# Topic 5: THEODOLITE

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# PREVIEW

## Introduction

The role of the theodolite in traversing and detail surveys is fundamental to all surveying. This topic covers the description of the theodolite and its use in traversing to provide a network of control points which may then be used as a base for gathering information for your engineering project.

The processes of computing and adjusting a traverse are also covered.

The use of the theodolite in detail surveys is covered in later topics.

## Objectives

After completing this topic you should be able to :

- set up a theodolite and read horizontal and vertical angles
- calculate angle means from your readings
- adjust angles to meet the geometric criterion
- compute and adjust a traverse by trigonometric process
- compute coordinates for your traverse points
- appreciate the nature of errors affecting the work

## Readings

REQUIRED

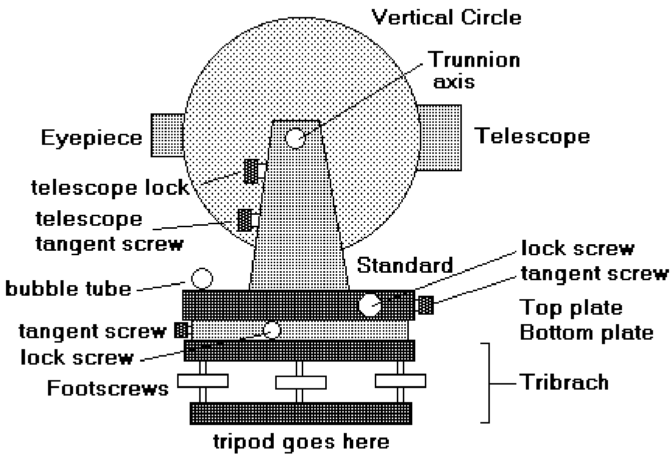
**Read:** *Muskett* Chapter 3 Sections 3.1 to 3.5 inclusive

# THEODOLITE

A theodolite measures horizontal and vertical angles

*	ours have moderate accuracy of 20".
*	Theodolites reading to 1" are in common use.

# BASIC OPTO-MECHANICAL THEODOLITE




*	the **standards** support the **trunnion or horizontal axis**.

*	the vertical circle is fixed with 0° being vertically upwards to the zenith (normally)

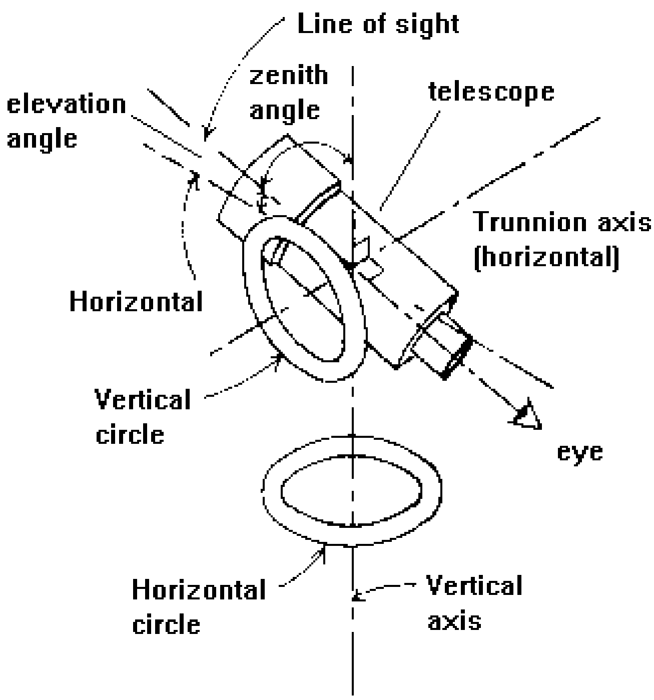
*	a horizontal plane passes through 90° and 270° (referred to as zenith angles).

*	the **Horizontal circle** is engraved on the top surface of the bottom plate.

*	the Top (Upper) plate holds the **plate bubble** that is used to level the instrument.

*	the Top and Bottom plates have **clamps** and **tangent screws**

*	**if the bottom plate is free** to rotate, and the top plate is clamped, the horizontal angle reading is fixed, (since the horizontal circle is on the bottom plate).




from Muskett, "Site Surveying", p. 33

* **if the bottom plate is fixed**, and the top plate rotates, the horizontal angle reading will change.

* If the telescope is rotated about the trunnion to point in the opposite direction, it's called **transitting**

* this is a **very important concept** when measuring horizontal angles accurately.

The **face** of the current observation (telescope position) is the side on which the vertical circle is, when viewed from the eyepiece, ie. either **face left** or **face right**

The **telescope** has its own **clamp** and **tangent** screws. (The clamp screws require **only finger tip pressure**!)

