Use of the Electronic Total Station -
I. Introduction and basic techniques

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Abstract

Total Stations, a combination of an electronic theodolote and distance meter, are a precise tool for many geological surveying projects. The fundamental measurements made by a Total Station are *slope distance*, *horizontal angle*, and *vertical angle*. All other values returned by the instrument, such as coordinates, are derived from these values. The precision of the instrument, which can give relative positions of points to millimeters, is only obtained through using appropriate surveying procedures. Surveyors have developed these procedures to minimize imperfections in the instrument, detect operator errors, and minimizing errors due to curvature and refraction. The most useful of these procedures is double centering. This is where readings are taken with the instrument in two different positions. This allows instrument and operator errors to be detected and corrected. Other procedures require that readings be taken between two points in each direction in order to eliminate refraction errors. In addition to using correct procedures, the user must also allow atmospheric conditions that change the speed of light in air and thus the measured distance between points.

Keywords: Surveying, Total Station, Field Methods, Mapping

Introduction

The Geology Department at Portland State University makes extensive use of Total Stations in our undergraduate *Field Methods*, *Surveying Methods for Archaeologists*, *Field Geophysics, Field Camp,* and *Anatomy of Landslides* classes, and offer graduate students a short-course on using the equipment for their research. A total station is a combination of an electronic theodolite (for measuring angles) and a distance meter. This combination makes it possible to determine the coordinates of a reflector by aligning the instruments cross hairs on the reflector and simultaneously measuring the vertical and horizontal angles and slope distances. A microprocessor in the instrument will take care of recording readings and the necessary computations. The data is easily transferred to a computer where it can be used to generate a map.

Recent papers in the *Journal of Geoscience Eduation* (Philpotts et al., 1997; Schlische and Ackermann, 1998) give an overview of the electronic total station and some of its uses in a field methods course. Whereas these papers focus on some of the things you can accomplish with a total station, this paper focuses on how to use a total station. The objective of this paper and it's companions (Cruikshank, in review-b; Cruikshank, in review-c) is to provide material that can be used to train students in the use of electronic total stations rather than illustrate the versatility of the instrument. The emphasis in the Philpotts *et al.* (1997) paper is on how well the instrument performs with relatively simple use, this paper will show how to obtain the accuracy that is inherent in the instrument.

As a teaching tool, a total station fills several purposes. Learning how to properly use a total station involves the physics of making measurements, the geometry of calculations, and statistics for analyzing the results of a traverse. In the field it requires teamwork, planning, and careful observations. If the total station is equipped with a data-logger, it also involves interfacing the data-logger with a computer, transferring the data, and working with the data on a computer. Surveying also provides direct feedback to the students, they gain confidence in their abilities when they see a survey closing within a few millimetres. If the survey does not close, they have to search for and correct the problem. The ability to recognize errors in your own work and correct those errors is a very important aspect of professional work.

The more the user understands how a total station works the better they will be able to use it. In this paper I will discuss how a total station makes the basic measurements, the calculations for derived values (such as coordinates) and procedures for using a total station to make accurate measurements. In companion papers (Cruikshank, in review-b; Cruikshank, in review-c) I present some exercises that we use in the *Field Methods* class at Portland State University to train the students in the various uses for a total station.

Although total stations can make precise measurements, field conditions do not always allow the instruments accuracy to be obtained simply by pointing the instrument at the target and taking a reading. There may be either internal instrument alignment errors, distance meter errors,

errors from curvature and refraction, or operator errors. These errors *cannot* be eliminated by the instrument. Surveyors have developed various surveying procedures to take advantage of the full precision of an instrument – these normally involve multiple readings taken with the instrument in the "normal" and "inverse" positions. Although total stations are easily operated, proper surveying procedures *must* be followed in order to obtain accurate readings. An essential element in surveying is making measurements so that sources of error can be eliminated, and that you have the ability to check the quality of your result.

There is a growing use of Global Positioning System (GPS) Total Stations in the surveying industry (*i.e.*, real-time kinematic GPS Systems), these instruments are very expensive and cannot be used in situations where the signal may be blocked or interfered with, such as under heavy tree cover and in urban areas. Therefore, an electronic total station is still a very useful field tool, as is a Plane Table under some circumstances.

Fundamental Measurements

When aimed at an appropriate target a total station measures three parameters (Figure 1): (1) The rotation of the instrument's optical axis from instrument north in a horizontal plane (horizontal angle), (2) the inclination of the optical axis from local vertical (vertical angle), and (3) the distance between the instrument and the target (slope distance). All other numbers that may be provided by the total station are derived from these three fundamental measurements.

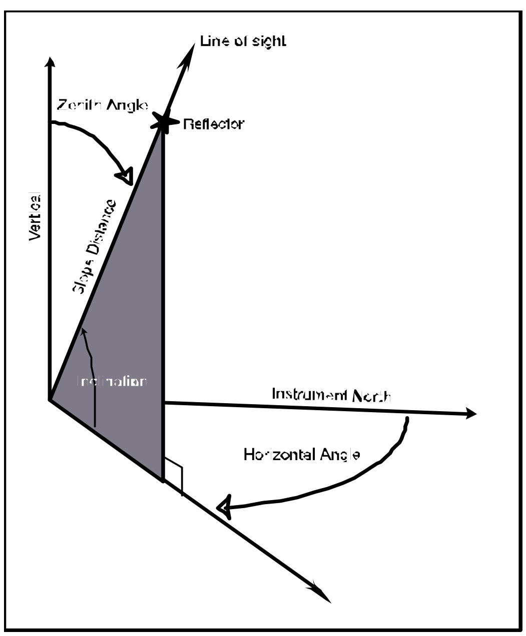

Figure 1. Fundamental measurements made by a Total Station: horizontal angle, vertical angle, and slope distance. All other values returned by the total station are derived from these measurements.

Horizontal Angle

The horizontal angle is measured from the zero direction on the horizontal scale (or *horizontal circle*). When the user first sets up the instrument the choice of the zero direction is made – this is *Instrument North*. The user may decide to set zero (North) in the direction of the long axis of the map area, or choose to orient the instrument approximately to True, Magnetic or Grid North. The zero direction should be set so that it can be recovered if the instrument was set up at the same location at some later date. This is usually done by sighting to another benchmark, or to a distant recognizable object. Using a magnetic compass to determine the orientation of the instrument is not recommended and can very inaccurate. Most total stations can measure angles to at least 5 seconds, or 0.0013888°, so aligning the instrument to true north as well as the instrument can measure is next to impossible. The best procedure when using a Total Station is to set a convenient "north" and carry this through the survey by using backsights when the instrument is moved. More about this is given in the companion papers (Cruikshank, in review-b; Cruikshank, in review-c), since different surveying tasks have different backsight requirements.

