Facilities Development Manual

Wisconsin Department of Transportation

Chapter 9 Surveying and Mapping

Section 35 Horizontal Control - Traverse

FDM 9-35-1 When Used *February 28, 2001*

The scope of an improvement project determines the usefulness or need for a horizontal control survey. However, for all projects, U.S. Public Land Survey System (PLSS) corners shall be identified and perpetuated in accordance with FDM 9-25-1.

Horizontal control surveys are recommended for projects where there is significant land acquisition or realignment of the facility. All projects where accurate center line surveys are established should be tied to the Wisconsin County Coordinate System (see FDM 9-5-10 and FDM 9-20-27).

Horizontal control surveys and reestablishment of PLSS corners are not required for projects where no land acquisition or realignment of the facility are planned. Examples of this type of work are a resurfacing project or a project to improve the operating characteristics of an intersection.

FDM 9-35-5 Classification, Standards and Specifications *October 28, 1994*

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 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. Thus, 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 survey's 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

Horizontal control established with conventional survey methods by the department adheres to the classifications set forth in the Federal Geodetic Control Committee publication, "Standards and Specifications for Geodetic Control Networks," as reprinted in October 1990, or subsequent revisions thereof. Attachment 5.1 details the recommended minimum classification requirements for horizontal control established by conventional surveys.

5.3 Standards and Specifications

Geodetic control established by the department adheres to the standards and specifications as set forth in the Federal Geodetic Control Committee publication, "Standards and Specifications for Geodetic Control Networks," as reprinted in October 1990, or subsequent revisions thereof. Attachment 5.2 details the recommended standards and specifications for horizontal control established by conventional traverse surveys.

LIST OF ATTACHMENTS

Attachment 5.1	Recommended Minimum Classification Requirements
Attachment 5.2	Standards and Specifications for Horizontal Control

FDM 9-35-10 Horizontal Control Data Base *October 28, 1994*

The National Geodetic Reference System (NGRS) and the Wisconsin High Precision Geodetic Network (WHPGN) are mathematical reference systems consisting of precisely measured networks of geodetic control points. Each provides a link between the physical earth and the mathematical coordinate systems of latitude, longitude and elevation. The National Geodetic Survey (NGS), U.S. Geological Survey (USGS), Wisconsin Department of Transportation and various local agencies are currently involved in establishing and perpetuating geodetic control throughout the state of Wisconsin.

10.1 The National Geodetic Reference System: NAD 27

The NGS publishes and makes available to surveyors location diagrams and complete descriptions of all their geodetic control adjusted to NAD 27 (North American Datum of 1927). Location diagrams are printed on a blue line planimetric base of the 1:250,000 scale map series. Each diagram spans one degree of latitude and two degrees of longitude, or an average of about 6,500 square miles per sheet. The work of the NGS is shown in black, the USGS in red, and other federal agencies in brown. These control diagrams provide a cartographic index of the available geodetic data. The quadrangle code number appears in the upper right-hand corner of the data sheets along with the station number identification.

The data sheets give general placement in relation to nearby towns and specific positions by means of distances and directions to several nearby reference monuments. The horizontal control descriptions generally include the station's geodetic latitude and longitude, state plane coordinates, distances to observed stations and azimuths to azimuth marks. Azimuths listed for lines that were not observed are enclosed in parenthesis. Distances were seldom measured to azimuth marks, so their positions are usually not available. The azimuths are computed clockwise from south (south is zero azimuth) and distances are reduced to mean sea level.

