I. Measurement Errors

A. *Error:* Difference between the *measurement* of a quantity and the *true value* of the quantity. The exact error in a measurement is unknown.

B. Measurement number vs Counting number

C. Error Sources - where they come from

1. Natural

2. Instrumental

3. Personal

D. Error Types - how they affect measurements

0. Mistake

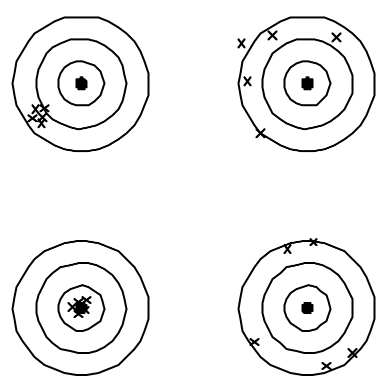
1. Systematic

2. Random

E. Measurement Quality

1. Accuracy

2. Precision



F. Minimizing error effects

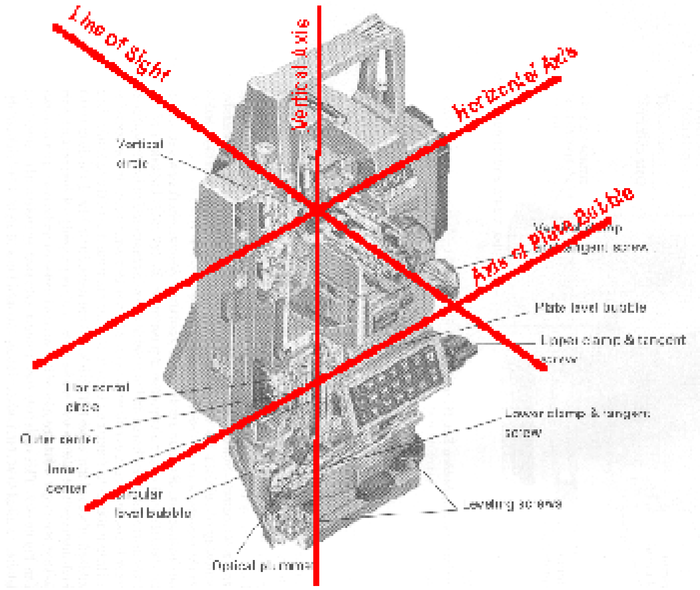
1. Mistakes

2. Systematic

3. Random

II. TSI Checks and Adjustments

A. TSI Axes



Vertical Axis -- the axis about which the instrument rotates in a horizontal plane.

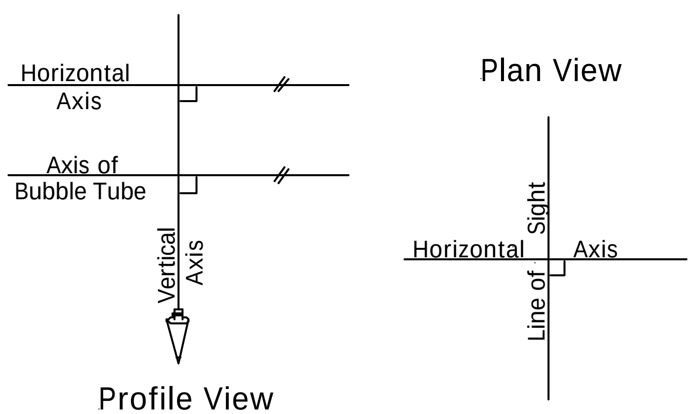
The *Horizontal Circle* is perpendicular to the Vertical Axis

Horizontal Axis -- the axis about which the telescope rotates in a vertical plane.

The *Vertical Circle* is perpendicular to the Horizontal Axis

Line of Sight - a passing thru the intersection of the cross hairs and the optical center of the objective lens.

The EDM path should be coincident with the Line of Sight.



B. General Considerations

TSI checks and adjustments are described in detail in the instrument's manual. Special adjustments or procedures unique to the particular TSI will also be indicated and those should be used in lieu of the ones covered here. Many adjustments can be performed by the surveyor while others require the TSI be sent in to a qualified repair facility.