Within a total station is a graduated glass circle – the spacing of the graduations depends on the accuracy of the instrument. On one side of the glass circle is a light-emitting diode, and on the other side are two photo diodes that receive the light from the light-emitting diode. The light from the light-emitting diode is interrupted when a graduation passes between the light-emitting diode and the photo-diode. By counting the number of interruptions, the amount that the instrument has been turned can be determined. Two photo-diodes are needed in order to detect which way the instrument is being turned. A chip in the total station counts the number of graduations that have passed and then increments or decrements the angle that is displayed. Graduations are often only every minute (so there are 21600 graduations). Seconds are interpolated by looking at the strength of the signal received by the two photo-diodes. This is accomplished by placing a third photo-diode in-line with the light-emitting diode to provide reference strength of the signal. The relative strength of the signal to the other diodes allows the number of seconds to be calculated (Sokkia, 1996).

This type of graduated circle requires that they are "indexed" when the instrument is turned on. Indexing allows the instruments to determine the position of an absolute reference marker on the horizontal and vertical circles. This involves turning the instrument about the vertical axis until the zero point on the circle passes the detectors. This allows the instrument to count the number of graduations from the zero-set. Most instruments allow you to set zero anywhere on the circle. The indexing allows the instrument to be turned off and then back on without loosing the current zero direction. Some instruments are self-indexing, and do not require the operator to index the instrument.

The default on most total stations is to measure angles in a clockwise sense (Horizontal Angle Right, abbreviated HAR on some instruments) which follows the normal mode for reading azimuths on a compass. Some total stations can also measure angles in a counterclockwise sense (Horizontal Angle Left, or HAL), which is the positive angle direction in a mathematical sense.

Vertical Angle

The vertical angle is measured relative to the local vertical (plumb) direction (Figure 1). The vertical angle is usually measured as a zenith angle (0° is vertically up, 90° is horizontal, and 180° is vertically down), although you are also given the option of making 0° horizontal. The zenith angle is generally easier to work with. The telescope will be pointing downward for zenith angles greater than 90° and upward for angles less than 90°. If you make horizontal 0° then you have to work with positive and negative vertical angles, this provides an unnecessary source of error.

Measuring vertical angles requires that the instrument be exactly vertical. It is very difficult to level an instrument to the degree of accuracy of the instrument. Total stations contain an internal sensor (the vertical compensator) that can detect small deviations of the instrument from vertical. Electronics in the instrument then adjust the horizontal and vertical angles accordingly. The compensator can only make small adjustments, so the instrument still has to be well leveled. If it is too far out of level the instrument will give some kind of "tilt" error message.

Because of the compensator, the instrument has to be pointing exactly at the target in order to make an accurate vertical angle measurement. In the instrument is not perfectly leveled then as you turn the instrument about the vertical axis (*i.e.*, change the horizontal angle) the vertical angle displayed will also change.

Vertical angles are measured using the same mechanical-optical system as the horizontal angles. Indexing the circle is common, since the horizontal direction on the graduated circle must he determined.

Slope Distance

The instrument to reflector distance is measured using an Electronic Distance Meter (EDM). Most EDM's use a Gallium Aresnide Diode to emit an infrared light beam. This beam is usually modulated to two or more different frequencies. The infrared beam is emitted from the total station, reflected by the reflector and received and amplified by the total station. The received signal is then compared with a reference signal generated by the instrument (the same signal generator that transmits the microwave pulse) and the phase-shift is determined. This phase shift is a measure of the travel time and thus the distance between the total station and the reflector.

This method of distance measurement is not sensitive to phase shifts larger than one wavelength, so it cannot detect instrument-reflector distances greater than 1/2 the wavelength (Figure 2) (the instrument measures the two-way travel distance). For example, if the wavelength of the infrared beam was 4000 m then if the reflector was 2500 m away the instrument will return a distance of 500 m.

Since measurement to the nearest millimeter would require very precise measurements of the phase difference, EDM's send out two (or more) wavelengths of light. One wavelength may be 4000 m, and the other 20 m. The longer wavelength can read distances from 1 m to 2000 m to the nearest meter, and then the second wavelength can be used to measure distances of 1 mm to 9.999 m. Combining the two results gives a distance accurate to millimeters. Since there is overlap in the two readings the meter value from each reading can be used as a check.

For example, if the wavelengths are λ_1 = 1000m and λ_2 = 10 m, and a target is placed 151.51 metres away, the distance returned by the λ_1 wavelength would be 151 metres, the λ_2 wavelength would return a distance of 1.51 m. Combining the two results would give a distance of 151.51 m.

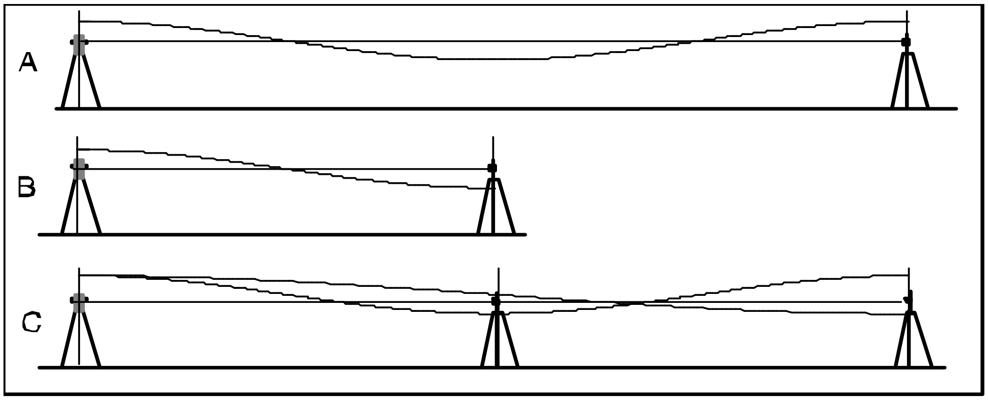

Figure 2. Distance measurement using an EDM. The EDM measures a phase shift between the transmitted and received signals and the phase shift is translated into a distance. This is because the reflectors are exactly 1 (A) and 1/2 (B) wavelengths away from the instrument. The limiting distance of an EDM is 1/2 of the longest wavelength sent out (the two-way distance would be one wavelength). If the EDM only sends out one wavelength, it cannot distinguish between the situations shown in A and B. To resolve this problem, multiple wavelengths can be sent out (C). In (C) a wavelength twice that of shown A & B is also used, this allows the distance to each reflector to be determined.

The instruments used in the Geology Department (Sokkia SET4B$_{II}$) series use three modulated frequencies with an unambiguous distance of 10 km, however the signal strength is only sufficient for distance measurements of 1.5 – 3 km depending on the atmospheric conditions and the number of reflectors used (Sokkia, 1996).

