Chapter 2 Levelling

2.1 Introductory Remarks

This Chapter introduces you to the theory and practical skills of levelling, a process of determining elevations (heights) or differences in elevations. It can be performed using either differential levelling using a level (discussed in this Chapter) or trigonometric levelling using a Total Station (discussed in Chapter 6). Levelling can be used in all aspects of surveying. Particularly for engineering and mining, levelling finds use in:

- ✓ Establishing vertical controls.
- ✓ To establish heights of points during constructions.
- ✓ Route surveys.
- ✓ For contouring purposes.
- ✓ For road cross-sections or volumes of earthwork in civil engineering works.
- ✓ For provision of levels of inclined surface during construction.
- ✓ For designing decline box cut in mining amongst other tasks, e.g., rescuing.

In Chapter 3 where we discuss the representation of relief and vertical sections, you will employ the skills of levelling that you will have learnt in this Chapter. Working through the materials of this Chapter and the workshop materials in Appendix A1-1, you should:

1. Be able to differentiate between heights, datum and bench marks (BM).
2. Know and understand the use of the levelling equipment.
3. Understand the field procedures for levelling.
4. Be able to calculate reduced levels (RL).
5. Know sources of errors in levelling and how to manage them.
6. Know the various levelling methods.

Essential references include, e.g., Uren and Price (2010), Schofield and Breach (2007), and Irvine and Maclennan (2006).

2.2 Definitions of Levelling Terminologies

- ➢ Level surface (see Figure 2.1).
  - o A (curved) surface orthogonal to the plumb line everywhere.
  - o More correctly an equipotential surface for which gravitational potential is constant.
  - o A still body of water unaffected by tides is a good analogy.
  - o They are not equidistant apart, but converge and diverge due to changes in density.
- ➢ Vertical line (see Figure 2.1 and Figure 2.2).
  - o The direction of gravity.
  - o Therefore, the direction indicated by a plumb line.
  - o In general, it deviates from a line emanating from the geometric centre of the Earth.
  - o In reality it is curved, but this can be neglected in small plane surveys.
- ➢ Horizontal plane (see Figure 2.2).
  - o A plane tangent to a level surface (orthogonal to the plumb line).
  - o The collimation axis (line of sight) of a levelling instrument that is in correct adjustment. Once levelled, it defines a horizontal plane as the instrument is rotated.
- ➢ Vertical datum.
  - o Any level surface to which heights are referenced.
  - o The vertical datum in Australia is the Australian Height Datum (AHD).
- ➢ Mean Sea Level (MSL).
  - o Mean height of ocean level taken with data from coastal tide gauges over a 19-year period.

J. Walker and J.L. Awange, *Surveying for Civil and Mine Engineers*,
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  - 30 tide gauges used in Australia.
  - 97 230 km of two-way levelling used with the tide gauge data to define the AHD.
- Tidal datum.
  - Average of all high waters observed over a 19-year period.
  - Mean high water (MHW).
- Elevation.
  - The vertical distance (height) above the datum.
- Bench mark (BM).
  - A permanent monument or feature for which elevation is known.
  - Vertical control.
  - A set of benchmarks used to “control the heights” of a project.

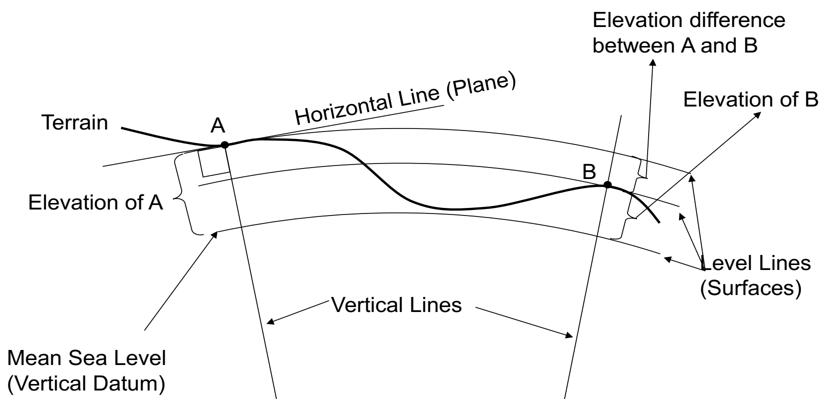


Figure 2.1 Diagrammatic illustrations of the levelling terminologies.

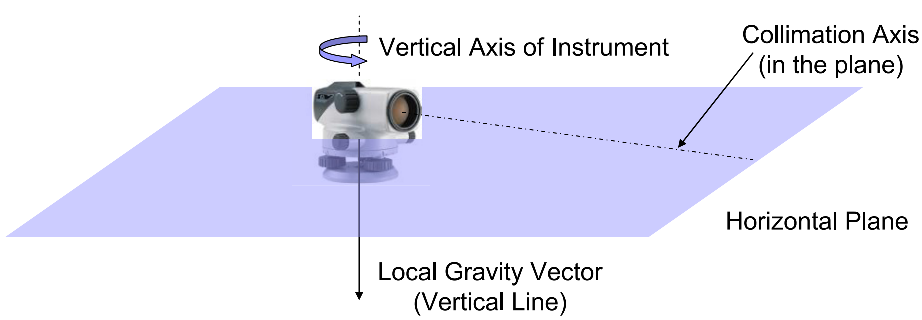


Figure 2.2 Horizontal plane.

2.3 Example: The Australian Height Datum (AHD)

Heights in Australia are referenced to the Australian Height Datum (AHD) defined as mean sea level at 30 tide gauges around Australia, observed between 1966 and 1968 (Figure 2.3).

Height control is established by **Bench Marks**, vertical control points tied to the AHD by differential levelling. The AHD, almost coincident with the geoid (an equipotential surface approximating the mean sea level), varies from the ellipsoid, the idealised mathematical shape of the Earth by a geoid-ellipsoid separation, N. The AHD N value is modelled to an accuracy of about 0.03m over Australia (Figure 2.4). The difference between the geoid and the AHD is due to the difference in water density between Northern and Southern Australia and accounts for a tilt of ±0.5m.