The variety of TSI designs does not allow for a single adjustment procedure for all. The more general are described; the surveyor should consult the TSI manual for specific adjustments. Primary checks and adjustments covered here include:

1. Plate Bubble
2. Circular Bubble
3. Optical Plummet
4. Line of Sight
5. Tilt Sensor
6. EDM/LOS collinearity

Checks and adjustments should be made in the order specified as later adjustments can be affected by earlier ones.

Some maladjustments can be compensated *procedurally* (eg, bubble run) as well as *mechanically*. In many cases it takes less time (and is less frustrating) to do this rather than pull out the adjusting pins or screw drivers when small maladjustments are encountered. A few require the instrument be sent in for repair if it is outside allowable tolerances.

Since TSI maladjustments can be compensated by either field procedures or physical adjustment they are *systematic errors*.

When performing checks it is important to ensure that any observed maladjustment is instrumental error and not due to poor testing condition. The operator should make sure:

- ✓ to use a sturdy tripod with secure hardware
- ✓ to have a stable setup
- ✓ set up in a shady location with flat level sights in opposite directions
- ✓ to avoid sighting over heat reflective surfaces (eg, asphalt) and to keep lowest part of sight line at least two feet above the ground
- ✓ to minimize pointing error by using longer sights (at least 200 ft)
- ✓ to use only the right tools
- ✓ weather are agreeable; this often affects the instrument operator more than the instrument itself

An instrument log should be kept to record when checks are performed and their results. A consistent maladjustment may indicate a needed repair.

Golden rule: Check, check again (maladjustment should be consistent), adjust, re-check.

C. Adjustments

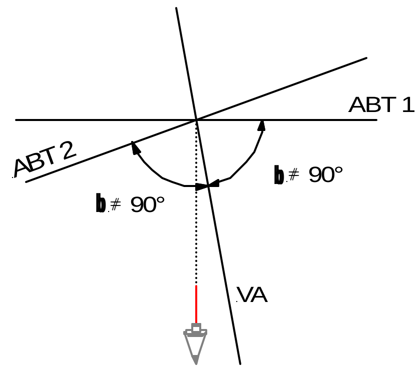
1. Plate Bubble

What it affects:

Pretty much everything as the instrument must be (at least reasonably) level in order to make angle or distance measurements.

Check:

Roughly level the instrument in all directions.
Align the plate bubble over two leveling screws and carefully center the bubble (ABT1).
Rotate the instrument approximately 180˚ and check the bubble run (ABT 2).



If the bubble runs:

Procedural: bring the bubble back half-way using the leveling screws. The bubble should stay the same number of divisions off-center as the instrument is rotated.

Mechanical: bring the bubble back half-way using the adjusting nut/screw at one end of the bubble vial.
Re-center the bubble using the leveling screws. The bubble should stay centered as the instrument is rotated.

Be sure to check the bubble 90˚ to the initial orientation.

2. Circular Bubble

What it affects:

Rough leveling of the instrument; the TSI can still be leveled using the Plate Bubble.
If tribach is used separately for prisms, etc, then primary leveling functions are affected.

Check:

Use the Plate Bubble to completely level the instrument then check the circular bubble.

If the circular bubble is not centered:

Procedural: ignore it and use the plate bubble to level the instrument

Mechanical: center the bubble using the adjusting nuts/screws.

3. Optical Plummet

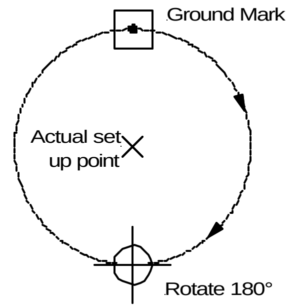
What it affects:

All measurements as the TSI may not be set up directly over the point.

(a) Plummet that rotates with the instrument

Check:

Level the instrument over a distinct mark.
Rotate the instrument 180˚



If the plummet is not still centered over the mark:

Procedural: bring the instrument back halfway toward the mark.
As the instrument is rotated it will inscribe a circle centered on the station mark.

Mechanical: Use its adjusting nuts/screws to bring the optical plummet back half-way toward the mark. Re-center the instrument over the mark.
The optical plummet should stay centered on the mark as the instrument is rotated.