The state plane coordinates listed on the data sheets are computed from adjusted geodetic positions using the projection tables. Plane coordinates of stations that are near state boundaries or near the boundary between two zones are computed in both states or both zones, the normal overlap being about ten miles. The theta (Q) or delta alpha (D a) angle is the angle between the meridian and the north-south grid line at the station. This angle may be applied to the geodetic azimuths to obtain the corresponding grid azimuths. This is expressed mathematically by the following equation:

Grid Azimuth = Geodetic Azimuth - Theta (or Delta Alpha) Angle

Occasionally the position of a control station will be indicated as "No Check," that is, no observational check. Positions determined from the intersection of only two lines or from a spur traverse measurement are considered "No Check." The note "Checked by Vertical Angles Only" may appear occasionally on a position that would otherwise be "No Check," but the agreement of the two elevations determined by vertical angles is fair proof that the lengths are satisfactorily determined and the position probably correct. However, positions indicated as "No Check" or "Checked by Vertical Angles Only" should be used with caution.

The data sheets also contain notes of the height of the telescope above the station mark when the station was occupied, the height of the light above the station mark when the station was observed from other stations, and a table of objects that can be seen from the ground at the station, including the distance and direction to each reference mark. This information makes possible the recovery and verification of the monument's position and a determination of available azimuth orientation. The standard numbered notes on the left side of the data sheet give information on the type of monument and whether an underground mark was set at the station. Special publication No. 247, page 121, "Manual of Geodetic Triangulation," National Geodetic Survey, describes each standard numbered note. If the station surface monument and its references have been obliterated, the standard numbered notes should be consulted to determine if excavation for an underground mark should be undertaken.

Although the NGS is the primary source of geodetic horizontal control adjusted to NAD 27, there are a number of other sources that should be investigated before performing a field reconnaissance. These include the Transportation region files, Technical Services Section, regional planning agencies, county surveyors and mapping and photogrammetry firms. The State Cartographers Office is also a potential source of information.

10.2 The National Geodetic Reference System: NAD 83 (1986)

The Wisconsin Department of Transportation has not, and never will, use horizontal control on projects adjusted to NAD 83 (1986). This system is used as an intermediate step to convert NAD 27 data to NAD 83 (1991) data.

10.3 The National Geodetic Reference System: NAD 83 (1991)

The Wisconsin High Precision Geodetic Network (WHPGN) is a network consisting of 80 primary stations located 50 km apart throughout the state and 18 secondary stations that form ties to the National Geodetic Reference System (NGRS). Each station was surveyed using GPS differential survey techniques to a relative accuracy of 1 part in 1,000,000 (Order B). The National Geodetic Survey has adopted, adjusted and published values for all stations of the WHPGN, as well as First and Second Order NGRS stations. Nomenclature for stations of the WHPGN is NAD 83 (1991), (the North American Datum of 1983, 1991 Adjustment).

A cartographic map of Wisconsin showing location diagrams of the WHPGN horizontal control stations can be obtained from the Wisconsin State Cartographer's Office. Subsequent maps will also be made available as further densification of the WHPGN takes place. Location diagrams of First and Second Order NGRS horizontal control stations tied to the WHPGN can be obtained from NGS.

Data sheets for NAD 83 (1991) individual horizontal control stations can be obtained from the State Cartographer's Office:

State Cartographer's Office
University of Wisconsin-Madison
550 N. Park Street
Room 160 Science Hall
Madison, WI 53706-1404
(608) 262-3065

For large orders of data contact:

NOAA
National Geodetic Survey, N/CG174
Silver Springs, MD 20910-3282
(301) 713-3242

Attachment 10.1 is a sample data sheet for a typical horizontal control station and an explanation of the data sheet terminology.

LIST OF ATTACHMENTS

Attachment 10.1	Sample Data Sheet for Typical Horizontal Control Station

FDM 9-35-15 Field Reconnaissance

October 28, 1994

The first step when performing the field reconnaissance is recovery of the horizontal control stations. The horizontal datum for the project will determine which horizontal control data base should be searched for available control stations. After determining the control stations that will be utilized, the field recovery of the control stations can begin.