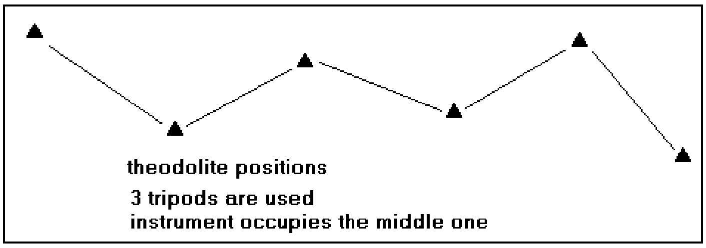
On some old theodolites, the 90° - 270° line is brought into a horizontal plane using the altitude adjustment screw and bubble (this is analagous to a tilting level).

## MODERN, OPTICAL THEODOLITE

The circles are etched on glass, usually every degree, and **micrometers** are used to increase accuracy of reading.

Most have **no altitude bubble**, and instead, it is replaced by an **automatic vertical index** that requires no adjustment once instrument is level (like an automatic level).

It is usually possible to remove the instrument from the **tribrach** and replace it with a target which occupies exactly the same position.




This reduces errors, particularly centring errors. It is very important for situations requiring many, short, traverse legs (eg. in mines). It's called the **three tripod system**.

**Some Notes**

An **optical plummet** is used for centring (plus a **plumb bob**).

Various **reading systems** (micrometer or electronic) are used for the horizontal and vertical angles. Check them out in the pracs.

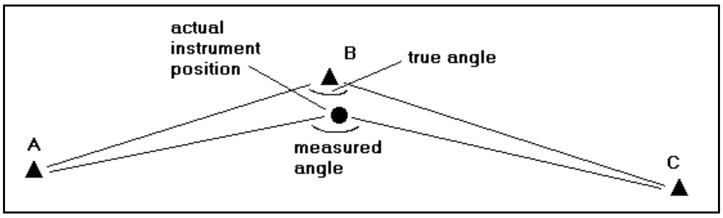
Some theodolites do not have an explicit bottom plate, but instead, some type of **horizontal circle adjustment screw** (for setting an angle, eg. 0°, on the horizontal circle). Electronic Theodolites have a 'set zero' button which effectively replaces the bottom plate.

## SETTING UP OVER A POINT

3 adjustments are necessary :
* **centring** (the hardest)
* **levelling**
* **collimataing** (removing parallax - as for a level)

## Centring over a known point

The instrument must be vertically above the ground station. This ensures that horizontal angles are correct.




1. Start with a **plumb bob** or centring rod to get it approximately right.

2. Using the footscrews, move the optical plummet cross hairs on to the ground mark.

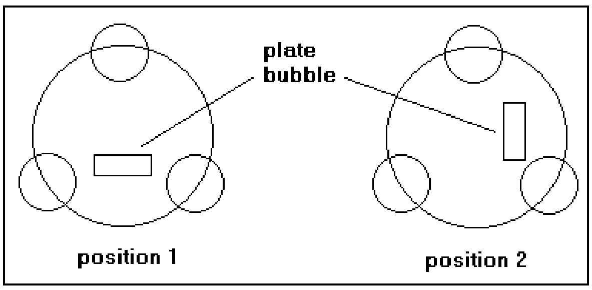
3. Roughly level the instrument using the **legs of the tripod** - the theodolite should stay almost on target

4. **Level with footscrews.** Move instrument above target; repeat level and move until done.

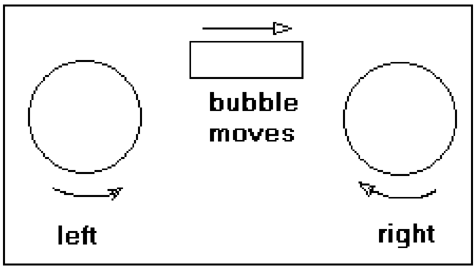
**NB**. This procedure is easier than levelling first with footscrews then centring by moving the instrument.

## Levelling the instrument

Similar to level, except that a more accurate bubble is used:




Turn bubble parallel to 2 footscrews; bring the bubble to the centre of its run by moving the footscrews in opposite directions (the bubble moves in the direction of your left thumb).




Turn the instrument through 90° and bring the bubble to the centre of its run by adjusting the third footscrew only.

Turn the instrument through a further 90° to check the adjustment of the plate bubble.

If the bubble remains in centre, then it's adjusted.

If not, move it back one-half of the movement from the centre and re-adjust for a further 90° turn.

**Repeat** the whole procedure, assuming this is the correct, stationary position for the bubble.

The bubble must remain in the same place in the tube during a 360° rotation of the instrument.

If the stationary position of the bubble is much off the centre it should be adjusted by an instrument maker.

## Collimating the instrument (removal of parallax)

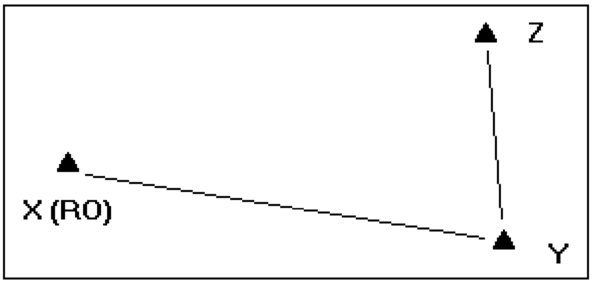
* as for level

* point instrument to infinity (the sky), adjust eyepiece so cross-hairs are fine and dark.