(b) Stationary plummet.

What if the optical plummet is built into the tribrach and does not rotate with the instrument? While not the case with most TSIs, separate tribachs for prisms usually have a built-in optical plummet. In this case the easiest way to check the optical plummet is to use a plumb bob. Most tripods have an insert for the instrument screw allowing a plumb bob to be used.

Check:

Using the plumb bob, center the instrument over a distinct mark. Remove the plumb bob and sight thru the optical plummet

If the plummet is not centered over the mark:

Procedural: leave instrument as is since it was correctly set up using the plumb bob.

Mechanical: Use its adjusting nuts/screws to bring the optical plummet to the mark.

Care must be taken to ensure that the insert allows the plumb bob to hang directly beneath the vertical axis of the instrument. An easy way to check this is using a TSI with an adjusted optical plummet. Set up over a mark using the plummet then hang the plumb bob. The plumb bob should be over the mark

4. Line of Sight (LOS)

Note: The reticule adjusting screws are covered and generally protected from accidental disturbance. In most cases these adjustment shouldn't be necessary unless the TSI has been dropped or otherwise roughly handled. If so it should probably be sent to an appropriate facility for repair, thorough cleaning and adjustment.

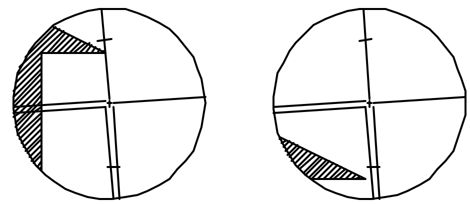
(a) Vertical cross hair

What it affects:

Horizontal angles if the upper or lower part of the vertical cross hair is used to point.

Check:

Set the upper part of the vertical cross hair on a distinct mark. Using the vertical slow motion, raise the line of sight until the mark is on the lower part of the cross hair.



If the mark is off the cross hair:

Procedural: Always use the cross hair intersection to point.

Mechanical: Remove the reticule cover near the eyepiece. Loosen a horizontal and a vertical reticule adjusting screw. While sighting through the telescope, rotate the reticule until the vertical cross hair is approximately half way back toward the mark. Carefully re-tighten the adjusting screws.

(b) Line of Sight perpendicular to horizontal axis

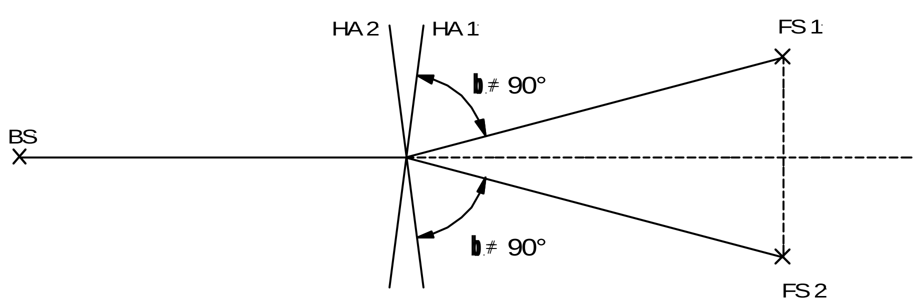
What it affects:

Horizontal angles; line prologation by scope reversal.

Check:

Manuals for newer equipment may detail a check and adjustment procedure specific to the particular TSI brand or model; if so, use it.

For all TSIs, as well as theodolites and transits, the traditional *double centering* method can be used to check and adjust the instrument:



Back sight a distinct point (BS), plunge the scope and set a fore sight point (FS 1). Rotate the TSI to re-sight the back sight point. Plunge the scope again and check against fore sight point.

If the sight is off the fore sight point:
Remove the reticule cover. Use the horizontal reticule adjusting screw(s) to move the cross hairs one-quarter of the way back toward the first fore sight point. A vertical adjusting screw may need to be loosened first to allow the reticule to be shifted horizontally. Carefully re-tighten the adjusting screws.