15.1 Recovery of Horizontal Control Stations

A visual inspection of the control station should be made in order to verify the markings on the cap and whether the monument has been disturbed. Any discrepancies or disturbances should be noted. To verify the position of a horizontal control station, observations and measurements to the reference marks should always be made. The observations to the reference marks should generally agree within stated accuracy of the reference ties. Whenever these limits are exceeded, some consideration should be given to notifying the NGS and the WisDOT Technical Services office. Unpublished information may resolve a particular problem or, if deemed necessary, further investigation into the problem will be required.

15.2 Horizontal Control Survey Configuration

There are two basic types of traverses: closed and open. There are two categories of closed traverses: polygon and link. In a polygon traverse, as shown in Figure 15.1(a) the lines return to one of the starting points, thus forming a closed figure (geometrically and mathematically closed). Link traverses, as shown in Figure 15.1(b) finish upon another control station with a positional accuracy of the survey desired (geometrically open and mathematically closed). Link traverses must have a closing reference direction. An open traverse (geometrically and mathematically open), as shown in Figure 15.1(c) begins on some known control station but never returns, this offers no means of checking for errors and mistakes and should be used with extreme caution. A closed traverse provides checks on the measured angles and distances. This method should be used extensively for control, construction, right-of-way and topographic surveys.

The optimum closed traverse design is a series of intervisible secondary points equally spaced in a straight line between known primary control stations. If loops are involved, the configuration should be in the form of squares or slightly rectangular. In selecting the secondary points, every effort should be made to space them at the maximum practical distance. Proper design of the traverse makes it possible to analyze errors and associate them with either the distances or the angles. In a traverse that generally runs west-east, an error in "X or Easting" can be related to the distances and an error in "Y or Northing" can be related to the angles.

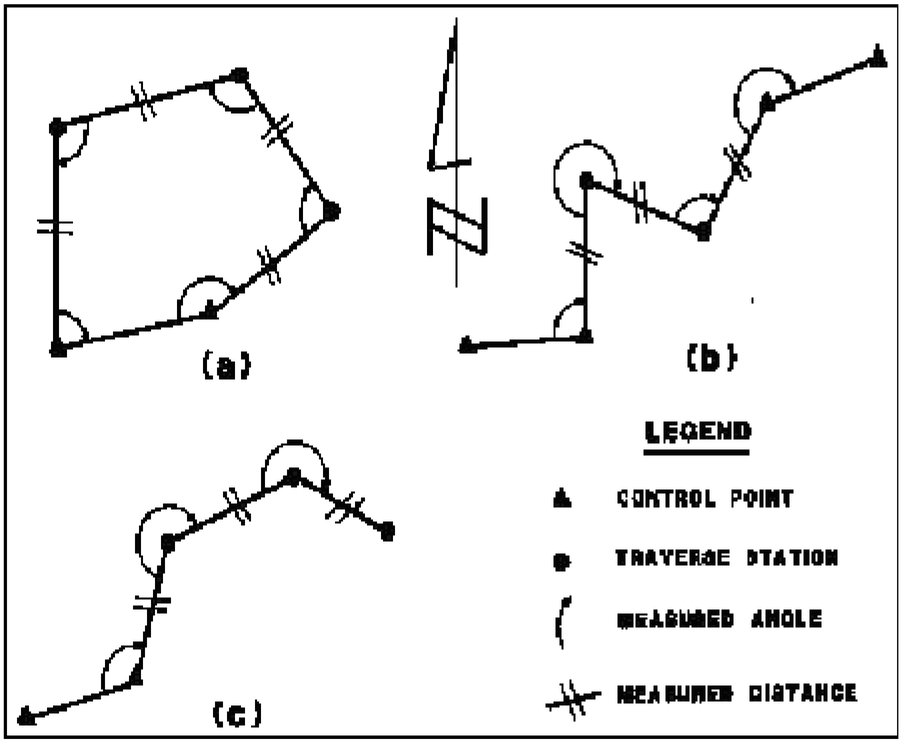

Figure 15.1. Types of Traverses

15.3 Field Sketches

As a part of the field reconnaissance, prepare field sketches that accurately depict the positions of existing primary control and the planned location of secondary control points. 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.