The speed of light depends on the density of the medium through which it is travelling, so temperature and pressure corrections have to be applied to the readings. These corrections can be significant, up to several centimeters per kilometer. These corrections are discussed in more detail below in the section on sources of error.

Basic calculations

Total Stations only measure three parameters: *Horizontal Angle*, *Vertical Angle*, and *Slope Distance*. All of these measurements have some error associated with them, however for demonstrating the geometric calculations we will assume the readings are without error.

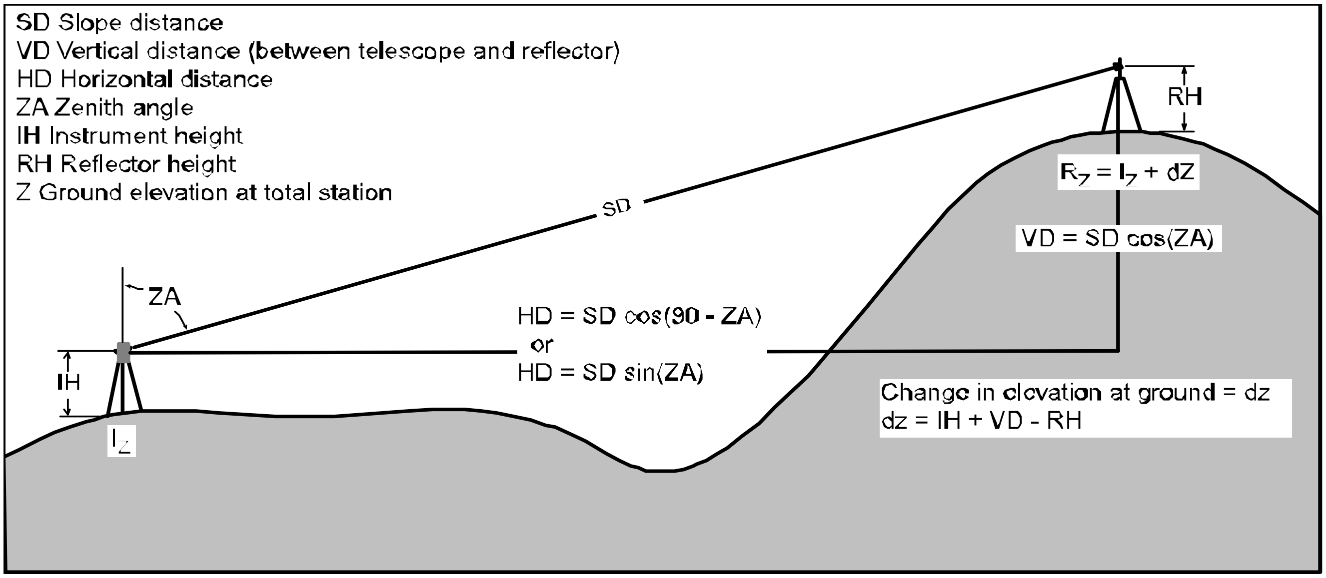

Figure 3. Diagram showing the geometry of the instrument and reflector looking at a vertical plane normal to the direction between the instrument and the reflector.

Horizontal distance

In order to calculate coordinates or elevations it is first necessary to convert the slope distance to a horizontal distance. From inspection of Figure 3 the horizontal distance (*HD*) is

$$HD = SD \cos(90° - ZA) = SD \sin(ZA) \tag{1}$$

Where *SD* is the slope distance and *ZA* is the zenith angle. The horizontal distance will be used in the coordinate calculations.

Vertical distance

We can consider two vertical distances. One is the *Elevation Difference* (*dZ*) between the two points on the ground. The other is the *Vertical Difference* (*VD*) between the titling axis of the instrument and the tilting axis of the reflector. For elevation difference calculation we need to know the height of the tilting-axis of the instrument (*IH*), that is the height of the center of the telescope, and the height of the center of the reflector (*RH*).

The way to keep the calculation straight is to imagine that you are on the ground under the instrument (Figure 3). If you move up the distance *IH*, then travel horizontally to a vertical line passing through the reflector then up (or down) the vertical distance (*VD*) to the reflector, and then down to the ground (*RH*) you will have the elevation difference between the two points on the ground. This can be written as

$$ED = VD + (IH - RH) \tag{2}$$

The quantities *IH* and *RH* are measured and recorded in the field. The vertical difference (*VD*) is calculated from the vertical angle and the slope distance (see Figure 3)

$$VD = SD\ \sin(90° - ZA) = SD\cos(ZA) \tag{3}$$

Substituting this result (3) into equation (2) gives

$$dZ = SD\cos(ZA) + (IH - RH) \tag{4}$$

where *dZ* is the change in elevation with respect to the ground under the total station. I have chosen to group the instrument and reflector heights. Note that if they are the same then this part of the equation drops out. If you have to do calculations hand it is convenient to set the reflector height the same as the instrument height.

If the instrument is at a know elevation, I_Z, then the elevation of the ground beneath the reflector, R_Z, is

$$R_Z = I_Z + SD\cos(ZA) + (IH - RH). \tag{5}$$

Coordinate calculations

So far we have only used the vertical angle and slope distance to calculate the elevation of the ground under the reflector. This is the *Z*-coordinate (or elevation) of a point. We now want to calculate the *X*- (or East) and *Y*- (or North) coordinates. The zero direction set on the instrument is instrument north. This may or may not have any relation on the ground to true, magnetic or grid north, the relationship must be determined by the user. Figure 4 shows the geometry for two different cases, one where the horizontal angle is less than 180° and the other where the horizontal angle is greater than 180°. The sign of the coordinate change (positive in Figure 4A and negative in Figure 4B) is taken care of by the trigonometric functions, so the same formula can be used in all cases.

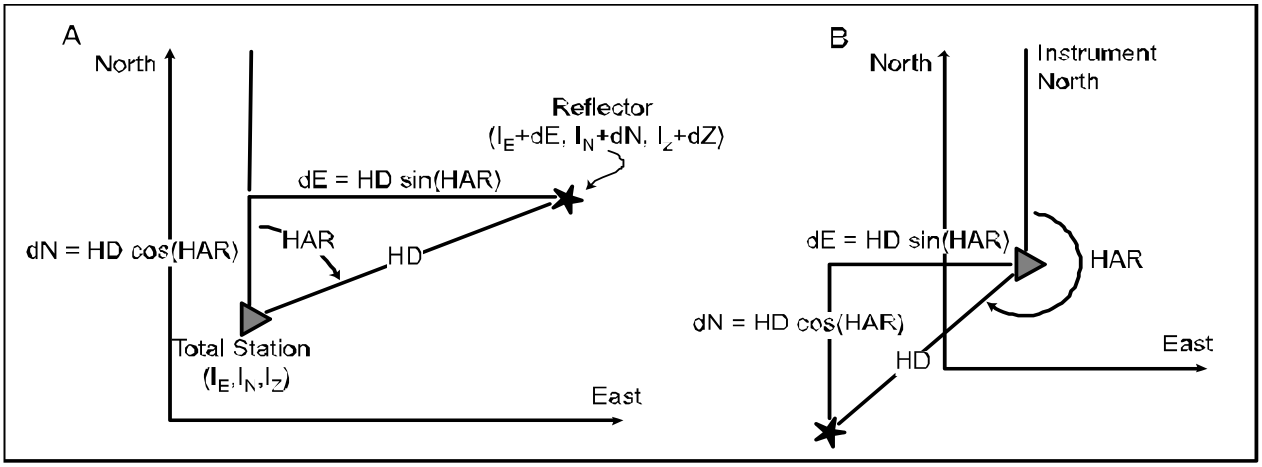

Figure 4. Definition diagram for calculating the East and North coordinate of the reflector.