* focus on the target using the focussing knob or collar and check for parallax by moving your eye slightly, and check for a stationary image with respect to the cross-hairs

# THEODOLITE - MEASURING ANGLES

## PRELIMINARIES




We have set up the theodolite at Y, and we want the angle XYZ.

We need a target at each of X and Z, preferably the station itself, but that's not always possible.

### Alternatives

(i) a **picket** or stake, pointed at top end, which is plumbed (with a plumb bob) over the station.

(ii) **pencil** (or arrow) on top of the station.

(iii) **target on tripod** plumbed over the station.

(iv) **ranging pole** on station held vertically (eg. using staff bubble).

The thickness of the target should be proportional to the distance.

## HORIZONTAL ANGLES (OPTICAL MICROMETER THEODOLITE)

(i) select one station as reference object (RO) (X above).

(ii) set the horizontal circle to approximately 0°.

(iii) sight the RO on face left, obtaining an exact coincidence between the vertical cross-hair and the target. Record the horizontal angle.

(iv) swing the telescope to the right, and sight other targets (Z in this case) and record these angles.

(v) transit the telescope (now face right), and sight Z again; record the horizontal angle. (Unlock top plate to do this).

(vi) swing the theodolite left to record other targets again. This completes one round of angles.

A second round of angles is often read for increased accuracy.

(vii) transit the telescope (back to face left again); reset horiz. angle to about 90° then repeat.

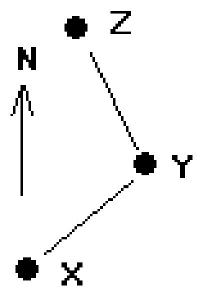
(viii) each angle is observed 4 times, and the mean can be calculated.

(ix) **Note**: Use the same point on the vertical hair (eg. the cross-hair intersection) for each sighting.

## HORIZONTAL ANGLES (ELECTRONIC THEODOLITE)

This method is designed to minimise the time spent by a pole person moving between the points defining the angle. The accuracy of the result may be slightly reduced by the extra theodolite manipulation.

1. Sight station X exactly, face left.
2. Set zero electronically on keyboard and book reading.
3. Change to face right, sight X exactly.
4. Book reading ( approx. $180^0$ )
5. Sight Z exactly.
6. Book reading.
7. Change face to face left and sight Z exactly.
8. Book reading (approx. $180^0$ different from <6.>
9. Extensions of this procedure may be used to measure multiple angles from a station.




When combining angle readings and electronic distance measurements for traversing, as you will in Prac's, measure the distance to the first point before you start your angles and the distance to the second point after you have completed your angles. This will avoid upsetting the theodolite angles when pressing the buttons on the edm (Topic 7).

## BOOKING ANGLES

| PROJECT NO.: | GROUP: |
|---|---|
| LOCATION: | PARTY NAMES: |
| WEATHER: | BOOKER: |
| EQUIPMENT NOS.: | DATE: |
| REMARKS: | TIME: |

| Station | | | Angles | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| At | To | Face | Horiz | Zenith | | | | | | | |
| *Y* | *X* | *L* | *$0^\circ 00' 00''$* [1] | *$90^\circ 10' 20''$* [2] | | | | | | | |
| | *X* | *R* | *$180^\circ 00' 40''$* [3] | *$269^\circ 49' 20''$* [4] | | | | | | | |
| | *Z* | *R* | *$273^\circ 41' 40''$* [5] | *$270^\circ 35' 00''$* [6] | | | | | | | |
| | *Z* | *L* | *$83^\circ 42' 00''$* [7] | *$89^\circ 25' 00''$* [8] | | | | | | | |

Superscripts show the order of readings.
This is a representation of the booking card you will use in Pracs. Other systems are used.

To reduce the horizontal angle from the readings, you must subtract left face from left face and right face from right face, viz:

Face left: $83^\circ 42' 00'' - 0^\circ 00' 00'' = 83^\circ 42' 00''$
Face right: $273^\circ 41' 40'' - 180^\circ 00' 40'' = 83^\circ 41' 00''$
Mean angle: $83^\circ 41' 30''$

This gives one reading of the horizontal angle, as you must read face left and face right pairs to eliminate theodolite geometry errors.

The face left and face right zenith angles to the same target should sum to $360^\circ$. If the sum is not correct, and there is no gross error, each angle is adjusted by the same amount to make the sum correct, viz:

To target Y: $90^\circ 10' 20'' + 269^\circ 49' 20 = 359^\circ 59' 40''$ so we must add *10”* to each angle:

$$90^\circ 10' 30'' + 269^\circ 49' 30 = 360^\circ 00' 00$$

## ANGLES & BEARINGS EXPLAINED

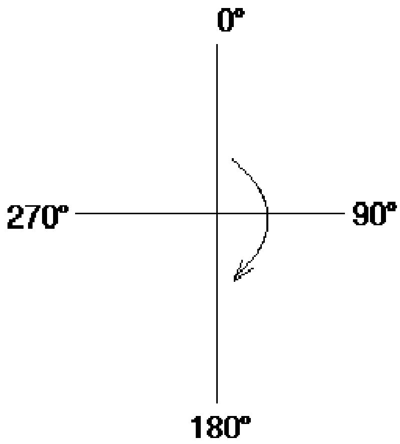
### Units

Arbitrary system : degrees, minutes, seconds.

