages over other adjustment methods:

- It computes a single solution, no matter how complex the survey.
- It does not distort field data.
- It allows more flexibility during data collection - data may be collected in any order and configuration.

The least squares method of adjustment is incorporated within the department's Polsast mainframe program and the CAiCE software package. Consult the appropriate user manual for the correct operation of each.

25.4 Accuracy Evaluations

One of the tests used to evaluate the accuracy of a vertical control circuit is to check the amount of misclosure at checkpoints or control benchmarks. The amount of misclosure is expressed in units of length and is evaluated for conformity to the desired specifications as detailed in FDM 9-40-5. The analyst should also verify conformance to the other specifications listed in FDM 9-40-5 such as minimal observation method, maximum sight distances and three-wire stadia differences.

Deviations from the desired specifications will require some further investigation into the source of the problem. If the least squares adjustment method was used the analyst should observe the residuals and error ellipses for each point in the survey. This, along with other blunder detection methods, can help to uncover errors within the survey.

FDM 9-40-35 Monumentation

March 14, 2016

All third-order and project vertical control stations shall be monumented in accordance with FDM 9-25-10, usually within department owned right-of-way. For each benchmark that is established, a description should be prepared. Standard information to be recorded includes project identification, point number, general location, specific location, and descriptive information. Additional information such as vertical datum, adjusted elevation, stationing, and other project related information may be added after adjustment computations are complete.

General location information should adequately describe how to drive or walk to the benchmark from nearby landmarks or roadways and include references to a mapped highway or street, city or village, and county. General location information should also include at least one of the following types of horizontal information:

- The Global Positioning System (GPS) geographic coordinates (latitude and longitude to at least the nearest second of arc);
- A grid coordinate value (X,Y) or ground coordinate value (N,E) of any rectangular coordinate system detailed in FDM 9-20-25.3.
- Project stationing and offset from the reference line; or
- The township, range, section, and quarter-section.

Specific location information should include the distance (usually less than 100 ft) and direction from the centerline of at least one roadway (highway, street, railroad track, etc.), and the distance (usually less than 100 ft) and direction from at least two nearby prominent features (roadway, building, bridge, culvert, pole, tree, etc.).

Descriptive information should describe the type of marker/monument used as the benchmark (e.g., a chiseled square on the north end of the east bridge abutment, a bronze C&GS benchmark disk stamped E 10 1930 set in a concrete post).