From inspection of Figure 3 the coordinates of the reflector relative to the total station are

$$dE = \text{Change in Easting} = HD \sin(HAR)$$

$$dN = \text{Change in Northing} = HD \cos(HAR)$$

Where *HD* is the horizontal distance and *HAR* is the horizontal angle measured in a clockwise sense from instrument north. In terms of fundamental measurements (*i.e.*, equation 1) this is the same as

$$dE = SD \cos(ZA) \sin(HAR) \quad (6a)$$

$$dN = SD \cos(ZA) \cos(HAR) \quad (6b)$$

If the easting and northing coordinates of the instrument station are known (in a grid whose north direction is the same as instrument north) then we simply add the instrument coordinates to the change in easting and northing to get the coordinates of the reflector. The coordinates of the ground under the reflector, in terms of fundamental measurements are:

$$R_E = I_E + SD \sin(ZA) \sin(HAR) \quad (7a)$$

$$R_N = I_N + SD \sin(ZA) \cos(HAR) \quad (7b)$$

$$R_Z = I_Z + SD \cos(ZA) + (IH - RH) \quad (7c)$$

Where I_E, I_N, and I_Z are the coordinates of the total station and R_E, R_N, R_Z are the coordinates of the ground under the reflector. These calculations can be easily done in a spreadsheet program such as Microsoft Excel (Appendix A).

All of these calculations can be made within a total station, or in an attached electronic notebook. Although it is tempting to let the total station do all the calculations, it is wise to record the three fundamental measurements. This allows calculations to be checked, and provides the basic data that is needed for a more sophisticated error analysis (Cruikshank, in review-b).

Sources of error

There is a misconception that a total station can make many of the corrections for you. Unfortunately, this is not the case. The elimination of errors requires that correct surveying procedures be followed. For example, since the total station uses optics to make measurements, several atmospheric factors affect the measurement. The curvature of the earth will affect the elevation and distance between points, and refraction of the light through air will cause aiming errors. Because of refraction you see the target in a location that is not its true location. You can make as many measurements as you like from a single station, but you cannot detect refraction. To correct for refraction you have to make measurements from both stations (e.g., Moffitt and Bouchard, 1992).

There are a number of sources of error in measurements. These sources are (1) operator errors, (2) systematic errors and (3) random errors (e.g., Wolf and Ghilani, 1997). Operator errors are usually caused by the operator's carelessness. They may arise from entering incorrect numbers, miss-reading temperature or pressure, and mistakes in reading or recording data. These are generally referred to as "busts". Operator errors can be minimized by having carefully prescribed procedures to follow and by using an electronic data-logger. It is possible to enter incorrect tripod heights etc. Although many transcription errors can be avoided, the key to eliminating operator errors is careful checking of readings and the use of data analysis procedures that will detect errors.

Systematic errors follow some well-defined physical law and can generally be predicted. These include things like balancing *foresight* and *backsight* measurements[1] to allow for curvature and refraction balancing *normal* and *inverse* shots to remove instrument alignment errors, and temperature and pressure corrections for EDM measured distances. Systematic errors are eliminated by using well-established surveying procedures. In many cases the steps performed to eliminate the systematic errors will also help catch operator errors.

Random errors are errors that are not operator or systematic. These generally arise from operator and instrument imperfections (or accuracy limitations). They are generally non-systematic and should average out with repeated measurements. Multiple readings are insufficient to control error, it is best to use a system of measurements where there are constraints on the correct result. The best way to do this is to survey a closed shape where all angles and distances are measured. For example, all three angles in a triangle should sum to 180° – if they do not then you have a measure of error. These techniques involve redundant measurements. You need only measure two angles (or one angle and two sides) in a triangle in order to calculate the third angle. However, it you only measure the minimum there is no way to assess your error.

EDM Errors

For distance measurements, the most important factor is the speed of light in air. The density of the air controls the speed of light. The velocity of light in air can be well determined from measurements of temperature, pressure and relative humidity. The empirical equations used are (after Moffitt and Bouchard, 1992):

$$n_{\mathrm{g}} = 1 + (287.604 + \frac{4.8864\ \mu\mathrm{m}^2}{\lambda_{\mathrm{c}}^2} + \frac{0.0680\ \mu\mathrm{m}^4}{\lambda_{\mathrm{c}}^4}\ 10^{-6} \tag{8a}$$

Where λ_c is the wavelength of the EDM carrier signal (in micrometres, μm, or 10^{-6}m), n_g is the refractive index of standard air (dimensionless).

The departure from standard air is given by

$$n_{\mathrm{a}} = 1 + \frac{2.\ 2767\times10^{-3}\ \mathrm{K/Pa}\ (n_{\mathrm{g}}\text{-}1)\ p}{t} + \frac{1.2704\times10^{-7}\ \mathrm{K/Pa}\ e}{t} \tag{8b}$$

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[1] The terms foresight, backsight, normal and inverse will be defined later in this paper

Where n_a is the refractive index of air, p is the pressure (in Pascals, Pa), t is air temperature (in Kelvin, K, or 273.2 + temperature in °C), e is the vapor pressure of air (in Pa). The pressure must be the absolute pressure. If an altimeter or barometer is calibrated for weather it will not work, since weather pressures are the pressure at sea level at a particular location, not the absolute pressure. As can be seen from the above equation the effect of the relative humidity is four orders of magnitude smaller than the pressure correction term. Thus, is it usually not considered in the calculation. The velocity of light in air is then:

$$V_a = \frac{c}{n_a} \tag{8c}$$

Where c is the speed of light in a vacuum (299,792,458 m/s).