### Types of Angles

1. **bearings** (by far the most important). The direction of a line measured clockwise from north.

2. measured **clockwise angles** (angles in theodolite are clockwise)

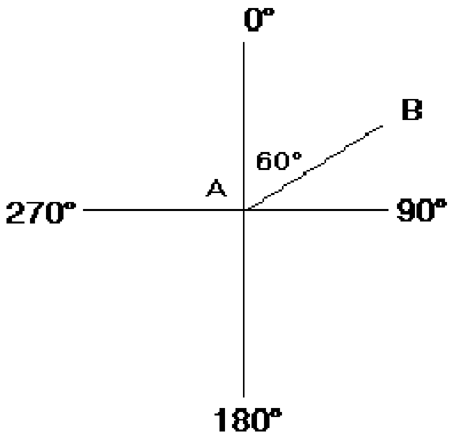



For horizontal angles, North is at 0°.

For vertical angles, 0° is normally vertically upwards.

## Bearings

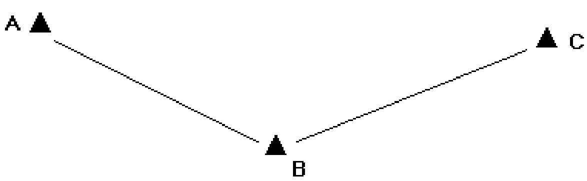
It is important to remember that a line has **2 bearings** (differing by 180°) depending on direction, eg:




**Bearing AB = 60°**
**Bearing BA = 240°**

## Setting Out a Horizontal Angle

1. We require to set out a horiz. angle ABC, knowing AB.




2. Set up instrument at B.

3. Set horiz. angle to 0° 0' 0" and sight to A.

4. Turn the angle off towards C (bottom plate locked, top plate unlocked).

5. Move signal (eg. arrow) until it is on the line of sight.

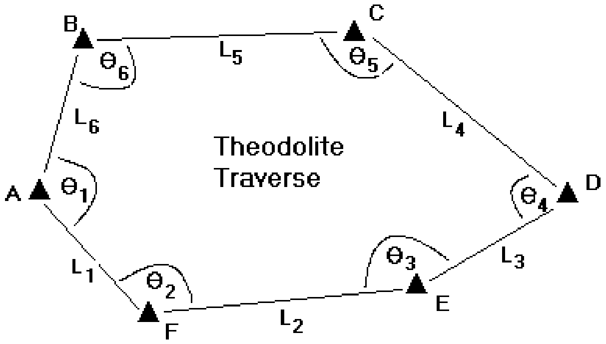
6. Repeat on opposite face. True position will be bisection of the two points (assuming they are close together).

> ***Activity 5.1***
> ***(45 Minutes)***
>
> Muskett, pp 61, 62, 3.1, 3.1.
>
> [These exercised give you practice with interpreting booking and doing angle calculations]

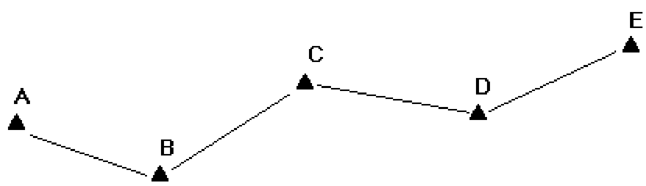
## THEODOLITE TRAVERSE

### Overview

A theodolite traverse is a method of **control survey**, which is used to establish a set of **control stations** (to which other survey work will be referred).




This is a **closed loop traverse**.



This is an unclosed traverse (if A and E are not known points). How would you check for correctness of the data?

That's why traverses are usually closed loop traverses (see first Diagram), or closed between 2 known points.

Each station is marked in some way

eg: nail embedded in concrete block
permanent survey mark
nail in wood peg (least desirable for a permanent marker)

Theodolite is centred over each station in turn, and the horizontal angles (and optionally the vertical angles) are recorded. The lengths between stations are measured.

You must be able to sight from one station to the next. The lines between stations are called traverse lines.

It's also useful to be able to see across the loop so that extra information can be collected, but it is frequently not possible (eg. you have run a traverse around a building).

## Categories of Traverse

**First order traverse** - lines of up to 50 km and angles measured with a precise theodolite. Error of 1:100000 might be expected. These are used for state grids, and for large scale mapping purposes.

**Precise control traverse** - lines up to 1 km (use an infra red EDM), angles measured with a 1 sec. theodolite. Used for large construction projects.