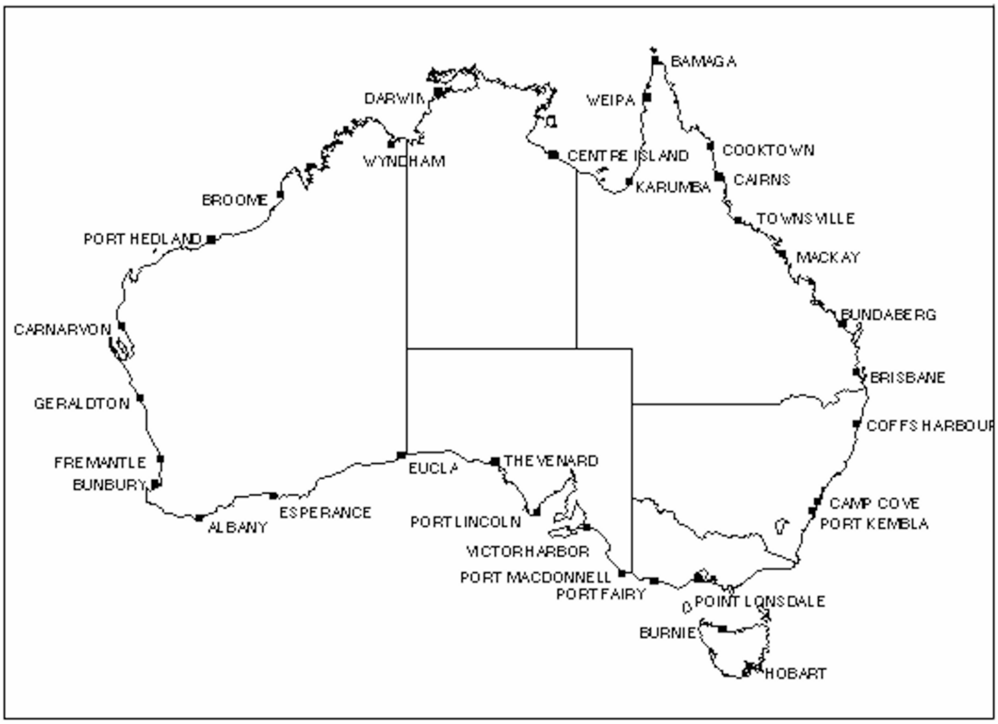


Figure 2.3 Map of tide gauges in Australia. Image source: Geoscience Australia

http://www.ga.gov.au/geodesy/datums/ahd.jsp

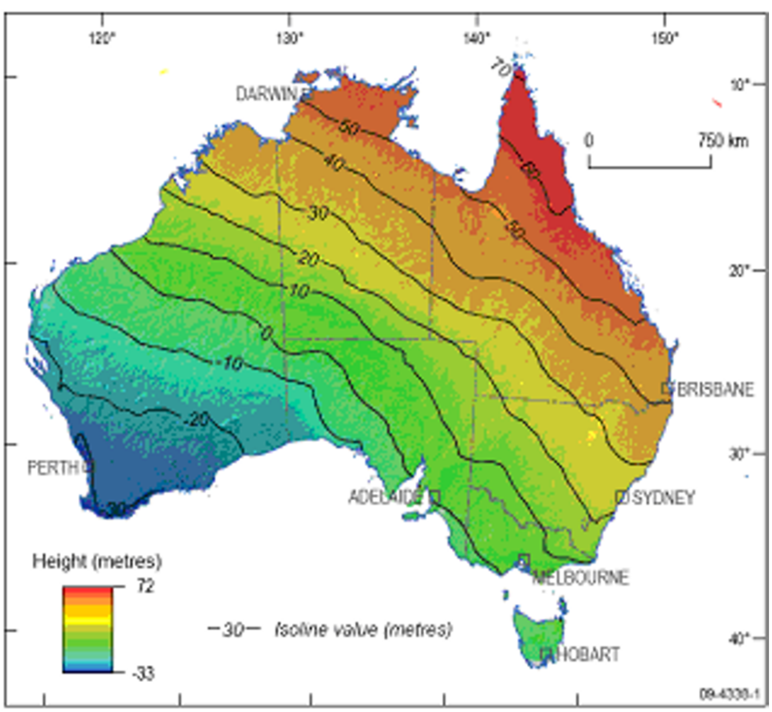


Figure 2.4 Ausgeoid09 – GDA94 separation, **N**, across Australia. AHD = $H_{GDA94} - N$

(see, e.g., http://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/geodetic-datums/geoid).

The important point to remember is that GPS/GNSS heights (see Chapter 10) refer to the **ellipsoid** and differential levelling heights refer to the **geoid**. Thus, any GPS/GNSS height must be corrected to the AHD by the separation value, N, before using GNSS derived vertical control. The current model of the AHD/geoid separation is Ausgeoid09, which is an upgrade from the original Ausgeoid98 (Featherstone et al. 2001). Illustrated in Figure 2.4 are the 10m isobaths of AHD and Geodetic Datum Australia (GDA94) separation over the AHD model area (http://www.ga.gov.au/ausgeoid/nvalcomp.jsp). The variation of the N values across Australia from Cape Leeuwin to Cape York are shown in Figure 2.5 - Figure 2.7. The model definitions are the AHD, Ausgeoid09/GDA94 separation scale is 1:1,250, and the terrain profile, i.e., the AHD/GDA94 separation is scale 1:12,500.

Height transfer between the GDA94 Ellipsoid and the Australian Height Datum is performed as follows:

1. AHD (roughly height above mean sea level on the local geoid) is transferred from Bench Marks using differential levelling or trigonometric height differencing.
2. GNSS (GPS) height surveying is referenced the GDA94 ellipsoid. This is very similar to the WGS84 ellipsoid used by GNSS satellites (see Chap 10 for more discussion).
3. GDA94 ellipsoid heights are transferred to the AHD using the AUSgeoid09 grid ellipsoid interpolation of the AHD – ellipsoid separation value, **N**.
4. **N** is realised to about 0.03m (1 sigma) over Australia, compatible with k = 12√d (3rd order) levelling.
5. GNSS RTK surveys over a local area can have the observed ellipsoidal heights transferred to AHD using a single N value for the area.

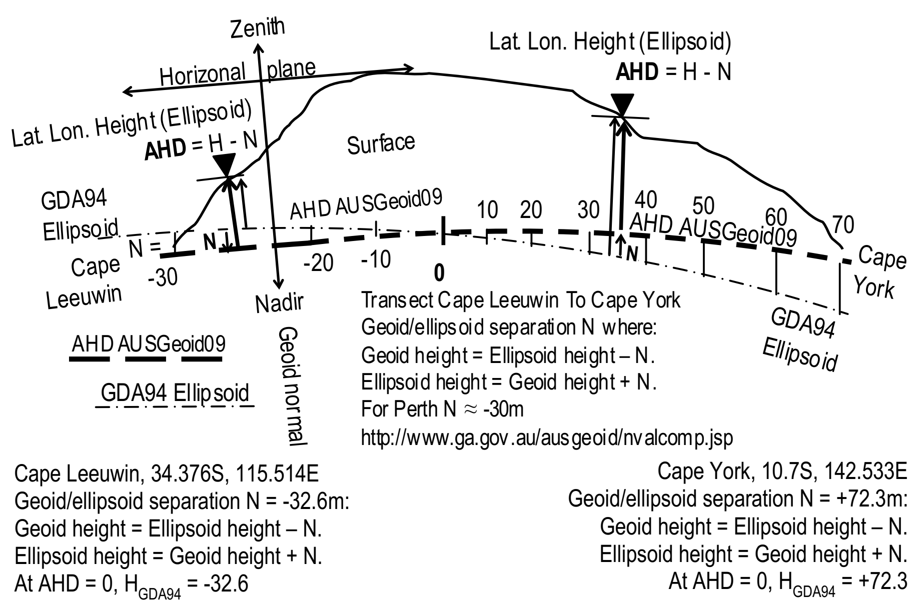


Figure 2.5 Variations of N from Cape Leeuwin to Cape York in Australia.