FDM 9-35-20 Field Procedures - Distance Measurement

October 28, 1994

20.1 Electronic Distance Measurements

The WisDOT currently has a variety of different electronic total stations that have the capability of measuring distances with an electronic distance measurement device (EDM) attached or built in to the instrument. The correct method of operation of each instrument is described in the manufacturer's operating manual that accompanies each instrument. This procedure describes the elements of precision distance measuring which are common to most EDMs.

20.2 Principle of Measurement

The underlying principle of modern EDM systems is based on the speed of light. A light source is modulated and transmitted at a very high frequency from the source (electronic total station) to a distant reflector (prism). The reflector returns the light to the receiving optics of the instrument and these light pulses are no longer in phase with the outgoing light pulses because it has taken a certain amount of time to travel from the instrument to the reflector and back again. These light pulses are converted to an electrical signal that is then compared to a reference signal and a resulting phase delay can be measured very accurately. This phase delay can then be related to a distance between the instrument and the reflector. Other methods are used such as timing the light pulse but the phase delay is currently the most popular among EDM manufacturers.

20.3 Sources of Error

Sources of error in EDM work can be categorized as either human, instrumental or natural. Human errors include misreading, improperly setting over stations, improper input of prism offset and incorrectly measuring meteorological data, staff heights and instrument heights. With careful field procedures these errors can be eliminated.

If EDM equipment is carefully adjusted and precisely calibrated, instrumental errors should become extremely small and thus negligible. Manufacturers specify the accuracy of an EDM with a two-part number, such as ±- (5 mm + 5 ppm). The first number, ±5 mm, means that at any distance, the EDM can have a spread in distance measured of up to 5 mm from the mean distance. The second number, ±5 ppm, is a proportional error which varies with the distance measured. These numbers can change over time and should be periodically verified against a calibrated base line. The National Geodetic Survey, in cooperation with the WisDOT and the Wisconsin Society of Land Surveyors, has established eight calibrated base lines throughout the state near the transportation region offices. When the reduced measurements (compared with the published values) agree within the instrument manufacturers stated accuracy, the instrument can be considered as being in good calibration.

Natural errors in EDM operations stem primarily from atmospheric variations in temperature and pressure. The speed of light through the atmosphere changes with temperature and pressure. If the incorrect temperature and/or pressure are entered, the distance displayed will not be correct. To record the proper distance, air temperature and pressure should be measured and a ppm correction computed. Air temperature should be measured in the shade and well above the ground to reduce the effects of ground radiation. Barometers should be calibrated periodically at the local airport. Barometric air pressures announced on the local radio station have traditionally been reduced to mean sea level. Air pressure readings for corrections to EDM distances must be absolute pressure at the station sites. As a rule of thumb, for every 90 feet above sea level the air pressure drops 0.10 inch. For long lines and lines of great elevation difference between the end points, temperature and pressure readings should be measured at both ends.

20.4 Prisms

Prisms are used with total stations to reflect the transmitted signals. A single prism is a corner cube of glass that has the characteristic of reflecting light rays back precisely in the same direction as they are received. Prisms are contained in a plastic or metal housing which can be tribrach mounted on a tripod and centered over a ground point with the aid of an optical plummet, or they can be attached to a telescoping range pole held vertical on a point with the aid of a bull's eye level. It should be noted that prisms should be tribrach mounted if the highest level of accuracy is desired. In control surveys, tribrach mounted prisms can be detached from their tribrachs and then interchanged with the total station. This interchangeability of prism and total station is known as “forced centering" or "leap frogging,” which not only speeds up work but also increases accuracy.

Manufacturers of prism assemblies specify a certain offset that must be accounted for when measuring distances. This offset is caused by not having the effective center of the prism in a direct plumb line over the ground point. This offset distance, usually expressed in (mm), must be added or subtracted from the measured distance. All EDMs have the capability for the user to input the proper offset that will be compensated for automatically before the distance is displayed. It is not good practice to mix prism assemblies of different types or manufacturers. Refer to manufacturer specifications for the correct offsets of prism assemblies.