Once you know the velocity in air, then you can express the velocity difference as a distance error per unit distance. This represents the difference in distance traveled by the EDM signal compared with light in a vacuum over the same time interval. This correction factor is usually given as millimetres of difference per kilometer of distance measured, or parts per million (ppm). For example, if you are measuring a distance of about 100 m, and your atmospheric correction is 5 ppm then you would expect about 0.5 mm of error due to atmospheric conditions. This is below the detection level of most EDMs, which is 3 to 5 mm. Although you could neglect the atmospheric correction under these conditions, it is wise to always enter the correction. If this is part of your normal routine then you will not forget to enter the correction when it is needed.

Many total station EDM's are calibrated so that there is no correction at 20°C and sea-level pressures (10.23 Pa). For the Sokkia instruments used in the PSU Geology Department 1 ppm corresponds to 1°C of temperature change or 3.3 hPa of pressure change. Most Total Stations have a similar correction factor.

Atmospheric conditions measured at the instrument station and will provide good values for short distances. For longer distances or where there is a lot of elevation change the atmospheric conditions should be measured at the instrument and reflector and averaged. If atmospheric conditions are changing then the readings should be repeated as necessary. Generally a good breeze will produce more uniform conditions between the instrument and reflector. For high-precision measurements over long distances (longer than one would normally make with a total station) a helicopter is often used to make continuous temperature, humidity and pressure readings along the line of sight.

Another source of error in distance readings is the *Reflector Constant* or *Prism Constant*. This potential source of error comes from three sources (1) the extra distance a light beam travels in a reflector before it is returned to the instrument, (2) the center of the reflector may not be aligned vertically with the point on the ground (due to the geometry of the reflector-mounting, rather than operator error), and (3) the center of the emitter may not be vertically over the point over which the instrument is setup. All of these errors are expressed as a prism constant. The source of error in the instrument (No. 3 above) may be in-part to cancel errors (1 and 2). Generally this sort of error will only come from mixing instruments and reflectors from different surveying systems. In a given system these errors will be expressed as a prism constant (for our systems the prism constant is –40mm).

Curvature and Refraction

Curvature and refraction can have a significant effect on measured elevations. Since surveying works with a plane coordinate system, and the earth is curved, elevations must allow for this curvature. Another important control on the accuracy of distance measurements (and elevation measurements) is refraction. This will result in a longer travel path and an optical illusion in that the reflector will not be where you see it! Under normal atmospheric conditions, the tendency is for a light ray to curve towards the earth's surface. This tends to reduce the effect of curvature (by about 18%). For this reason, curvature and refraction are normally handled together, since it is difficult to separate them in a survey.

The curvature effect is (Moffitt and Bouchard, 1992):

$$C = 0.0785\,\frac{\text{m}}{\text{km}^2}\,HD^2 \tag{9a}$$

Where C is the curvature effect on elevation in meters, and HD is the horizontal distance in kilometers. Thus over a distance of 1 km the curvature effect would be 0.0785 m or almost 8 cm. Over a distance of 100 m the error would be a little less than a mm. 200 m would give a curvature effect of about 3 mm.

Inverting this equation gives:

$$HD = \sqrt{\frac{C}{0.0785}} \tag{9b}$$

This equation indicated that 1 mm of vertical error due to curvature would occur over a horizontal distance of approximately 112 m; 1 cm of vertical error would occur over 357 m. What these equations show is that the elevation difference due to curvature increases dramatically for distances over 100 m to the point of becoming within the error detection of total stations. 1 cm in 357 m represents and angle of almost 6 seconds. The type of error described above is present for total stations and levels.

The refraction error is smaller than the curvature correction and tends to reduce the effect of curvature. The combined correction for curvature and refraction can be estimated from (Moffitt and Bouchard, 1992):

$$\mathrm{C + R} = 0.0675\,\frac{\mathrm{m}}{\mathrm{km}^2}\,HD^2 \tag{9c}$$

Although curvature and refraction can be estimated through the above equations, the only way to eliminate the error is to observe the vertical angle from both ends of the line. In shooting uphill the observed elevation difference is greater than the actual, and in shooting downhill the elevation different will be less than the actual difference. The average of the two values will be the actual value. The observations at either end of the line would ideally be made at the same time, however under the same atmospheric conditions would be acceptable. If there is significant elevation difference between the two stations, you will want to average the temperature and pressure correction for the EDM.

We can get an idea of the magnitude of the curvature and refraction corrections by examining the above equations. The correction applied by the Sokkia total stations used by the Geology Department is:

$$ZA_{\mathrm{cor}} = ZA - \frac{(1-k)\,SD}{2R} \tag{9d}$$

Where ZA is in radians. SD is the slope distance, R is the spheroid radius (3670000 m), and k is the coefficient of refraction (0.14 or 0.20 for common atmospheric conditions). The correction (in radians) is approximately 10^{-7} of the slope distance. According to this equation, (with k = 0.20) a 1 second correction will be made for a slope distance of about 45m, a 5 second correction will be made over a distance of 222.5 m. 1” over 45 m is a 0.00021 m is elevation difference; 5” over 222.5 m is 0.0054 m (5 mm) elevation.

For most cases, curvature and refraction errors do not have to be applied for distances less than 300 m. For distances beyond that, the correction should be made. The best way to make the correction is making uncorrected (with respect to curvature and refraction) observations from each end of the line and averaging the elevation difference (Moffitt and Bouchard, 1992). If observations can only be made from one end of the line then corrections with the above formula are the best solution. This is the solution applied by many total stations.

Collamation

Collamation error is the miss-alignment between the optic axis of the instrument and the bubble levels. Although the levels (including the internal compensator) indicate the instrument is level, the telescope may in fact be tilted slightly up or down. A miss-alignment of 5 seconds will result in an elevation error of 2.5 mm over a 100 m distance. A 1-minute miss-alignment would be about 3 cm over 100 m. Since this is an error within the instrument, repeated measurements will not show up the error. This type of error is associated with all typed of surveying equipment.

Following surveying procedures such as double centering (see below) will eliminate this error. If you routinely find that you have significant differences (see instrument manual for suggested tolerances) between normal and inverted readings then you should have the instrument collamation checked. Most total stations give you instructions for making this correction in the field.

Vertical Index

Vertical Index error is the error in vertical angle that is a result of the instrument not being perfectly level. Modern instruments have an internal sensor (internal compensators) that can make corrections for the instrument not being perfectly level. The compensator only works when the instrument is close to level and will warn the user if the instrument is too far out of level. Compensators may be turned off. Even with a compensator, it is important to get the instrument as level as possible level, since this affects how well you align over a benchmark if you are using an optical plumet.

The compensator will change both the vertical and horizontal angles, so it is important to make sure that the instrument is aligned vertically and horizontally with a target before a reading is taken.

Centering Errors

Centering errors arise from the instrument not being vertically above a ground station. This may be a result of operator error, or a miss-aligned optical plummet. Overall this should be a small random error within a survey. However, vertical alignment is important, and should be checked repeatedly during a survey. There is also the centering error at the reflector station. This will be small for tripod-mounted reflectors, but will be larger for handheld reflectors. The person holding the reflector must make sure that the reflector pole is vertical and centered over the point of interest.