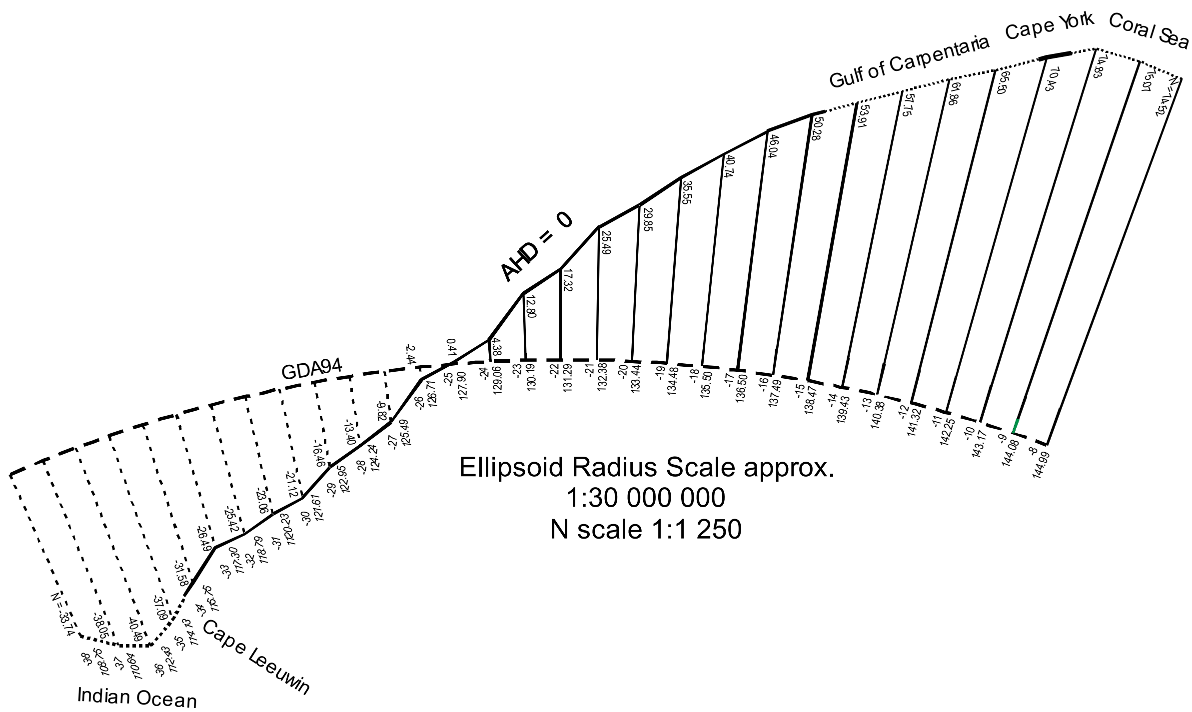


Figure 2.6 10 times vertically exaggerated scale of Figure 2.5.

Variations of N from Cape Leeuwin to Cape York in Australia

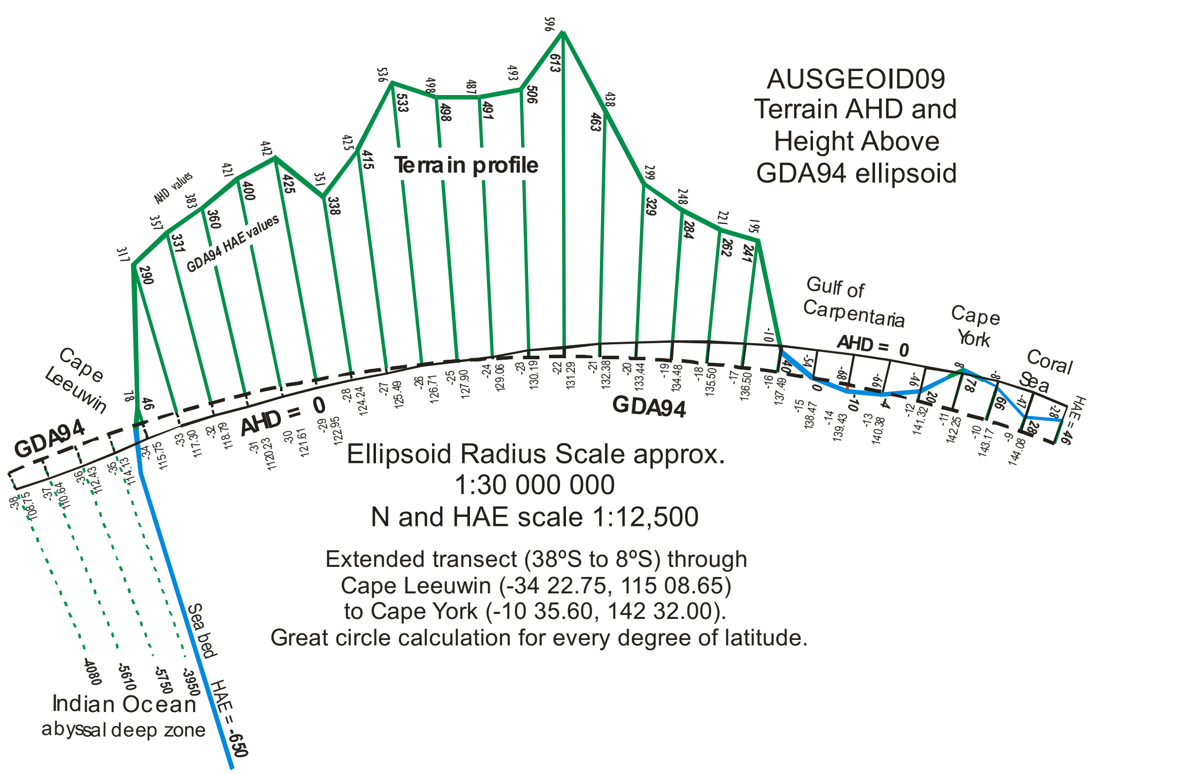


Figure 2.7 Terrain and seabed profile from Cape Leeuwin to Cape York in Australia

2.4 Instrumentation: Automatic Level and Staff

The instruments one needs to carry out levelling procedure discussed in Section 2.5 are a level and staff (Figure 1.5). In addition, one may need to have a measuring tape and a change plate (a metallic/plastic plate used on soft ground), see Figure 2.8. The staff “bubble” ensures the staff is held vertically. Before being used, the instrument has to be setup and levelled as discussed below. Refer to the Leica Geosystems NA724 User Manual, Version 1.0, English. Document NA720/724/NA728/NA739-1.0.1en which is generally provided in the instrument case.

a b c d e

Figure 2.8 Levelling equipment.

(a) Leica automatic level, (b) 5m levelling staff, (c) staff “bubble”, (d) change plate, (e) tape measure.

2.4.1 Setting the instrument for area levelling

Leica manual, page 11. “Setting up the tripod”.

For differential levelling with an automatic level (Section 2.5.2), it is only necessary to roughly centre the circular level bubble on the instrument plate. The automatic compensator (pendulum) will provide the final levelling.

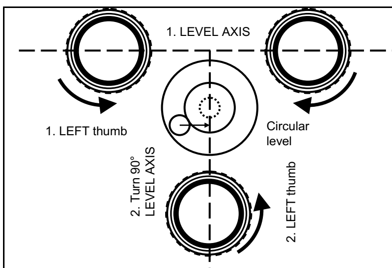


Figure 2.9 Levelling the instrument.

2.4.2 Levelling the instrument

Leica manual, page 12. “Levelling up”.

Mount the level on the tripod head using the centre bolt (e.g., Figure 1.5)

1. Centre the three foot-screws on the base plate (there is a mid-point mark on screw housing), see Figure 2.9.
2. Centre the circular level using the foot screws,
   - turn the level until its axis is parallel to two foot screws
   - simultaneously turn the two parallel foot screws in opposite direction
     - move the bubble towards the centre following your LEFT thumb,
   - then turn the level through 90°, perpendicular to the first axis foot screws,
     - using ONLY the remaining foot screw
       - move the bubble towards the centre following your LEFT thumb
   - you may need to repeat the procedure to centre the bubble correctly.

2.4.3 Focusing the instrument

Leica manual, page 13. “Focusing telescope”.