**Less accurate** - 250 m lines, steel band (or EDM), 20 sec theodolite. Smaller construction projects.

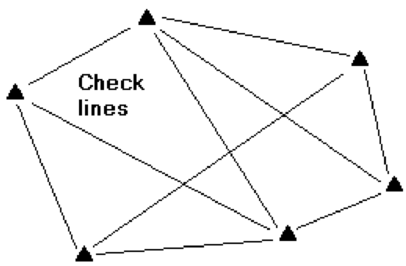
Engineers are usually interested in the last 2 categories.

## Choice of Traverse Stations

* Map, plan, or sketch is required. Walk over the site first.

* Keep lines as long as possible to minimise centring errors.

* Good visibility is needed between stations for the main lines. Use additional sights (across the survey) as checks.



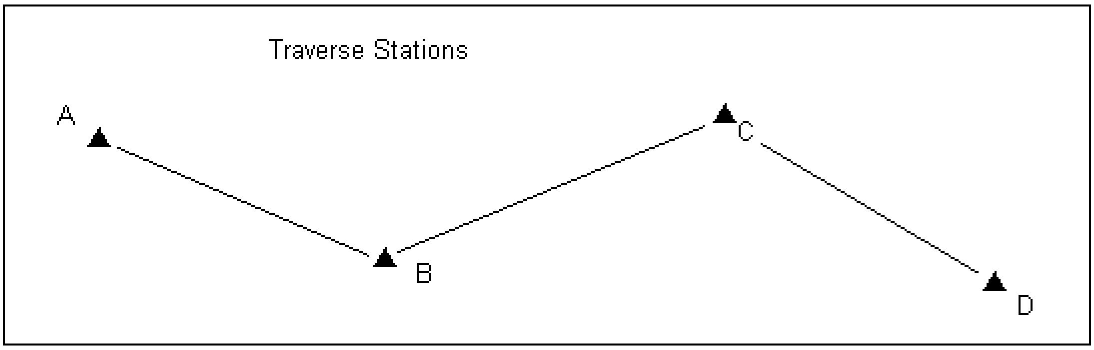
* Establish the points of the traverse as appropriate (steel star pickets or markers in concrete, etc).

* Keep sight lines at least 1 m above ground to avoid refraction.

## MEASUREMENT OF LINES

Most theodolite traverses would now use an EDM to measure distance. EDMs usually share the same locations as theodolites (ie. they piggy-back on top of the theodolite).

1. Tripods at A, B, C. Targets at A, C. Theodolite at B. Measure ABC.




2. Move tripod from A to D. Remove theodolite minus tribrach from B and install on tribrach at C. Targets on tribrachs at B, D.

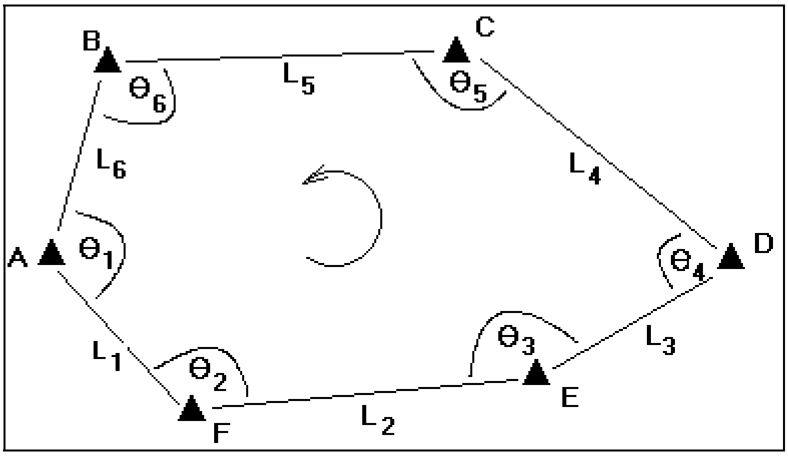
Note: Only 1 new centring required at D.

### Measuring lines by tape

Spring balance (tension), Abney level (slope), thermometer required to achieve accuracy of 1:10000. If a theodolite is available, slopes are better read using it in preference to an Abney Level.

## ANGULAR MEASUREMENTS

You need a **Reference Bearing** (ie. you must know the bearing of one of the lines, eg. AB).




Record and book the horizontal angles as previously described.

NB. alternative booking methods exist (see text):

### Check

Sum of all internal angles = (2n-4) * 90° (where n = no. of angles or sides).

The error should not exceed 20" $\sqrt{n}$ for our Prac theodolites

A large error in the sum of angles means that some angles must be remeasured.

Check sights can help isolate the incorrect reading or readings, so that only some (and not all) angles need to be remeasured.

## TRAVERSE COMPUTATION

## Theodolite Traverse

### Case 1:

Closed loop traverse

All angles of a polygon, and the lengths of all sides, measured.

Bowditch's method used for adjustment of computed delta eastings and delta northings.

Bowditch's method was originally developed for the adjustment of compass traverses where the lengths are more accurate than the bearings (angles). It produces reasonable results for theodolite/tape traverses. It is more applicable to theodolite/edm traverses, as the distances are more accurate than taped distances.