Total stations are classified as either coaxial or modular. A coaxial total station has the EDM line of sight in the same plane as the optical line of sight while a modular total station will have an EDM line of sight above the optical line of sight. The coaxial configuration is easier to use. When a distance is to be measured, the cross hairs in the telescope are pointed at a target centered about the prism. Conversely, a total station of the modular type must use the proper prism and prism-target assembly to account for the difference in the EDM line of sight and the optical line of sight. Most instrument manufacturers provide prism target assemblies to account for their particular configuration.

20.5 EDM Operation

The operation of all EDMs involves the following basic steps: (1) setup, (2) aim, (3) measure, (4) record. It should be noted that most EDMs are interfaced with an angle measuring instrument and the combination of these capabilities results in an instrument termed the Total Station. Refer to the instructions that accompany the EDM device.

The measured data can be recorded conventionally in field book format or preferably in the AASHTO SDMS electronic data format on an electronic data collector. The slope distance must be accompanied by all necessary data to properly reduce it to a horizontal distance component.

20.6 Data Collection

All EDM equipment measures slope distances between stations. Reduction of slope distances to horizontal distances is necessary for proper adjustment and can be based on difference in elevations or determined from zenith angle observations. For precise distance measurements, measure and record all instrument heights, staff heights, slope distances, zenith angles, point identification numbers, meteorological data, and prism offsets electronically in the AASHTO SDMS data format. When horizontal distances are computed by zenith angle observations, the measuring of instrument and staff heights allows for computation of the trigonometric elevation of station points. For precise work measure the zenith angle from both ends of the line in direct and reverse modes and then average each. For detailed instructions on how to reduce slope distances to horizontal distances (See FDM 9-35-30).

20.7 Taping

When performing precision taping, hold the tape horizontal and use a plumb bob at one or perhaps both ends. It is recommended to break tape when plumb lines exceed chest height. A specified tension, generally 15 lbs is applied to one end and a steady pull should be maintained. The line to be measured should be marked at both ends, with intermediate points as necessary, to ensure unobstructed sight lines. Distances should always be double checked to ensure accuracy and record each length separately.

FDM 9-35-25 Field Procedures - Angle Measurement

October 28, 1994

All theodolites measure angles with some degree of imperfection. These imperfections result from the fact that no mechanical device can be manufactured with zero error. In the past very specific measuring techniques were taught and employed by surveyors to compensate for the minor imperfections in theodolites. With the advent of electronic total stations the imperfections still exist but are corrected in a different way with somewhat modified field procedures. The department currently has a variety of total stations that are utilized for design and construction surveying. The correct method of operation of each instrument is described in the manufacturer's operating manual that accompanies each instrument. This procedure describes the elements necessary for measuring precise horizontal and vertical angles that are common to most total stations.

25.1 Total Stations

"Total Station" is the term applied to modern surveying instruments that incorporate an EDM, a digital theodolite and a microprocessor. This combination of components provides the capability of electronically making simultaneous slope distance and horizontal and vertical angle measurements. Total stations measure very rapidly and display the data automatically in digital format. The microprocessors within the total station display the horizontal and vertical components of sloping lines in real time. Total stations can also be connected to data collectors that enable the automatic recording of field measurements for further processing and plotting capabilities.

25.2 Horizontal Angles

When measuring horizontal angles, the choice of a proper total station depends on the level of accuracy desired. For control surveys, a total station with a stated accuracy of one arc second is most adequate. For construction surveys, a total station with a stated accuracy of six arc seconds is adequate. At each station occupied with a total station, the interior clockwise angle between the lines of sight to stations observed will eventually be determined by taking differences between their relative directions expressed in angular units.