Correct focus of the eyepiece reticule and the object focus is critical to accurate observations. The following points apply to all optical observations.

The eyepiece focus is set once for EACH individual observer.

But the object focus (see Figure 2.8a. Figure 2.10), using the focussing knob on the side of the telescope, must be done for EACH observation.

Figure 2.10 Eyepiece focus, circular level.

2.4.3.1 Eyepiece focus

1. Place a light-coloured card in front of the OBJECT lens
2. Looking through the eyepiece, turn the EYEPIECE (dioptre) focus ring until the reticule engravings are sharp and dark (Figure 2.11).

2.4.3.2 Object focus

1. Point to the level staff, the point to be focused.
2. Looking through the eyepiece, turn the OBJECT focusing knob (Figure 2.12) until the image is in sharp focus on the reticule (Figure 2.13).
3. Observing the object, move your head up and down slightly to confirm there is no parallax in the focus between the line of sight of the reticule and the object.

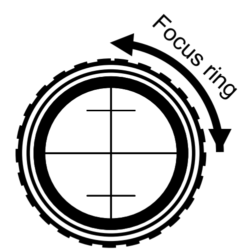


Figure 2.11 Eyepiece focus.

2.4.3.3 Backsights and Foresights

“Sight” is the word meaning either an observation or a reading.

A **Backsight (BS)** is the **first** sight (reading) taken after setting the instrument in position for a reading. It is the beginning sight.

A **Foresight (FS)** is the **last** sight (reading) taken before moving the instrument to a new position. It is the ending sight.

An **Intermediate sight (IS)** is any sight taken between the BS and FS.

A **Change point (CP)** is the common position between two instrument setups. A CP has a **FS** from the previous instrument position and a **BS** from the next instrument position.

Figure 2.12 Object focus.

2.4.4 Reading the staff interval

Leica manual, page 15. “Height reading”.

The face of the staff is marked with an E pattern of 1cm graduations (see Figure 2.15). The observer is expected to interpolate the millimetre readings. Because of the eye’s ability to discriminate proportions, it is relatively easy to interpolate to the millimetre.

The levelling staff should be extended only to the amount needed for the exercise. Ensure the correct section segments are extended. Each segment is about 1m long.

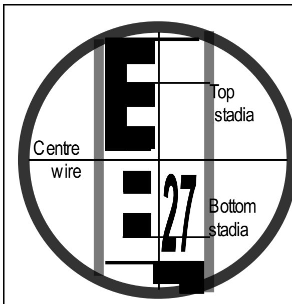


Figure 2.13 Sharp image focus

Object focus:

1. Focus on the staff with the OBJECT focus knob; the depth of field is shallow and requires critical focusing
2. Check for parallax in reticule.
3. Gently tap the side of the level to ensure freedom of the automatic pendulum compensator.

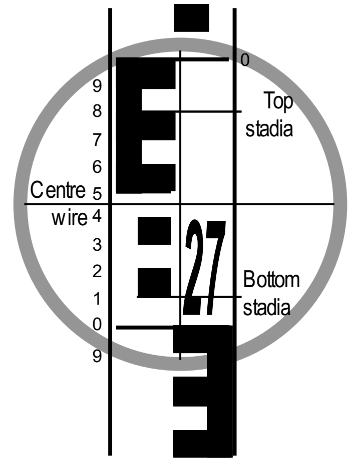


Figure 2.15 E pattern staff reading.

2.4.4.1 Staff reading

1. Using the **centre** cross hair, read the staff, estimating millimetres.
   The illustrated staff on reads 2.745, the decimal point is inferred in the 27
2. Record the reading in **metres**.
3. Note that the two stadia wire, used for measuring distance, can be used as a check of the centre wire reading,
   Top wire (TW) = 2.780
   Mean = 2.745 = centre wire
   Bottom wire (BW) = 2.710
   Distance = (TW – BW) x 100 (stadia constant) = 0.07 x 100 = 7m
   Recording top and bottom wires can be a useful method of blunder detection.

The observer and the booker must work together to ensure that the readings have been recorded correctly. The booker should be able to reduce the readings, calculating RL from either rise/fall (Section 2.5.5) or height of collimation method (Section 2.5.7), and check for consistency. Furthermore, the booker should ensure an adequate description of the observed point. The final reduced level (RL) and all checks can be concluded quickly, before leaving the job. There is nothing worse than having to return to the job to fix a blunder.

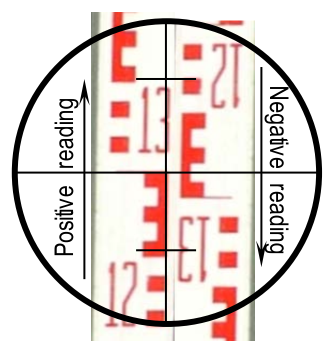


Figure 2.14 Inverted staff reading.

2.4.4.2 Staff handling

1. Make sure the required staff sections are fully extended and locked.
2. When transferring heights, ensure that the base of the staff is on a stable point;
   a peg, a recoverable point or a firmly embedded change plate (Figure 2.8).
3. Minimum reading on the staff occurs when it is held vertical. This is achieved by using the “staff bubble”, a circular level held on the side of the staff. Slightly rocking the staff backwards and forwards to find the minimum reading is another method that could be used in the absence of a bubble.

2.4.5 Collimation checks (Two peg test)

Leica manual, page 21. “Checking and adjusting line-of-sight”.

To check that the instrument’s line of sight is horizontal it is necessary to perform a line-of-sight test. This is commonly called the “two peg test”. It should be performed on any instrument that is to be used in production prior to any project. The object of the test is to ensure that the line of collimation of the level is within manufacturer’s recommendations. Outside this limit the instrument should be re-tested and if still deficient, adjusted or sent for rectification.

The principle of the test is to find the difference in height between two points:

1. Eliminating collimation error by observing, Δh, from the mid-point (Figure 2.16)
   - line of sight (LoS) errors are cancelled (deflections, δ, cancelled).

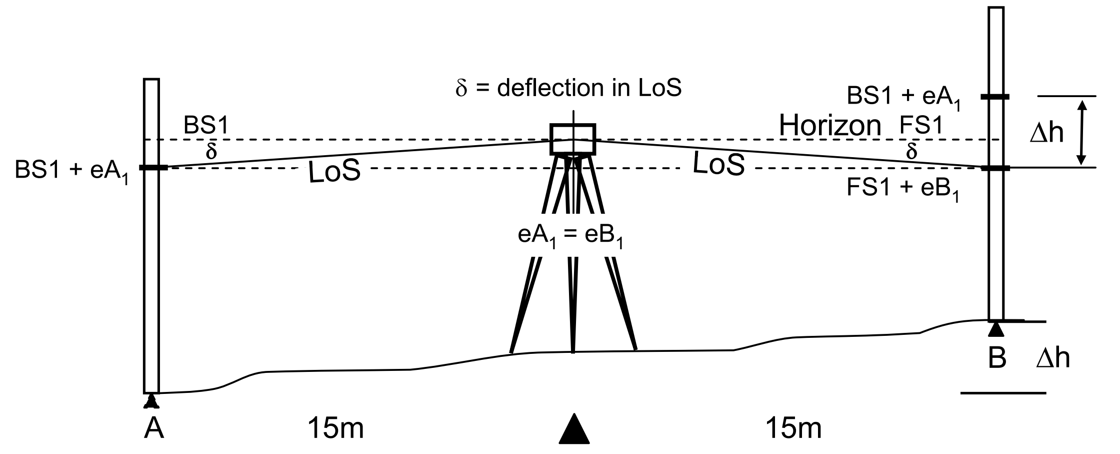


Figure 2.16 Balanced (midpoint) observation of height difference.