5. Tilt Sensor

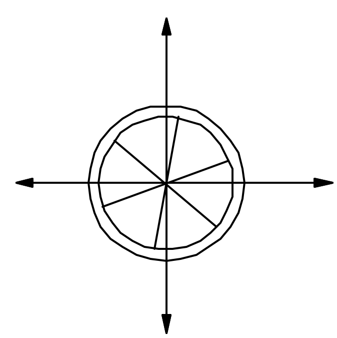
What it affects:
Zenith/vertical angle measurement which also affects horizontal and vertical distance determination.

Check and Adjustment:
The procedure for the particular TSI is explained in its manual. It generally involves reading the zenith angle to a point in the direct and reverse positions. The allowable difference is specified in the manual as are the steps necessary to adjust the instrument.

6. EDM/LOS collinearity

What it affects:
Signal acquisition on long sights. Distance attainable due to signal dispersion.
This adjustment is not applicable to all TSIs. Those having an audible tone or other method to indicate a return signal can use this method as a check.

Check and Adjustment:
Sight the center of a fixed prism with the TSI. Zero out or record the horizontal angle.
Turn on the audible tone and using the slow motion scan horizontally to the right until the signal drops off. Record the horizontal angle reading.
Scan to the left until the signal picks up; continue to the left until the signal drops off. Record the horizontal angle. The angle difference between the right and left signal loss positions approximates the signal width.



Re-point to the center of the prism and repeat the process this time scanning vertically.

The center pointing should be between both horizontal and vertical extremes (ideally it would be in the middle of both). This will assure that sighting a prism, as long as it is within the instrument's range, will result in a return signal.

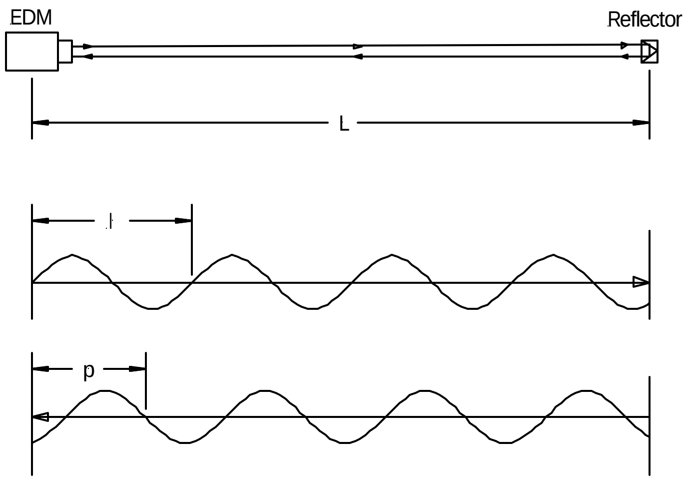
Check the TSI manual for specifics on maximum or minimum signal widths. If the TSI does not meet these then it must be sent in for adjustment.

III. TSI - Distance Measurement Considerations

A. Distance Measurement - EDM

1. Principles of Operation - Electro-optical

a. Phase shift



$$L = \frac{1}{2}\left[n l + p\right]$$

λ : wavelength
n : number of full wavelengths
p : partial wavelength

b. Distance determination

l.(m)	p. (m)
10.000	7.142
100.00	67.14
1000.0	867.1
10000.	3867.