A “position” is defined as one observation of the horizontal direction from an arbitrarily selected initial station to each of the other stations, with the telescope both direct and reversed. For greatest precision, a number of positions are turned and the mean is used for further computations. The number of positions required to turn varies depending on the accuracy of the survey desired. Any position that deviates ± 5 seconds from the mean should be rejected and re-observed.

25.3 Vertical/Zenith Angles

The vertical angle measured by a total station is not a true vertical angle but rather a zenith angle. The angle measured is the clockwise angle measured from zenith (the point directly above the instrument). The measurement of vertical angles throughout a survey allows for the proper reduction of slope distances to horizontal distances as well as computation of elevation differences between stations sighted. For control surveys, two positions should be observed for each line. Any position that deviates ± 10 seconds from the mean should be rejected and re-observed. It is recommended vertical angles be observed from both ends of the line to reduce effects of earth curvature and refraction.

When reciprocal vertical angle observations are not practical or warranted for some surveys, it should be remembered that in order to minimize the errors introduced by curvature and refraction, sight distances should be restricted to under 800 feet (240 m).

25.4 Instrument Orientation

The first step necessary in any surveying project with a total station is instrument orientation. Depending upon the particular project or task at hand, horizontal, vertical, or both horizontal and vertical orientation may be required.

25.5 Horizontal Orientation

With total station instruments, three different ways for horizontal orientation are commonly used: orientation by

(1) azimuth, (2) coordinates, or (3) resection. The first two procedures are used when an existing control station is occupied by the instrument and the third when an arbitrary station is occupied. The three orientation procedures are described below.

1. Azimuth Orientation. In this procedure the coordinates of the occupied station and the azimuth to the back-sight station are entered into the total station or data collector. The back-sight station is then sighted and when completed, the azimuth of the back-sight line should appear on the instrument display.
2. Coordinate Orientation. This procedure is the same as the azimuth approach except that the coordinates of both the occupied and back-sight station are entered into the total station or data collector. The microprocessor capability of either the total station or data collector can calculate the azimuth of the back-sight line. The back-sight is then sighted and when completed, the azimuth of the back-sight line should appear on the instrument display.
3. Resection Method. In this procedure, a station whose coordinates are unknown is occupied, and the instrument's position is determined by sighting two or more stations whose coordinates are known. This is convenient if a certain point of high elevation would give good visibility to all or a good percentage of the area to be surveyed.

25.6 Vertical Orientation

Two procedures are generally applicable for establishing the instrument's elevation. The simplest case occurs if the elevation of the occupied station is known; then, simply measure and add the IH (instrument height) to this elevation. If the occupied station's elevation is unknown, then a benchmark or station of known elevation must be sighted in order to back in or carry an elevation throughout the survey. Project conditions and project type will normally dictate which orientation procedure to use in any given situation.

25.7 Data Collection

The department has adopted The American Association of State Highway and Transportation Officials (AASHTO) Survey Data Management System (SDMS) data collection software for use on all WisDOT highway surveys. It is an IBM compatible data collection software package that utilizes a nationwide standard for field coding of survey data. The following items should be recorded in the AASHTO SDMS format while performing horizontal control survey work for the department:

1. Project Header Information
    - Task (TRA, COM, RTO etc..)
    - Project ID
    - Project description
    - Time, date and crew
    - Weather conditions, temperature and barometric pressure
    - Instrument type and serial number
    - Units of angles, length, temperature and pressure
    - Prism offset
    - Combination factor (optional)
    - 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
    - Point number
    - Attribute data, such as a feature code of a control point
    - Point description, such as type of station mark (e.g. 5/8" rebar w/cap)
    - Instrument height
    - Y, and Z coordinates if known (optional)

    Note: The coordinates may be entered into a system control file for access just before field data reduction and adjustment if desired.
3. Sighted Station Entries

- Point number
- Attribute data, such as a feature code of a traverse point
- Point description, such as type of station mark (e.g. 5/8" rebar w/cap)
- Staff height
- X, Y, and Z coordinates or fixed azimuth if known (optional)
- Angle set # and instrument face position (direct/reverse) if applicable
- Measured horizontal angle, vertical angle and slope distance

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 9-35-30 Computations

October 24, 1994

The department currently uses a variety of software packages and computer programs for data reduction and adjustment of horizontal 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 horizontal control adjustment.