2. From a point close to A, 1 – 2m (Figure 2.17), determine $\Delta h'$ by observing over the full (30m) line-of-sight. The error in the line-of-sight is the discrepancy between the two observed height differences;
   - $|error| = |\Delta h'| - |\Delta h|$ (unbalanced deflection, δ).

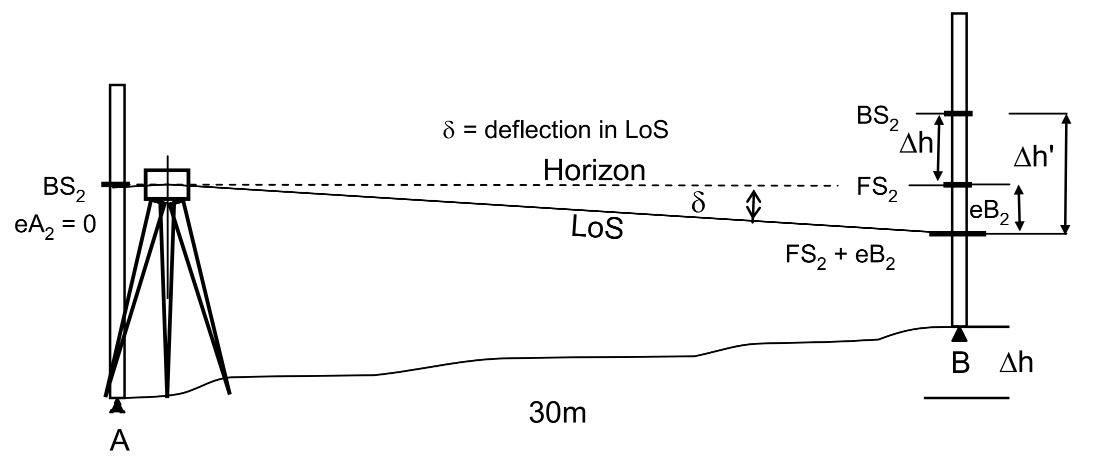


Figure 2.17 Offset observation of height difference. Height error.

3. The recommended maximum error for the Leica Level NA720/724 is 3mm (0.003m) or 0.01ft. Imperial, or foot, staffs are marked in 1/100 of a foot.
4. Example of record sheet using the rise and fall booking method:

BS	IS	FS	Rise	Fall	Remarks
1.742					A_1. Mid point. Equal error
		1.622	0.120		B_1. Mid point. Equal error
1.580					A_2. At staff. Zero error
		1.456	0.124		B_2. 30m to B. All error
$\Delta h = 0.120$		$\Delta h' + eB_2 = 0.124$		$|Error| = 0.124 - 0.120 = 0.004$	

Figure 2.18 Booking and analysis of a collimation test.

5. Figure 2.18 shows an error of 4 mm, outside manufacturer's specifications. The test would be repeated to confirm the result before any decision on adjustment is made. Or extra care could be used to balance foresight/backsight observations.
6. If this measurement was confirming that the reticule needed adjusting, then the reading to B_2 would have to be adjusted so that the staff reading was:
   - 1.580 - 0.120 = **1.460.**

2.5 Measuring and Reduction Techniques

2.5.1 Basic Rules of Levelling

In using an automatic level for vertical control and height differences, you need to remember the following ***six*** rules of levelling:

1. The instrument must be properly levelled, pendulum free; check circular bubble, pendulum "tap".
2. Backsight distance should be approximately equal to the foresight distance. Stadia wires can be used to approximate the distances (see staff reading above).
3. Instrument, staff and change plate must be stable, and the staff kept on the change plate.
4. Staff must be vertical. Check that the staff bubble is centred.
5. Remove parallax, **read the centre wire**; sharp, coincident focus of reticule and object. Reticule (cross wire) focus set with eyepiece (dioptre) ring; object focus to eliminate parallax.
6. Close the traverse.

For all exercises in Appendix (A2-1), we assume that the Earth is FLAT. All calculations are based on plane trigonometry, and the horizontal plane is perpendicular to the local **geoid** normal. Distance measurements are generally less than 100 m and level observations are rarely over a distance of 50 m, generally 30 m is sufficient. These limitations then allow us to ignore the effects of Earth's curvature and scale factor. Heights will be referenced to the Australian Height Datum (AHD). The AHD was defined as mean sea level at 30 tide gauges around Australia, observed between 1966 and 1968 (Figure 2.3).

2.5.2 Levelling Specifications in Australia

The Intergovernmental Committee on Surveying and Mapping (ICSM) through its Special Publication 1 (SP1), Version 2.0 (2013) provides guidelines for Differential Levelling to achieve various levels of misclose.

Allowable misclose: When conducting differential levelling or Total Station differential levelling, errors propagate in proportion to the square root of the travelled distance. A misclose assessment should be undertaken to verify that forward and backward runs of a levelling traverse, including any individual bays, are within the maximum allowable misclose. The allowable misclose is calculated using the formula:

$$\boldsymbol{r_{mm} = n\sqrt{k}} \text{ (k in km).}$$

Three standards, using empirical values, are recommended:

$$n = 2\text{mm}\sqrt{k},\ n = 6\text{mm}\sqrt{k} \text{ and } n = 12\text{mm}\sqrt{k}.$$

Equipment: For the recommended maximum allowable misclose of $12\sqrt{k}$ (forward and back). A 2 mm/km optical level; collimation check at start of project; wood or fibreglass staff, calibrated within 5 years; staff bubble attached and accurate to 10′ verticality, telescopic tripod; standard change plate; thermometer accurate to 1°C.

Observation techniques: Two-way levelling; foresight approx. equal to backsight; staff readings to 1 mm; temperature recorded at start and at 1 hour intervals, or at pronounced changes to conditions; maximum sight length 80 m; minimum ground clearance 0.3 m. One of the automatic level used for the levelling exercises is the Leica NA720/NA724, a general-purpose surveying and construction level. Accuracy is quoted as 2.5 mm/km for the NA720, not meeting SP1 specifications.

Refer to the "Leica NA720/724/728/730 Instruction Manual, English, Version 1.0" by Leica Geosystems. This manual is contained in most instrument cases.

2.5.3 Differential Levelling: The "Rise and Fall" method

Levelling procedure:

- ✓ A horizontal line of sight is established using some form of levelling mechanism:
  - o Spirit level tube
  - o Swinging pendulum
- ✓ A graduated staff is read through the telescope of the level
- ✓ The elevation of points can be established by first reading the staff on a Bench Mark (BM)
- ✓ The staff is then moved to the desired point, the level is turned and the staff is read again
- ✓ The reading at the benchmark (BM) is called the backsight (BS), see BS1 in Figure 2.19.
- ✓ The reading taken after turning the instrument and moving the staff is the foresight (FS), see FS1 in Figure 2.19.
- ✓ To continue levelling, the staff is kept on the point at B and the instrument moved to the midpoint between B and the next point, C, i.e., STN 2.
- ✓ B is called the change point (CP) or turning point (TP)
- ✓ The staff at B is carefully turned toward the instrument and a BS reading taken
- ✓ Then the staff is moved to C and a FS reading is made
- ✓ The procedure is repeated as many times as needed
- ✓ The levelling should always end on a BM (i.e., D) as a check!