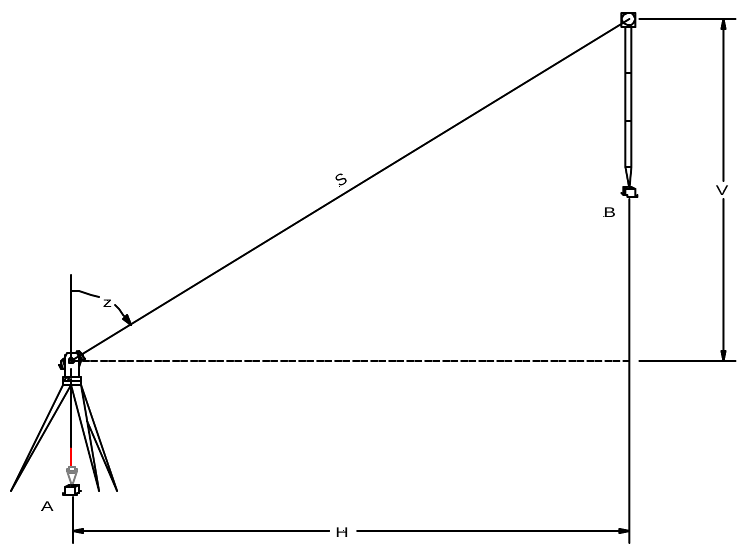
Length = 3867.142

÷ 2 = 1933.571

c. Slope reduction - general

Slope distance & Zenith angle ➜ Horizontal & Vertical distances

$$H = S * \sin(z)$$
$$V = S * \cos(z)$$



2. Error Sources

a. Personal

(1) Set up and centering - TSI and reflector

(2) Instrument and reflector height determination

(3) Temperature and atmospheric pressure determination

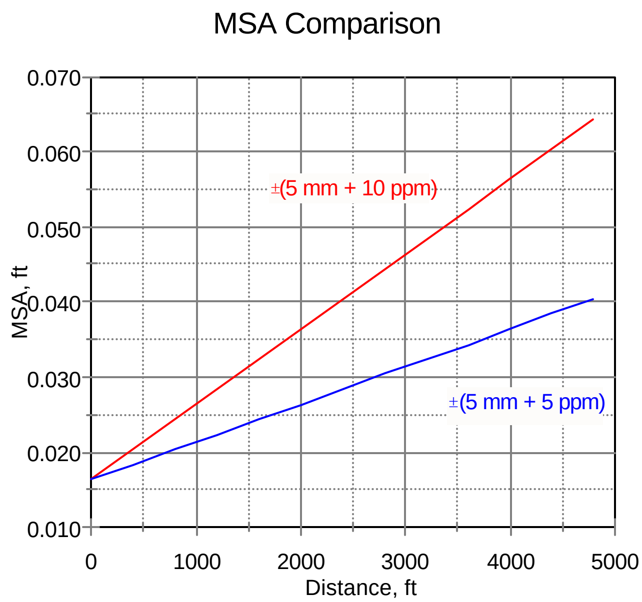
b. Instrumental

(1) MSA: stated as a constant and a proportional part

eg, ±(5mm + 3 ppm)

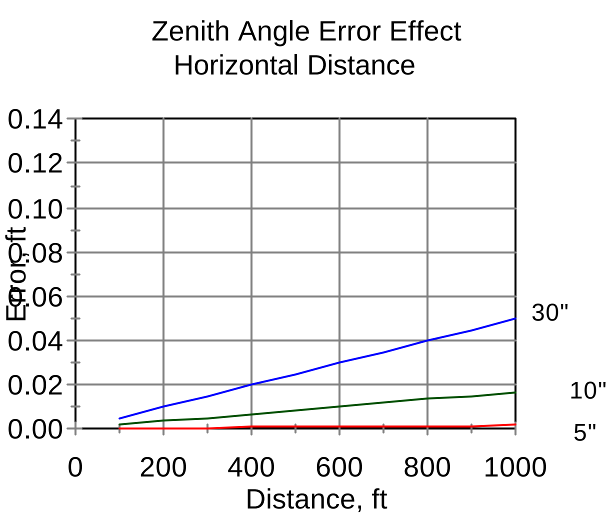
example: expected error in a 1000.00 ft distance?

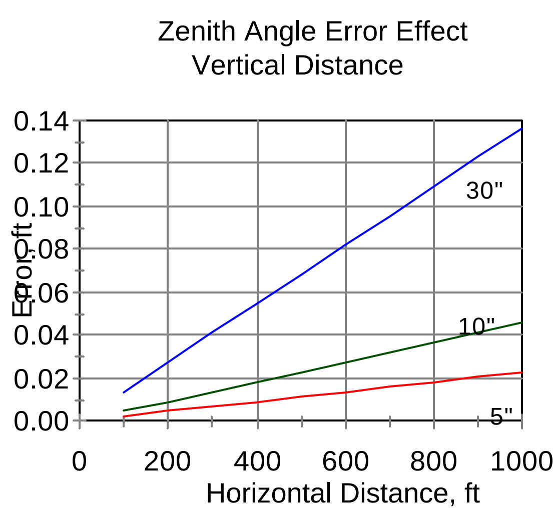
$$\text{MSA} = \pm\left(5\text{ mm} * \frac{39.37\text{ in}}{1000\text{ mm}} * \frac{1\text{ ft}}{12\text{ in}} + \frac{5}{1{,}000{,}000} * 1000.00\text{ ft}\right)$$
$$= \pm(0.016\text{ ft} + 0.005\text{ ft})$$
$$= \pm 0.021\text{ ft} \approx \frac{1}{47{,}600} = 21\text{ ppm}$$