**In the following example, the recommended tolerances have been exceeded to make the example easier to follow.**

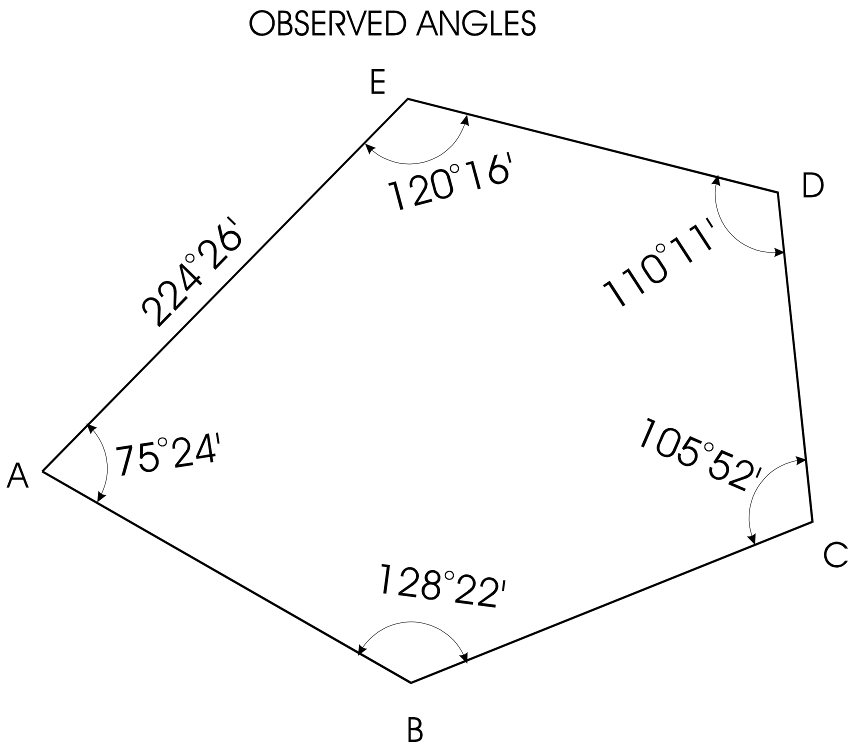
**Step 1**

Check the sum of the internal angles equal to (2n-4) * 90°

Tolerance or allowable misclose 20" * √n

Less than tolerance proceed to step 2

Greater than tolerance go back to the field and re-measure.




**Step 2**

Distribute error equally to all angles to adjust out error.

| | Observed angles | | Adjusted angles | |
|---|---|---|---|---|
| A | 75 | 24 | 75 | 23 |
| B | 128 | 22 | 128 | 21 |
| C | 105 | 52 | 105 | 51 |
| D | 110 | 11 | 110 | 10 |
| E | 120 | 16 | 120 | 15 |
| Sum | 540 | 5 | 540 | 0 |

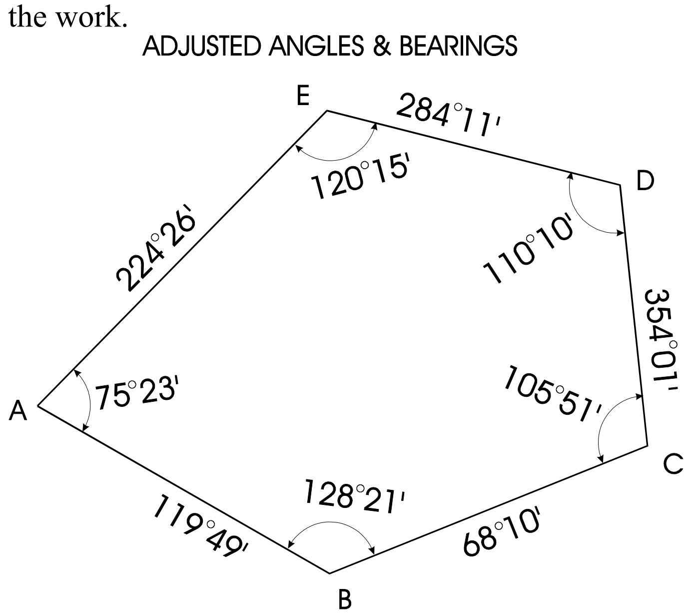
**Step 3**

Calculate bearings of sides from angles.

- Bearings are in the range $0^o$ to $360^o$.
- Start at the known bearing ($224^O26'$) and work anticlockwise round the figure, adding angles. (If you work clockwise, the angles must be subtracted which is more prone to error.)
- In calculating bearings, alternate bearings will be in the opposite sense. Write bearings on plan or sketch so that they are all in the one sense, anticlockwise.