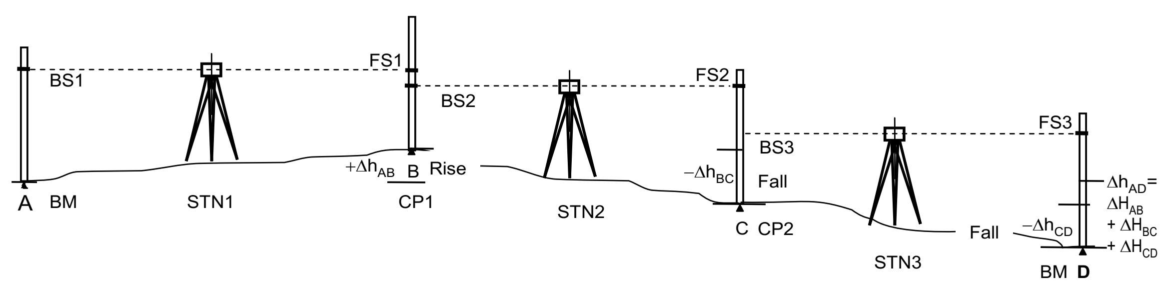


Figure 2.19 Levelling procedure.

Starting from BM(A) and ending at another BM(D).

2.5.4 Booking and field reduction procedures for levelling

Two note reduction methods for calculating elevations from the BS and FS observations exist. Each of the methods uses only two equations for the computations. These methods are

- ➢ Rise and Fall method (i.e., a fall is simply a negative Rise);

$$Rise\,(or\ Fall) = BS - FS$$

$$Elev = Previous\ elev + Rise\,(or\ Fall)$$

- ➢ Height of Collimation method;

$HI = Elev + BS$

$Elev = HI - BS$

In what follows, a detailed examination of the methods is presented.

2.5.5 Rise and Fall Booking and Reduction Procedures

The “rise and fall” method of booking allows three sets of checks to be applied to the booked values. It only checks the calculations, not the booked observed values. Transfer a control point level (bench mark) at A to a new control points at B and C, checked by closing to control point at D. Referring to Table 2-1, the field book recording and checking by “rise and fall” observations are:

Control point A has a known RL of 10.125
Control point D has a known RL of 8.930
difference Δh_{AC} = 8.930 – 10.125 = –1.195

Table 2-1 Rise and fall, checking calculations.

BS	IS	FS	Rise	Fall	RL	Remarks
1.742					10.125	A. Control point.
1.580		1.522	0.220		10.345	B. Change point 1
0.625		1.892		0.312	10.033	C. Change point 2
		1.732		1.107	8.926	D. Observed R.L.
Sum		Sum	Sum	Sum		
3.947		**5.146**	**0.220**	**1.419**		
Σ BS – Σ FS			**Σ Rise – Σ Fall**		**Last RL – First RL**	
	-1.199		**Diff =**	**-1.199**	**-1.199**	**$\delta h'_{AD}$ Last – First**
Three checks agree. The math checks agree with the booked observations.						

However, Table 2-2 shows there is a discrepancy (misclose) between the booked observations and reductions and the known RLs of A and D of 0.004. This may need to be investigated, or accepted (with justification in relation to job specifications).

Table 2-2 Establishment of misclose.

					10.125	A. BM (fixed)
					8.930	D. BM (fixed)
					-1.195	**δh_{AD} Last – First**
			Misclose		+0.004	**δh_{AD} — $\delta h'_{AD}$**

Three wire booking: using the stadia wires

Leica manual, page 16. “Line levelling”.

At each level reading, the three wires, the horizontal centre wire and the two stadia wires, may be booked so as to provide, a) a check against blunder readings and b) a calculation of distance to the staff. (Stadia constant 100).

Table 2-3 Three wire readings.

BS	IS	FS	Rise	Fall	RL	Remarks
1.542						Top wire
1.742					10.125	A. Control point.
1.943						Bottom wire
1.653		1.627				Top wire
1.590		1.522	0.220		10.345	B. Change point 1
1.407		1.417				Bottom wire

The above snippet of field book, Table 2-3, shows:

BS to A. The middle wire (MW) is in agreement with the top wire (TW) and the bottom wire (BW). Distance = (1.943 – 1.542) x 100 = 40.1 m

FS to CP1. MW agreement. (TW+BW)/2 = MW. Distance = (1.627 – 1.417) x 100 = 21 m

After **changing** observation station, reading: **BS to CP1**. MW disagrees with (TW+BW)/2 = 1.580. Is it a booking blunder?

- **Check.** Distance 24.6 m. Further checking: (TW – MW) x 200 = 12.6 m, (MW – BW) x 200 = 36.6.
- **Solution**. Re-observe BS to check before the next FS reading.

Do not take the "mean" value between TW and BW to get a "refined" MW reading. Use it as a **check**.

Could you "assume" a misreading of the mid-wire, correct the reading to 1.580 and then use this as the "correct" BS reading to the next fore station?

2.5.6 Area Levelling: The "Rise and Fall" Method

The "rise and fall" method of booking will be used instead of the illustrated "height of collimation" method in Section 2.5.7. Again, we are only checking the calculations, not the booked observed values. In the two levelling exercises in Appendix A2-1, there will normally be a mix of "line" and "area" levelling observations. All observations, other than the back sight (BS) and the fore sight (FS) are considered intermediate sights (IS) and are booked in the IS column of the "rise and fall" booking sheet.

Exercise 1 is the transfer of reduced levels (RL) to temporary control points (temporary bench marks, TBM) from existing BMs. You may have to use intermediate sights (IS) to establish these TBM, and will have to use them to answer some of the exercise questions.

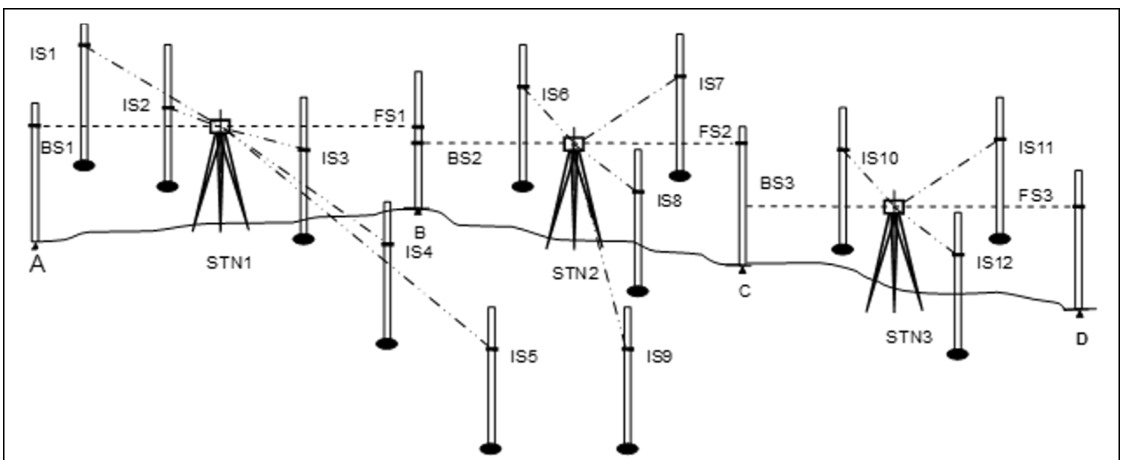


Figure 2.20 Area levelling.

Exercise 2, the area levelling and mapping exercise, will use mainly IS to pick up cross section levels, but will also require a number of change points (CP) to carry observations through the area.