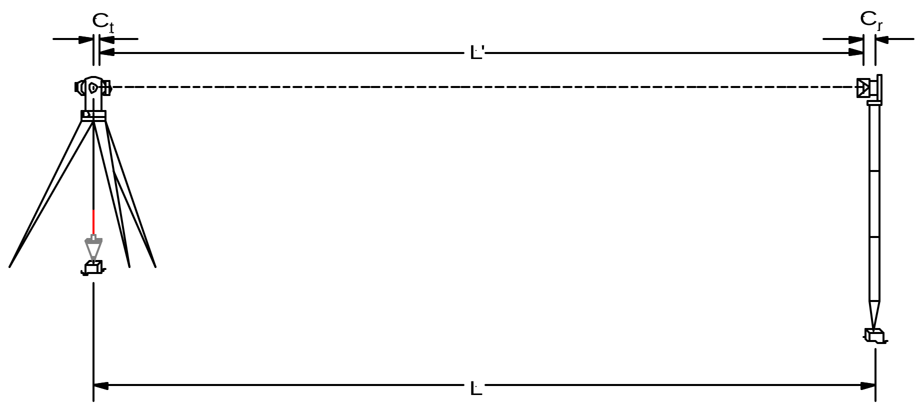
(2) Vertical indexing

Affects slope reduction
Single- and Dual-Axis Compensation





(3) Instrument and reflector constant



$$L = L' + C_t + C_r$$

L' : distance between TSI and reflector “centers”
C_t : TSI offset
C_r : prism offset

Determine the combined constant, $k=C_t+C_r$, by:

- Calibration base line - rigorous
  Reference: NOAA Tech Mem NOS NGS-10
  Use of Calibration Base Lines
  Data and *CALIBRATE* program at
  http://www.ngs.noaa.gov/CBLINES/calibration.html
- Local base line - periodic checks
  Refer to attached procedure

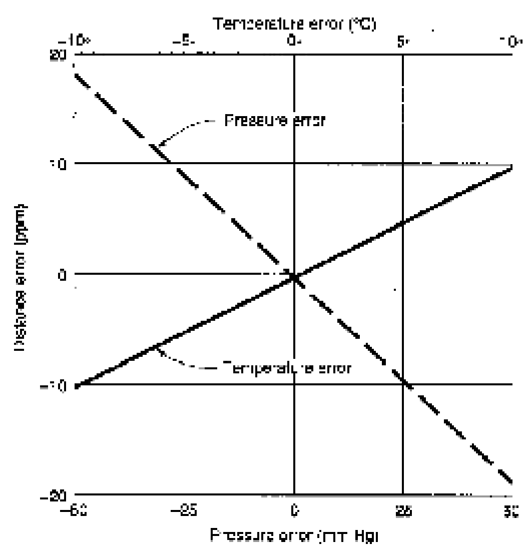
c. Natural

(1)Temperature and atmospheric pressure

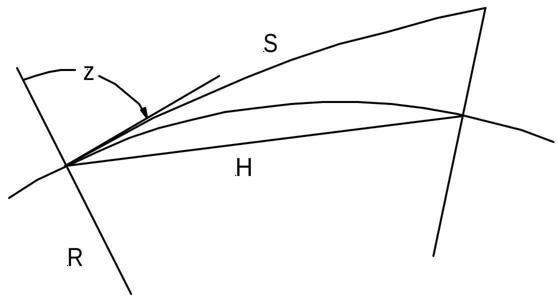
$$ppm = 278.96 - \frac{10.5 * P}{1 + 0.002175 * t}$$