30.1 Horizontal and Vertical Angle Reduction

Horizontal and vertical angles should be validated and reduced to a mean angle. They should be checked to verify that correct observational procedures were employed for the accuracy of survey desired. This includes verification of number of positions turned, re-observation of rejected positions and ensuring that all necessary information was recorded for proper reduction. Some total stations will perform this reduction in real time while out in the field. For instruments of this type only the mean angles are recorded, thus it is important to record in arc seconds the appropriate errors of the horizontal and vertical pointings. These error values are important for the proper weighting of that angle in the least squares adjustment program.

30.2 Horizontal and Vertical Distance Reduction

The actual observations made with a total station are horizontal angle, vertical (zenith) angle and slope distance, from the instrument to the prism/target assembly. These observations can be used to generate the horizontal distance and vertical distance (difference in elevation).

The figure below shows an instrument measuring a slope distance (DS) and a vertical (zenith) angle (VT).

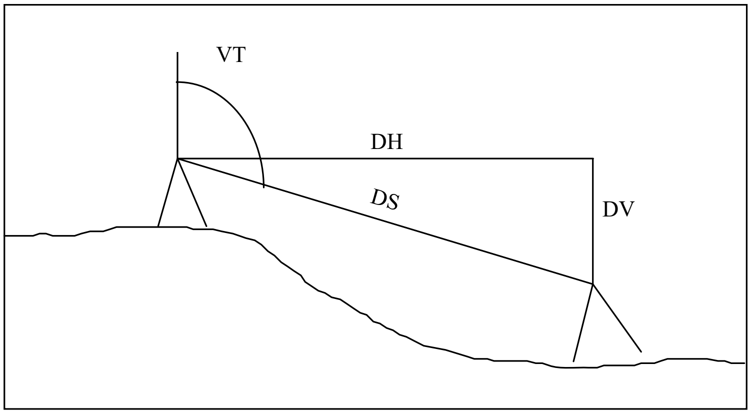

Figure 30.1. ***Measuring Slope Distance & Vertical Angle***

The horizontal distance, (DH), can be determined by the equation: DH+DS*sinVT

The vertical distance, (DV), can be determined by the equation: DV=DS*cosVT

The accuracy of either the horizontal or vertical distance is directly related to the accuracy of the measured slope distance and, more critically, the zenith angle. By taking direct and reverse vertical angle pointings, errors in the measurement of the zenith angle can be minimized.

30.3 Curvature and Refraction

If the horizontal and vertical distances are computed by only multiplying the measured slope distance by the sine and cosine of the measured vertical angle respectively, the errors can be considerable due to the effects of earth curvature and refraction. Ideally, the surveyor should measure the reciprocal zenith angles and slope distances from both ends of the line and use the mean value to correct for earth curvature and refraction. However, this is not always practical or warranted. Thus, all total stations and reduction programs are capable of applying a correction based on a simple formula with assumed values for earth radius (Re) and a refraction constant (K). This correction will be applied each time a horizontal or vertical distance is displayed on the total station or can be applied during office reductions with any of the accepted programs.

The standard formulas used by most total stations and software programs are as follows:

$$DH = \left[DS * \sin(VT) \right] - \left[\frac{(DS)^{2} * \sin^{2}(VT)}{2Re} * \left(1 - \frac{K}{2}\right) \right]$$

$$DV = \left[DS * \cos(VT) \right] + \left[\frac{(DS)^{2} * \sin^{2}(VT)}{2Re} * (1 - K) \right]$$

DS = Slope Distance
DH = Horizontal Distance
DV = Vertical Distance
VT = Zenith Angle
Re = Radius of Earth - 20,902,000 ft (6,372,000 m)
K = Refraction constant mean = 0.142

30.4 Methods for Traverse Adjustment

For any closed traverse, the angular and positional misclosure must be distributed throughout the traverse to close the figure. The process of distributing these errors throughout a survey is termed an adjustment. The adjustment provides the user with the statistically "best" solution of coordinates or distances and bearings between successive points in the survey. The department currently uses two methods for traverse adjustment: (1) Compass Rule and (2) Least Squares.