Table 2-4 is an example of booking intermediate sights (IS) between back sights and fore sights, and checking the reductions for observations taken in area, Figure 2.20.

Table 2-4 Rise and fall method. Check calculations.

BS	IS	FS	Rise	Fall	RL	Remarks
1.742					10.125	A. Control point.
	1.628		0.114		10.293	IS1
	1.205		0.423		10.662	IS2
	1.585			0.380	10.282	IS3
	1.625			0.040	10.242	IS4
	1.550		0.075		10.317	IS5
1.580		1.522	0.028		10.345	B. Change point 1
	1.635			0.055	10.290	IS6
	1.640			0.005	10.285	IS7
	1.825			0.185	10.100	IS8
	1.745		0.080		10.180	IS9
0.625		1.892		0.147	10.033	C. Change point 2.
	1.254			0.629	9.404	IS10
	1.365			0.111	9.293	IS11
	1.158		0.207		9.500	IS12
		1.732		0.574	**8.926**	D. Observed R.L.
Sum		Sum	Sum	Sum	8.930	D. **BM RL 8.930**
3.947		**5.146**	**0.927**	**2.126**		closed to 0.004m
Σ BS – Σ FS			**Σ Rise – Σ Fall**		**Last RL – First RL**	
	-1.199		**Diff =**	**-1.199**	**-1.199**	**$\delta h'_{AD}$ Last – First**
Three checks agree. The maths agrees with the booked observations.						

Note that while the checks agree with each other, no maths problems, there is still a discrepancy between the calculated RL of BM D and its true value. This is likely a random error misclose

The check sums only validate the mathematics of the reduced observed values. It does not mean that the individual observed values are correct. A blunder reading itself can't be isolated between check points.

2.5.7 Area Levelling: The "Height of Collimation" Method

This method, see Table 2-5, using the area in Figure 2.20, is easy to use both for level pick-up and for level set-out. A staff back sight (BS) to a known level (point or BM) is taken and added to the known RL. This becomes the "height of collimation" of the level. It is the RL of the observed horizontal plane, the instrument horizon, i.e.,

$$HC = Known RL + BS$$

$$RL\ of\ any\ point = HC - IS\ or\ FS$$

The RL of any point = HC – IS/FS, the staff reading. This method allows change points (CP) to be introduced as temporary bench marks (TBM). The next instrument set-up has a new HC based on the RL of the CP and the new FS.

The method is used for setting-out of vertical control and is the basis of setting-out using rotating laser levels and detectors. Once the HC has been established from a known RL, it is merely a case of raising or lowering the staff until the required level coincides with the base of the staff. The established level is marked by be a peg driven to level, or a line on a stake.

Table 2-5 Height of collimation booking and reduction.

BS	IS	FS	HC	RL	Remarks
					.
1.742			11.867	10.125	RL A. BM . HC for STN1.
	1.628			10.293	IS1
	1.205			10.662	IS2
	1.585			10.282	IS3
	1.625			10.242	IS4
	1.550			10.317	IS5
1.580		1.522	11.925	10.345	B. CP 1. HC. For STN2. RLB + FS
	1.635			10.290	IS6
	1.640			10.285	IS7
	1.825			10.100	IS8
	1.745			10.180	IS9
0.625		1.892	10.658	10.033	C. CP 2. HC. For STN3. RLC + FS
	1.254			9.404	IS10
	1.365			9.923	IS11
	1.158			9.950	IS12
		1.732		8.926	D. **BM D. RL 8.930**
Sum		Sum			closed to 0.004m
3.947		**5.146**			
Σ BS – Σ FS = -1.199				**-1.199**	**$\delta h'_{AD}$ Last – First**

From CP2 (Table 2-6), you wish to establish a design level of RL10.5 over an area. The instrument has been moved and the RL of BM B is used as a control. Additional levels, for other design RLs, are also illustrated. Store the HC in your calculator and use that value, minus the required level, to find the staff reading.

Table 2-6 Calculate IS to setout of design levels.

BS	IS	FS	HC	RL	Remarks
1.370				10.345	RL B.
			11.715		HC. For CP2. RLB + FS
	1.215			10.500	Finish level required.
Set IS	**1.215**				11.715 – 10.5 = 1.215
	1.315			10.400	Calculated IS. Design RL
	1.415			10.300	Design RL
	1.515			10.200	Design RL
	1.615			10.100	Design RL

There is no easy way to check the RL of intermediate levels compared with the "rise and fall" method.

Distribution of misclose? Not in this course.
If the traverse misclose is within allowable limits, then there is an argument for the distribution of a correction through the points. It is carried out in proportion to the number bays; above we have –0.004 over 3 bays (A – B, B – C, C – D). The correction is +0.004/3 per bay cumulative as, say, +0.001 A to B, +0.002 B to C, +0.004 C to D.

Uren and Price (2010), section 2.4, p49 gives details. However, it is hard to differentiate between random errors and systematic errors (collimation caused by unequal BS/FS). Thus, distribution of misclose is **not** used in this course. Miscloses must always be judged on tolerances and the aim of the task, and an engineering decision made.

2.6 Examples of Levelling for Height Control

Two exercises were designed for the Curtin University Civil and Mine engineering courses. The exercises illustrate the use of appropriate practical exercises in available area:

Establishment and transfer of levels using **differential** levelling is used to find the level of new and established control points. The method transfers the **orthometric** height throughout a level network. Control levelling must always close back to a known point or to, at least, a previously established intermediate point in the network. Students use this differential method in Field Practical 1 to set level control for their area levelling exercise in Field Practical 2 (see Appendix A2-1).

2.6.1 Civil Engineering for a Road Excavation Exercise

The exercise (Figure 2.21) area is about 100m x 50m on a sloping site, falling to the south east over a height difference of some 3.5m. The area features pine trees, paths and service boxes. These features lend themselves to various forms of mapping which are explored through the course.

a. Exercise 1 involves a level collimation test, then establishment of vertical control to be used in exercise 2. It is an opportunity for students to become familiar with instrument setup, focussing and staff reading and recording.

   The level collimation exercise provides a practical example of balanced back sight/fore sight observation carried out by each student as an independently (moving and re-setting the level). Booking and field reduction, and evaluation of results, is practiced. The exercise includes an introduction to site reconnaissance, location of control points and establishment of task objectives.

b. Exercise 1 then examines level runs of two type for control establishments:
   - an open traverse from an established bench mark, via an inversion observation to check portal clearance.
     It introduces change points for the rise and fall method of booking.

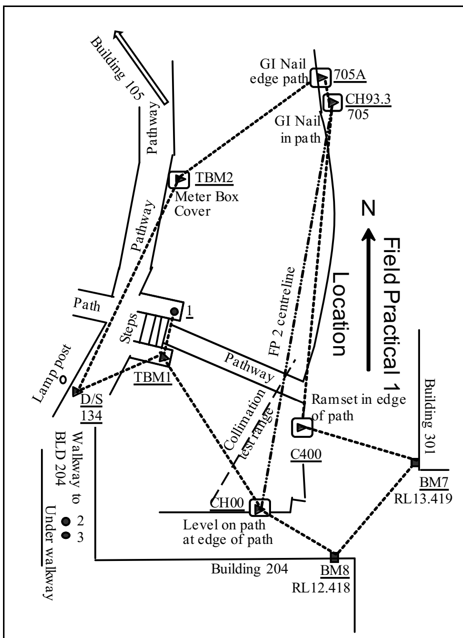


Figure 2.21 Civil field practical 1.