P: pressure; “Hg
t: temp; °F

$\Delta 2°F \approx 1$ ppm
$\Delta 0.1'' Hg \approx 1$ ppm



(2) Earth curvature and refraction



$$H = S * \sin(z) - \left(\frac{S^2 * \sin(2z)}{2R}\right)\left(1 - K/2\right)$$

$$V = S * \cos(z) - \left(\frac{S^2 * \sin^2(z)}{2R}\right)\left(1 - K\right)$$

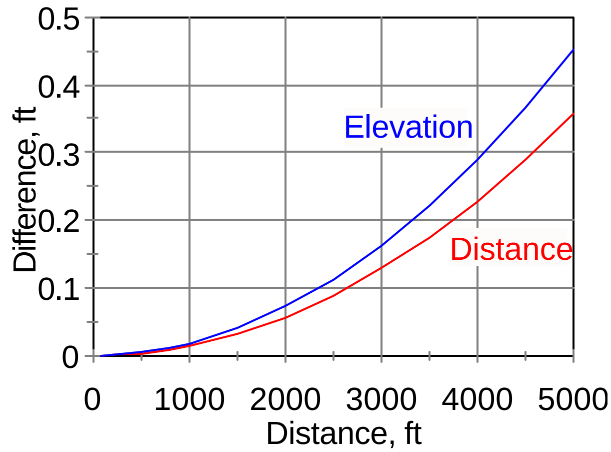
S: measured slope distance
z: zenith angle
K: refraction constant; 0.142
R: radius of earth; $2.09\text{x}10^7$ ft

Curvature and refraction effect:

Zenith angle of 70°; All units are feet

S	H	H, c&r	diff	Prec: 1 in	V	V, c&r	diff
100	93.969	93.969	0.000	657,776	34.202	34.202	0.000
500	469.846	469.843	0.004	131,554	171.010	171.006	0.005
1000	939.693	939.678	0.014	65,777	342.020	342.002	0.018
2500	2349.232	2349.142	0.089	26,310	855.050	854.937	0.113
5000	4698.463	4698.106	0.357	13,155	1710.101	1709.648	0.453

Curvature and Refraction
(70° zenith angle)



d. Combined Random Errors: MSA and TSI &reflector set up errors

Ref: Section 6.12, *Adjustment Computations*, Wolf & Ghilani

$$\sigma_D = \sqrt{\sigma_i^2 + \sigma_r^2 + a^2 + (D * b)^2}$$

- σ_D Estimated distance error
- σ_i TSI centering error
- σ_r Reflector centering error
- a MSA constant
- b MSA proportional part
- D measured distance

example:

A distance of 453.87 feet is measured with a TSI with an MSA of ±(5 mm + 10 ppm). Instrument centering error is estimated as ±0.003 ft and the pole mounted reflector centering error is ±0.01 ft. What is the total expected error in the distance?

$$\text{MSA constant: } 5\text{ mm} * \frac{39.37\text{ in}}{1000\text{ mm}} * \frac{1\text{ ft}}{12\text{ in}} = 0.0164\text{ ft}$$

$$\sigma_D = \sqrt{(0.003)^2 + (0.01)^2 + (0.0164)^2 + \left(453.87\frac{10}{1{,}000{,}000}\right)^2}$$

$$= \pm 0.020\ ft$$

IV. TSI - Combined Instrument/Prism Constant Determination

Objective

To accurately determine the combined instrument and prism constant for a particular total station and prism combination without using a calibration baseline.

Equipment

Total station with tripod, prism, prism pole with tripod, three stakes, note form.

Preliminary Considerations

For distance measurements the prism will be mounted on a prism pole and held in place with a pole tripod. Use the rod bubble to set the prism pole vertical (*note:* the pole bubble adjustment should first be checked).

Determine the atmospheric correction, record it, and dial it in (if necessary).

The prism constant should be set to 0 on the total station.

It is preferred that the prism be nearly at the same elevation as the total station. Prior to measuring a distance rotate the telescope until the zenith angle in the direct position reads 90˚ (use the vertical lock and slow motion). Raise or lower the prism until it is centered on the cross-hairs. Lock the prism pole and check the pole bubble.