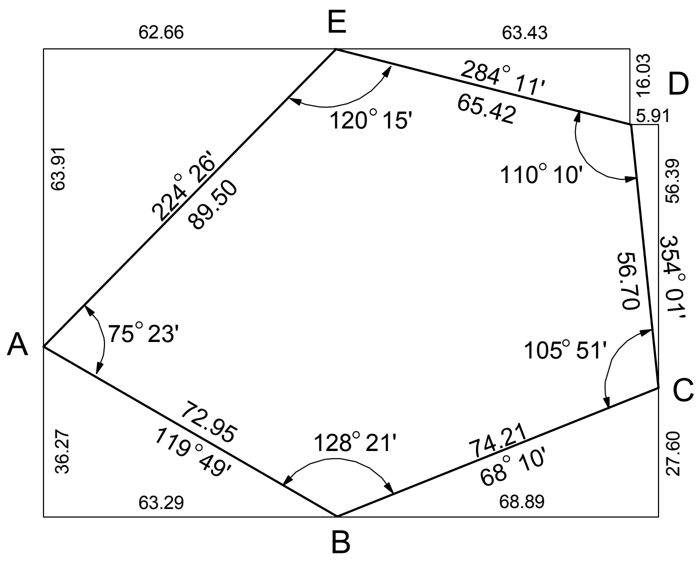
| *Bearing Calculation* | | | | |
|---|---|---|---|---|
| | | | **Sense corrected** | |
| **EA** | **224** | **26** | **224** | **26** |
| A | 75 | 23 | | |
| **AB** | **299** | **49** | **119** | **49** |
| B | 128 | 21 | | |
| **BC** | **428** | **10** | | |
| | -360 | | | |
| **BC** | **68** | **10** | **68** | **10** |
| C | 105 | 51 | | |
| **CD** | **174** | **1** | **354** | **1** |
| D | 110 | 10 | | |
| **DE** | **284** | **11** | **284** | **11** |
| E | 120 | 15 | | |
| **EA** | **404** | **26** | | |
| | -180 | | | |
| *EA* | **224** | **26** | **224** | **26** |

On the last line the calculation comes back to the starting bearing, providing a check on the work.



**Step 4**
Reduce distances for slope, temperature, sag, tension and standard and write on plan

**Step 5**
Prepare tabulation of bearings and distances, delta eastings and delta northings
Calculate




MEASURED DISTANCES
COMPUTED EASTINGS AND NORTHINGS

$\Delta E = d \times \sin \beta$ $\Delta N = d \times \cos \beta$

| | Bearing $\beta$ | | Distance | | |
|---|---|---|---|---|---|
| | Deg | Min | *d..* | *ΔE..* | *ΔN..* |
| AB | 119 | 49 | 72.95 | 63.29 | -36.27 |
| BC | 68 | 10 | 74.21 | 68.89 | 27.60 |
| CD | 354 | 1 | 56.70 | -5.91 | 56.39 |
| DE | 284 | 11 | 65.42 | -63.43 | 16.03 |
| EA | 224 | 26 | 89.50 | -62.66 | -63.91 |
| | | | **358.78** | **0.19** | **-0.16** |
| | | | | **0.25** | |

**Step 6**

Take algebraic sum of columns distance, *ΔE and ΔN.*

For a closed traverse $\Sigma\Delta E = \Sigma\Delta N = 0$

Calculate misclose vector = $\sqrt{(\Sigma\Delta E^2 + \Sigma\Delta N^2)}$

$$\sqrt{(0.19^2 + 0.16^2)} = 0.25$$

Misclose vector should be less than perimeter/4000

$$358.78 / 4000 = 0.09$$

$$\text{or} \qquad 358.78 / 0.25 = 1435 \text{ (not very good!!!)}$$

If less go to Step 7

If more, go back to the field to find error. (We will continue with this larger than allowable error so that the calculation is easy to follow.)

**Step 7**

Adjust traverse by Bowditch Rule. The corrections to the delta eastings and delta northings are proportional to the lengths of the traverse sides.

$$\delta\Delta E = -\frac{\Sigma\Delta E}{\Sigma d} \times d \qquad \delta\Delta N = -\frac{\Sigma\Delta N}{\Sigma d} \times d$$

$$\Delta E' = \Delta E + \delta\Delta E \qquad \Delta N' = \Delta N + \delta\Delta N$$

**Step 8**
Calculate coordinates. You may have to calculate the adjusted bearings and distances

| | | | | | | ***Coordinates*** | | |
|---|---|---|---|---|---|---|---|---|
| | | Corrections | | Corrected | | East | North | |
| $\Delta E$ | $\Delta N$ | $\delta\Delta E$ | $\delta\Delta N$ | $\Delta E'$ | $\Delta N'$ | **1000.00** | **2000.00** | A |
| 63.29 | -36.27 | -0.04 | 0.03 | 63.25 | -36.24 | 1063.25 | 1963.76 | B |
| 68.89 | 27.60 | -0.04 | 0.03 | 68.85 | 27.63 | 1132.10 | 1991.39 | C |
| -5.91 | 56.39 | -0.03 | 0.03 | -5.94 | 56.42 | 1126.16 | 2047.81 | D |
| -63.43 | 16.03 | -0.03 | 0.03 | -63.46 | 16.06 | 1062.70 | 2063.87 | E |
| -62.66 | -63.91 | -0.05 | 0.04 | -62.70 | -63.87 | 1000.00 | 2000.00 | A |
| **0.19** | **-0.16** | **-0.19** | **0.16** | **0.00** | **0.00** | | | |
| **0.25** | | | | | | | | |

***Activity 5.2***
***(30 Minutes)***

Calculate the adjusted bearings and distances from the corrected $\Delta E$'s and $\Delta N$'s.