Techniques

In the previous section we saw some of the sources of error in making measurements. There are also a whole series of corrections that need to be made in order to carry out successful surveys over large areas. In this paper I assume that students will not be working in an area any larger than a 2 km^2. In this section I discuss surveying techniques that can be used to minimize or correct for many of the errors above. In this paper I am only addressing how to make single measurements, companion papers (Cruikshank, in review-b; Cruikshank, in review-c) go into details for different types of surveying tasks.

What surveying instruments do well is measure the angle between two points measured from the instrument station. It is measuring one angle in a triangle. In the following discussion we talk about measuring an angle, not the angle from "north".

Before making any reading with the instrument, the user should eliminate any parallax error by having both the crosshairs and image in sharp focus. As the operator moves her eye slightly there should be no apparent shift in where the crosshairs are in relation to the image.

Double centering or double sighting

Double centering is perhaps the single most important technique. This technique has been found to eliminate the majority of surveying errors (Moffitt and Bouchard, 1992, p. 150). Angles are first measured in the *normal* position (this may also be referred to as the *direct*, *erect* or *face-1* position). The telescope is then *inverted* (turned horizontally and vertically through 180°) and the reading repeated. If there was no error then the horizontal angles observed should be different by exactly 180°, and the two vertical angles should sum to exactly 360°. Any difference from these values is a measure of the error. The source of the error will be imperfections in the operators use of the instrument, and miss-alignments between true level and the optical axis (collamation error). The angles are then adjusted by an equal amount so that they are different by 180° for horizontal angles or sum to 360° for vertical angles. Often the correction is as simple as averaging the seconds portion of the horizontal angle, however there are situations where the adjustment is more complex.

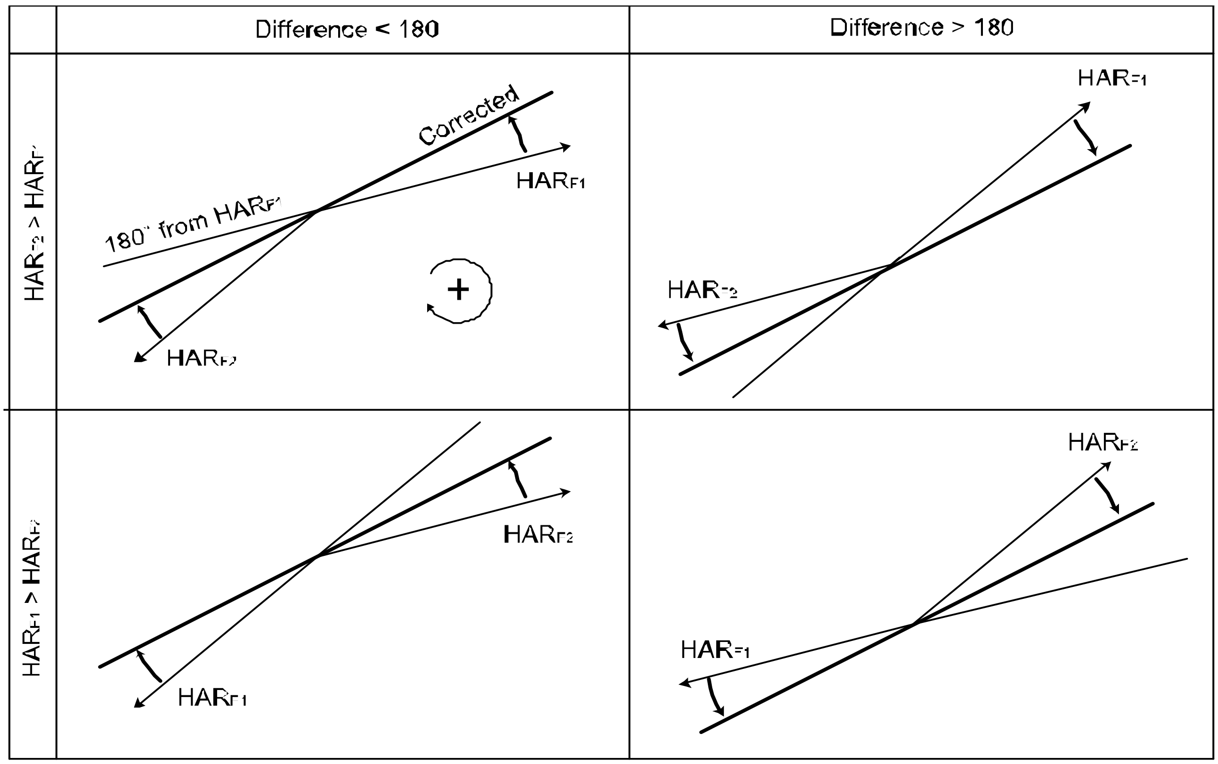

Figure 5. Correction of horizontal angles. There are four different cases that need to be accounted for, depending on the difference between the two angles (measured clockwise from the smaller reading), and if HAR_{F1} is greater or less than HAR_{F2}. When corrected the two angles should be 180° apart (heavy dashed lines). The formula shown in equation (10) will take care of these four cases.

The correction for the horizontal angle (HAR) angle can written for all the cases shown in Figure 5 with a single worksheet formula:

$$\begin{aligned} HAR_{cor} = IF(\ & HAR_{F1} > HAR_{F2}, \\ & HAR_{F1} + (180° - (HAR_{F1} - HAR_{F2}))/2, \\ & HAR_{F1} - (180° - (HAR_{F2} - HAR_{F1}))/2\ ) \end{aligned} \tag{10a}$$

Where the subscript *F1* refers to the normal or face-1 observation and the *F2* subscript refers to the inverted or face-2 position. The corrected zenith angle (ZA_{cor}) will be

$$ZA_{cor} = ZA_{F1} + (360° - ZA_{F1} - ZA_{F2}) / 2 \quad (10b)$$

These corrections can be made with electronic notebooks, although care must be taken. Some notebooks will return a corrected vertical angle that is the orientation of the line between the two *ground* stations rather than the line between the instrument and the reflector. This vertical angle cannot be used in some of the formulas presented earlier in this paper. You should consult the documentation for your data logger to find out how it treats vertical angles.

Double centering checks for the accuracy of the instrument. If the adjustments are too large (for example, 20”) then the reading should be repeated until the adjustments are within acceptable limits. If the adjustment remains large then the collamation should be checked (which can often be done manually following instructions provided by the instrument manufacturer) or the instrument should be serviced. Double centering will also increase the accuracy of the angle that is measured. In general, the angle obtained will have half the error of the possible instrument error. That is a 5-second theodolite can measure to 2.5 seconds.