30.4.1 Compass rule adjustments

The compass rule adjustment assumes that all angles and distances within a traverse were measured with equal precision. The angle misclosure is first applied equally to all angles in the survey. The adjustment then distributes the positional misclosure errors (after azimuth adjustment) in latitude (Y) and departure (X) for each traverse course in the same proportion as the course distance is to the traverse perimeter. Corrections are made by the following general rules:

$$\text{Adjustment per angle (sec)} = \frac{\text{Total angle misclosure (sec)}}{\text{Number of setups}}$$

$$\frac{\text{Correction in latitude (Y) for AB}}{\text{Misclosure in latitude (Y)}} = \frac{\text{Length of AB}}{\text{Perimeter of traverse}}$$

$$\frac{\text{Correction in departure (X) for AB}}{\text{Misclosure in departure (X)}} = \frac{\text{Length of AB}}{\text{Perimeter of traverse}}$$

Note:The corrections are opposite in algebraic sign to the errors.

The compass rule adjustment method is incorporated into most surveying software packages as well as the AASHTO SDMS data collection software package and the SDC-PC program. The use of this adjustment procedure should be limited to single thread or single loop low-order accuracy surveys.

30.4.2 Least Squares Adjustments

Higher order, single thread, or single loop surveys, and surveys that contain multiple loops with common control points and traverse stations 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 angular and linear measurements to make the sum of the squares of the weighted residuals a minimum - hence its name.

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 (distance, angle, etc.) can be assigned an individual weight, either mathematically derived from the repeated measurements or assigned a constant based on either 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, 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 is mathematically correct for all types of surveys, including traverses, GPS, resection, intersection, and triangulation etc. in any combination.
- 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 several of the department's programs currently in use. Consult the appropriate user manual for the correct operation of each.

30.5 Accuracy Evaluations

One of the tests used to evaluate the accuracy of a traverse is its azimuth closure at checkpoints or control stations. The angular misclosure is expressed in arc seconds and is evaluated for conformity to the desired specifications as detailed in FDM 9-35-5.

Another one of the tests used to evaluate the accuracy of a traverse is its position closure. This standard (position closure) is usually expressed as a ratio (e.g. 1:10,000). Put simply, it states that the relative accuracy between directly connected points is greater than or equal to the ratio specified. This ratio is evaluated after azimuth adjustment or conformity to the desired specifications as detailed in FDM 9-35-5. It should be noted that position closures given in FDM 9-35-5 are the minimum acceptable for the desired standard. The specifications for the field work are such that, as a general rule, the closures should be better by a factor of two.

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 9-35-35 Monumentation Required October 28, 1994

All Primary and Secondary horizontal control stations shall be monumented with Type I or Type II monuments. Some secondary control stations may be monumented with an occasional Type III monument, such as a PK nail in the pavement.

For each horizontal and/or vertical control station that is established, a control station description should be prepared. The standard information that should be recorded for both horizontal and vertical control stations includes project identification, point number, general location and specific descriptive information. Additional information such as horizontal and vertical datum nomenclature, coordinates, elevation and station value can be added after adjustment computations are complete.

General location information should adequately describe how to find the station from nearby landmarks or roadways. Specific descriptive information should describe the type of monument marking the point and, for horizontal control stations, should include at least three references with horizontal tie distances to the station measured and documented.

A sketch should always be prepared portraying the point's relationship to existing topographic features as an aid in recovering the point. It is most useful to give the nominal distances to nearby fences, driveways, or other features, and to give distances to nearby pavement edges if they exist.