### Transit Rule

This works on the assumption that corrections $\delta\Delta E$ and $\delta\Delta N$ should be in proportion to $\Delta E$ and $\Delta N$, not $d$ as in the Bowditch rule. This results in a smaller change to the bearings.

$$\delta\Delta E = -\frac{\Sigma\Delta E}{\Sigma[\Delta E]} \times [\Delta E] \qquad \text{similarly } \delta\Delta N$$

where the square brackets represent the "magnitude" or "absolute value".

## Unaltered Bearings

If the bearings are not to change, then we require that:

$$\frac{\text{Correction to DE}}{\text{Correction to DN}} = \frac{\text{DE}}{\text{DN}}$$

This is a complex procedure that is usually only needed for precise traverses. It assumes that the bearings are more accurate than the distances. where distances are measured by edm, this is rarely so.

## Least Squares

Least Squares can be used for adjusting a wide range of surveying data.

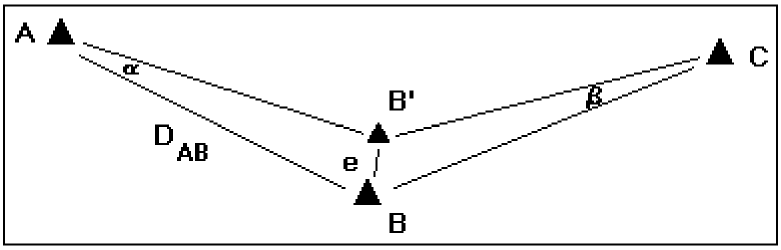
## OTHER CONSIDERATIONS

## Possible Errors

1. inaccurate **centring** - theodolite
   - signal
2. non-vertical **signal**
3. inaccurate **bisection** of signal (signal too wide)
4. **parallax**
5. **atmospheric** effects
6. theodolite **not level**
7. **incorrect use** of theodolite
8. **mistakes** in reading or booking

Here is more detail on a couple of these problems:

## Centring Errors




$$a = \frac{e}{D_{AB}} \quad \text{(rads)}$$

$$a'' = \frac{206265.e}{D_{AB}} \quad \text{(secs)}$$

for e = 10 mm, $D_{AB}$ = 300 m, a" = 7"
for e = 10 mm, $D_{AB}$ = 100 m, a" = 20"
Hence there is a need to keep $D_{AB}$ as long as possible.

The angle AB'C measured above will be incorrect by a + b, or 14" if $D_{BC}$ = 300 m, or in error by 40" if $D_{BC}$ = 100 m.

If using a 1" theodolite, centring is clearly important. Even using a 20" theodolite, the errors in centring are of the same order as for levelling and reading.

The **Three Tripod System** (as explained earlier) is a useful way of minimizing centring errors. It is particularly good for short traverse lines eg. in mines, tunnels, and streets. The theodolite is lifted off the tribrach and replaced with a special target. Centring errors are greatly reduced. by requiring a smaller number of centring operations.

## Station Signal

**Station Signals** are used where the station peg itself is not visible.

They must be perfectly straight, and be set up vertically over the station, otherwise a centring error occurs. For example:

Always sight on the **lowest point** on a prism pole to minimize centring error, and use a signal width proportional to distance.

Finally, here are some notes on the **Accuracy** that should be achieved:

## Accuracy

**Accuracy** required: (N = number of stations)

| Order of traverse | Horiz. distance | Horiz. angles | Task |
|---|---|---|---|
| A | 1:25000 | 5 N sec | (i) aerial mapping<br>(ii) large engin. projects |
| B | 1:10000 | 10 N sec | Engineering surveys |
| C | 1:5000 | 30 N sec | including setting out |
| D | 1:2000 | 60 N sec | Small site survey |

***Activity 5.3***
***(35 Minutes)***

Adjust the figure ABCDE using the Transit rule. Check the differences between this and Bowditch's method.

## KEY CONCEPTS

- Theodolites in correct adjustment have their axes and line of sight of the telescope mutually perpendicular. All three should intersect at one point.
- Setting up a theodolite involves centring it over a ground mark, levelling it and collimating it (adjusting the eyepiece focus).
- Angles must be read in both the 'face left' and face right' positions to eliminate most instrumental errors.
- Horizontal angle readings on face left and face right will be $180^o$ different.
- Vertical angle reading (zenith angles), face left and face right should sum to $360^o$.
- A bearing is a direction (in degrees, etc.) measured clockwise from north.
- All angles and distances of a traverse are measured to provide redundancy.
- Adjustments to angles, and to bearings and distances are made only when the error is within the expected tolerance.
- Adjustment is not used to disguise gross errors.

## REVIEW QUESTIONS

Do exercises 5.2 and 5.3 from Muskett pp 150, 151.