All measurements made with the total station, except for certain crude ruses such a plane table mapping (Cruikshank, in review-c), should use double centering. Many data recorders can be set to enforce use of the double centering method.

Errors in measuring angles will be greatest where there is a large variation in vertical angle, or where one point is much further away than other points. This error can be reduced by taking at least two sets of double-centered readings to each point and averaging the readings.

In measuring a horizontal angle surveyors will often measure both the interior and exterior angles using double centering, and then check that the two angles sum to 360°. The interior angle is the angle smaller than 180° between two points, and the exterior angle is the angle greater than 180°. If the interior and exterior angles do not sum to 360° then each angle is corrected by the same amount so that the sum is 360°.

Some total stations allow the graduated circle to be turned. Turning this between sets of measurements allows the angle to be measured on different parts of the graduated circle, this helps eliminate potential errors on one part of the circle when the angles are averaged or otherwise corrected. When the graduated circle is turned in this way instrument North changes for every pair or readings. Generally, this is not a problem since it is changes in angles that are being measured. This procedure is not recommended for beginning users!

Angles by repetition

The accuracy of the angle can also be improved by repeatedly measuring the same angle. Each measurement of the angle is regarded as being a double-centered measurement.

Some Total stations allow you to "accumulate" angles. That is, after turning the angle from point *A* to *B* you can return to *A* without the angle counting backwards. After aligning it on *A* you can again turn the angle to *B* and the display will increase the angle. This allows you to “accumulate” a large angle. Averaging the angle by the number of times you turned the angle gives you a more accurate reading. This is not as good a procedure as double centering.

Reciprocal vertical-angle observations

Double-centering will remove most of the error associated with making a single angle measurement that is related to instrument and operator imperfections. There is still the problem of dealing with curvature and refraction errors. That is, for long distances you have to allow for the curvature of the earth and refraction of the distance-measuring light beam. This is best handled by readings from both ends of the line, and averaging the elevation difference. This is a good procedure to follow since it will always provide a check on your work, and will be a natural part of measuring closed shapes (Cruikshank, in review-b).

A first exercise

The laboratory exercise consists of measuring an angle and performing coordinate calculations on two reflectors. This exercise familiarizes students with the operation of the instrument without having to worry about the logistics of a more complex surveying task. It also provides practice in the basic procedure for measuring the angle between two stations, which is the basic measurement in surveying. Measuring a more complex shape is just a function of how the various angles and distances are related.

The angle is first measured without an electronic data logger, and is then repeated using an electronic data logger. This is done for two reasons: First students have to learn what they are measuring, and this lets them measure the angles without the complexity of also learning how to use the data logger. The first time this exercise was used the students worried more about working the data logger that what they were measuring. The goal is to get the students comfortable with what is being measured and then to have the electronic notebook supplement their paper notebooks. The exercise also emphasizes that the key to understanding surveying is that it is best when the angle between objects is measured – there is no need to be concerned with measuring angles with respect to North. Trying to establish North and set the instrument precisely as is impracticable. This is something that needs to be done later by rotating the surveyed network to North.

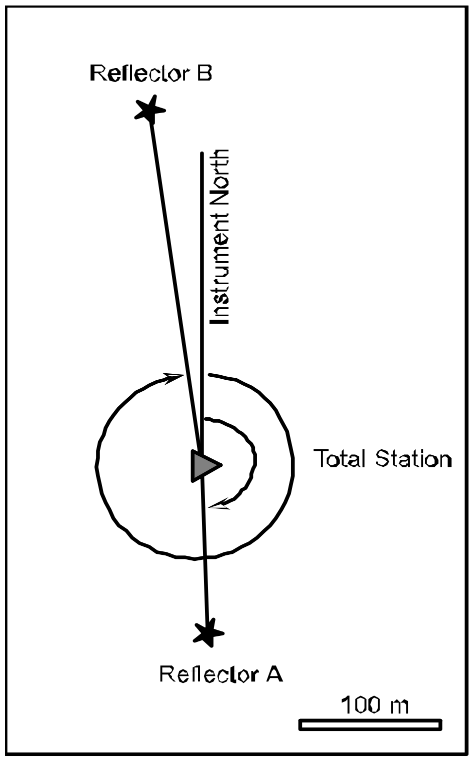

Figure 6. Geometry for first exercise on making measurements with a total station. The objective is to determine the angle between the two stations, and calculate the coordinates of the reflectors with respect to the instrument using an arbitrary coordinate system.

How to Proceed

1) Set up a page in your notebook, containing date, location, project name, name of individuals in the group and a sketch of the reflector and instrument setup. Label each station, and the instrument or reflector height at each station. A well-labeled sketch is invaluable in surveying. Record temperature and pressure and determine the EDM correction factor.

2) Decide on instrument north, and set the zero direction of the instrument appropriately. In this exercise we are measuring an angle between two reflectors, so true north is not important. The calculations are made easier if instrument north is set just counter-clockwise of the first reflector, with the second reflector in a clockwise direction from the first reflector.
3) Take a Face 1 – Face 2 (F1/F2) reading to the first reflector. Compute the corrected F1 value.
4) Take a Face 1 – Face 2 (F1/F2) reading to the second reflector. Compute the corrected F1 value.
5) Take the difference between the values from parts (4) and (5). This is the angle between the two reflectors. Repeat the measurement 2 more times for repeatability. Average the three readings to get a final angle. The number of times you repeat the measurement depends on how well your readings are grouping. You will want to discard any data that is very different from the other readings.

You should always make an F1/F2 reading to reflector *A*, and then *B*, then *A*, then *B*, and if needed to *A*, and then *B* again. This is *not* the same as making 3 F1/F2 readings to *A* and then 3 to *B*. The reason is that there may be some slight drift in the instrument. Secondly, it is harder to detect error. The above procedure should be followed when measuring angles.

Typical results from a set of readings

a) The measurements should result in 12 measurements, for space only two sets (or 8 measurements) are shown. A 5-second total station was used for these measurements by students.

Instrument Name	Instrument Height (m)	Point Name	Reflector Ht (m)	Instrument Position	Horizontal Angle (°)	Vertical Angle (°)	Slope Distance (m)
C	1.749	A	1.739	Face 1	179.99889	90.43639	128.461
C	1.749	A	1.739	Face 2	359.99861	269.55833	128.459
C	1.749	B	1.776	Face 1	352.21139	89.68944	273.232
C	1.749	B	1.776	Face 2	172.21028	270.30500	273.233
C	1.749	A	1.739	Face 1	180.00167	90.43667	128.459
C	1.749	A	1.739	Face 2	0.00111	269.55917	128.459
C	1.749	B	1.776	Face 1	352.21222	89.69000	273.231
C	1.749	B	1.776	Face 2	172.20861	270.30528	273.233

b) Each of the pairs of F1/F2 readings is then corrected (using equations 10).