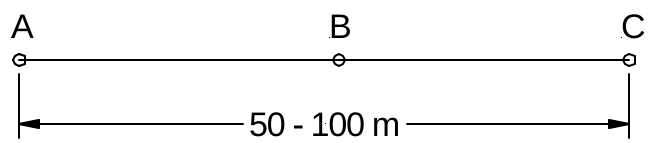
All horizontal distances are to be measured five times and averaged. Always ensure that you are measuring and recording a *horizontal* distance, not slope or vertical.

Each stake must have a distinct mark on its top (eg, tack, small hole, inked cross, etc) and the total station or prism pole must be carefully set with respect to the mark.

Field Procedure

1. Establish a baseline

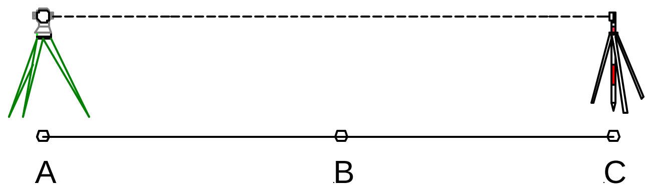
Select an area of open flat terrain allowing a clear sight of 50 to 100 meters.
Firmly pound a stake at each end of the area; these are points A and C on the diagram below.
Set up and level the TSI over point A.
Use the TSI to place the third stake at point B, **about** midway and **accurately** on-line between points A and C.



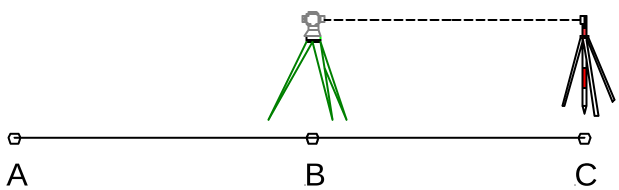
2. Measurements
The procedure detailed below should be performed twice: first with the instrument in the *direct (face left) position* and then in the *reverse (face right) position*.

Set up the total station over point A and the prism over point C.
Measure the horizontal distance AC.
Move the total station to point B.
Measure the horizontal distance BC.
Move the prism to point A.
Rotate the total station and measure the horizontal distance BA.

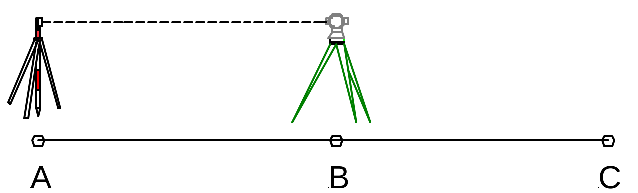
First measurement



Second measurement



Third measurement



In the Reverse position you may start at point B and reverse the measurement order. Reset the instrument and prism poles, however, to ensure independent measurements.

Computations

The equation to determine the combined constant is: k_i = AC - (BA +BC).
Compute the combined constant twice, once for each measurement set; k_1 and k_2.
When calculating use averaged distances carrying one more decimal place than shown by the instrument.

If the two k's are not within 5mm of each other then repeat the measurement set.
Record the combined constants and show their average to the nearest millimeter.

If you initially set the offset in the instrument to 0 then the average k represents the combined instrument and reflector constant. If you left the instrument set at the prism constant (eg, 30 mm) then the computed k should be close to 0 mm.

k_1 = ________________ – (________________ + ________________)

k_1 = ________________ *feet meters*

k_1 = ________________ *mm*

k_2 = ________________ – (________________ + ________________)

k_2 = ________________ *feet meters*

k_2 = ________________ *mm*

average k = ________________ *mm*

multiply feet by 304.8006 to get millimeters

Inst Manuf & model: ____________________ S/N: ________________

Prism type: ____________________ ID#: ________________

Crew: ________________________ ________________________

________________________ ________________________

Date: ____________________ Press: ____________________

Temp: ____________________ ppm: ____________________

Inst/prism constant preset to: ________ mm

Distance units are (circle one): *feet* *meters*

Segment	Meas #	Direct	Reverse
AC	1	________	________
	2	________	________
	3	________	________
	4	________	________
	5	________	________
	average	________	________
BC	1	________	________
	2	________	________
	3	________	________
	4	________	________
	5	________	________
	average	________	________
BA	1	________	________
	2	________	________
	3	________	________
	4	________	________
	5	________	________
	average	________	________