For example, taking the first pair of readings:

$$HAR_{F2} - HAR_{F1} = 359.99861 - 179.99889 = 179.99972$$

Since this number is less than 180°, and $HAR_{F2} > HAR_{F1}$ we must decrease HAR_{F1} and increase HAR_{F2} by the same amount so that they will be 180° apart:

$$HAR_{F1*} = HAR_{F1} - (180 - 179.99972) / 2 = 179.99875$$
$$HAR_{F2*} = HAR_{F2} + (180 - 179.99972) / 2 = 359.99875$$

The two readings are now 180° apart. This calculation can also be done using equation 10a.

For the vertical angle, we first sum the two vertical angles

$$\text{Angle Sum} = 90.43639° + 269.55833°$$

and then find the difference from 360°

$$360° - 359.99472° = 0.00528°$$

The angles sum to less than 360°, so we have to increase each angle by the same amount

$$ZA_{F1*} = 90.43639° + .00528° / 2 = 90.43903°$$

or we can just apply equation (10b). The corrected angles for the remainder of the data set are then:

Corrected Angles	HAR	ZA
To A, reading 1	179.99875	90.43903
To A, reading 2	180.00139	90.43875
To B, reading 1	352.21083	89.69222
To B, reading 2	352.21042	89.69236

c) Finally the vertical angles and slope distances are averaged, and the difference between each pair of corrected horizontal angles is calculated and averaged. This gives the best measurement of the angle between the two stations.

Vertical Angles	
Average ZA from C to A	90.43889°
Average ZA from C to B	89.69229°
Range of ZA from C to A	0.99936"
Range of ZA from C to B	0.50148"
Slope Distances	
From C to A	128.460 m
From C to B	273.232 m

Interior Angle	
Angle ACB from first set	172.21208°
Angle ACB from second set	172.20903°
Average of both sets	172.21056°
Difference	11"

d) These angles are now used in the coordinate calculations (using equations 7, and an instrument position of 0 N, 0 E and 0 Z). No great care was taken to orient the instrument, so the coordinate system is arbitrary. If equations (7) are used in a spreadsheet the angles will have to be converted to radians for the sine and cosine functions.

The east coordinate of reflector A is:

$$\text{Easting} = I_E + SD \sin(ZA) \sin(HAR) \tag{7a}$$

$$E_A = 0 + 128.460 \text{ m} \times \sin(90.43889°) \times \sin(179.99875°) = 0.002 \text{ m}.$$

This value looks correct. We know the station is almost due south (4.5 seconds to the east of south). 4.5 seconds over a distance of 128 m is only going to be a couple of mm of easting.

The north coordinate of reflector A is:

$$\text{Northing} = I_N + SD \sin(ZA) \cos(HAR) \tag{7b}$$

$$N_A = 0 + 128.460 \text{ m} \times \sin(90.43889°) \times \cos(179.99875\ 248) = -128.456 \text{ m}.$$

Again, this value looks correct. The coordinate is about 128 m to the south (negative northing) of the instrument station.

The elevation of the ground under reflector A is:

$$\text{Elevation} = I_Z + SD \cos(ZA) + (IH - RH) \tag{7c}$$

$$Z_A = 0 + 128.460\text{m} \times \cos(90.43889°) + (1.749\text{m} - 1.776\text{m}) = -1.011 \text{ m}.$$

Again, this value looks resonable. The tripod heights are about the same, and the vertical angle is greater than 90° so the instrument was pointing downwards about 0.4°. Over 128 m this is about 1m of vertical distance

Summary

Total stations are valuable field tools for geologists. Although they are capable of great precision, this precision is only realized through correct surveying procedures. In this paper the basic method for making observations and the basic calculations were presented: They can be summarized as follows:

1) There are three fundamental measurements - horizontal angle, vertical angle and slope distance. Everything else is derived from these three.
2) Instrument north is arbitrary, and is best set internally to a survey.
3) Surveying procedures are extremely important in eliminating, controlling, as assessing errors. All measurements have error.
    a) Use double centering to help remove instrument and operator errors.
    b) Make observations from both ends of a line, to eliminate curvature and refraction errors
    c) Apply atmospheric corrections to obtain correct distances from an EDM

Knowledge of how the instrument operates and the consequences of various errors is important, since it allows the user to judge how important corrections are going to be. This makes for a more efficient use of the instrument. A simple exercise was outlined that allows students to make basic measurements and get familiar with the operation of the instrument.

Some useful rules of thumb

Surveying often involves judgements on how much work you need to do for the precision that you want. Also, when trying to figure out if an error is an error in calculation or in observation, certain rules of thumb are useful.

- Distance errors normal to the line of sight: 1 second is 0.5 mm over 100 m of distance. A 20 second error is 1 cm per 100 m of distance.
- 1°C difference from 20°C causes a 1 ppm or 1 mm/km correction in EDM distances.
- 1 hPa from standard atmospheric pressure causes a 1 ppm or 1 mm/km correction in EDM distances
- The curvature correction on vertical distances is about 1 mm over 100 m of horizontal distance, and about 1 cm over 350 m of horizontal distance (equation 9).

Web Resources

Links to sources of surveying information and software that the reader may find helpful are located at the PSU Geology Total Station Resource Page: http://www.geol.pdx.edu/Courses/TotalStation/

Acknowledgements

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Appendix A. Using Microsoft Excel for Coordinate Calculations

A spreadsheet is a convenient way to perform data reduction and coordinate calculations. There are two things that you have to be careful with, one is that the worksheet trigonometric functions use radians, and the other is the difference between orientations expressed as an azimuth and the mathematical definition of an angle. The latter is important so that the trigonometric functions return values with the correct sign.

Using Radians

Worksheet functions tend to use radians, so angles must be expressed as radians. Excel provides the RADIANS() function for converting degrees to radians, and the DEGREES() function for converting radians to degrees. These functions can simply be used within a trigonometric function:

=COS(RADIANS(D5))

Using Angles

Azimuth's, and the angles measured by a total station are measured in a clockwise sense from north. In mathematics, a positive angle is measured counter-clockwise from the x-axis. In the calculations presented in this paper this would be the east direction. In order for the calculations in equations 7 to be correct, we have to represent HAR as an angle, not as an azimuth. The conversion is quite simple. For azimuths from 0° to 90° the angle is simply 90° – Azimuth. For azimuths from 90° to 360° the angle is 450° – Azimuth. If an azimuth is in cell D5, the correction can be entered using Excel's IF() function:

=IF(D5 > 90, 90–D5, 450–D5)

If the user converts azimuths from the total station to angles using the above functions, then equations 7, which return the change in easting and change in northing will have the correct sign.