- a closed loop traverse, finishing at a different bench mark, traverses through some of the open loop marks. The exercise requires a number of change points to be used, giving team members the opportunity to carry out observation, booking and staff handling tasks. The exercise timing allows field checking of results before task completion.

c. Exercise 2 (Figure 2.22) incorporates field set-out of a perpendicular offset grid along an established centre line. The task continues from control established in exercise 1 and introduces area levelling observation, booking and reduction. Multiple change points allow rotation of observation tasks.
   - the chainage and offset method of field mapping is used to locate trees, services and feature boundaries. From this field data, a scaled plan of the exercise area is produces showing feature and the boundaries of a design excavation along the centre line.
   - field data is used to calculate the volume of a cutting of designated slope and batter intercepts.

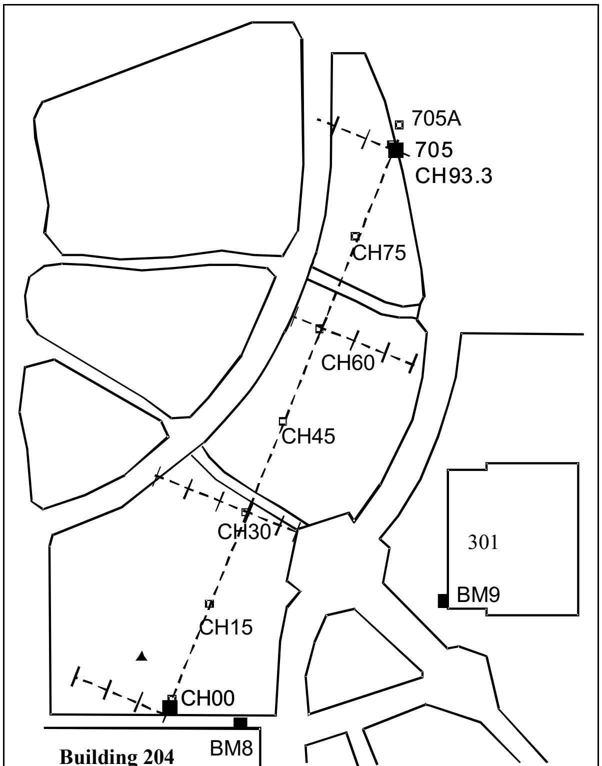


Figure 2.22 Civil field practical 2.

2.6.2 Mining Engineering Surveying for a Site Development

The exercise area is about 120 m x 90 m on a sloping site, falling to the south east over a height difference of some 6 m. The area features pine trees, paths and service boxes. These features lend themselves to various forms of mapping which are explored through the course.

a. Exercise 1 (Figure 2.23) involves a level collimation test, then establishment of vertical control to be used in exercise 2. It is an opportunity for students to become familiar with instrument setup, focussing and staff reading and recording. The level collimation exercise provides a practical example of balanced back sight/fore sight observation carried out by each student independently (moving and re-setting the level). Booking and field reduction, and evaluation of results, is practiced.

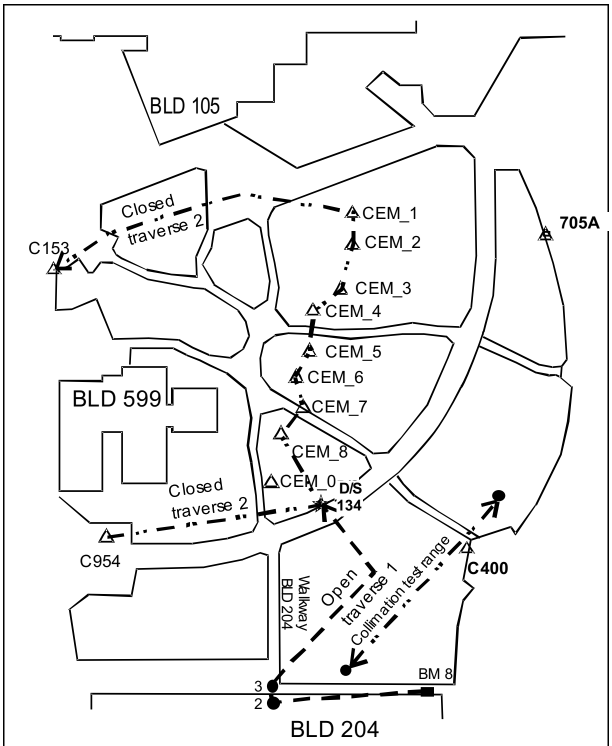


Figure 2.23 Mining field practical 1.

The exercise includes an introduction to site reconnaissance, location of control points and establishment of task objectives.

b. Exercise 1 then examines level runs of two type for control establishments:
   - an open traverse from an established bench mark, via an inversion observation to check portal clearance. It introduces change points for the rise and fall method of booking.
   - a closed loop traverse, finishing at a different bench mark, traverses through some of the open loop marks. The exercise requires a number of change points to be used, giving team members the opportunity to carry out observation, booking and staff handling tasks. The exercise timing allows field checking of results before task completion.

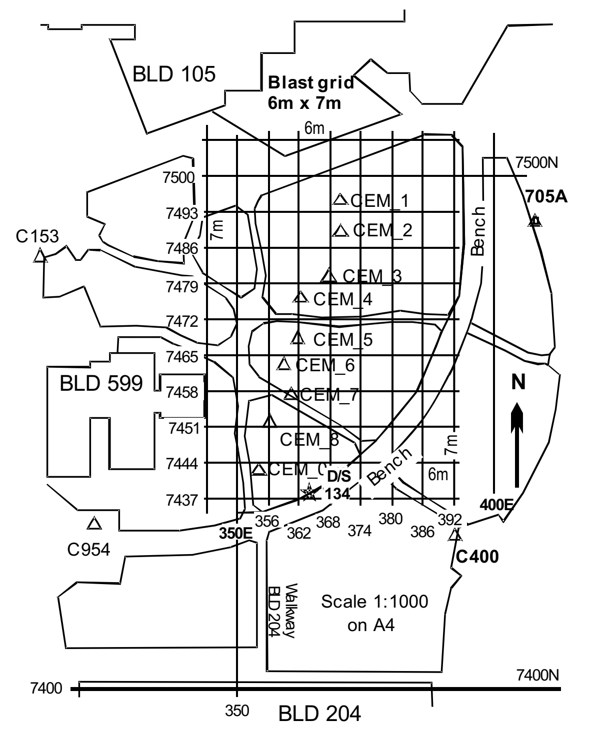


Figure 2.24 Mining field practical 2.

c. Exercise 2 (Figure 2.24) incorporates field set-out of a rectangular grid along over a designated area. The task continues from control established in exercise 1 and introduces area levelling observation, booking and reduction. Multiple change points allow rotation of observation tasks.
   - grid layout of a typical blasting grid. Area levelling, using the Height of Collimation method illustrates field practice.
   - grid method (estimating position in grid cell) of field mapping is used to locate trees, services and feature boundaries. From this field data, a scaled plan of the exercise area is produces showing feature and the boundaries of a design excavation area.
   - field data is used to calculate the volume of an excavation down to a design level.

2.6.3 Grid Layout for levelling

The survey area should be gridded in a rectangular pattern aligned N-S and E-W, or as dictated by the main axis. This will allow easy integration to the local coordinate system for the GIS/CAD systems. A plan of the work area allows **determination** of the grid area, and its alignment. The base control points should be referenced to known control to allow incorporation of the grid coordinates into the local survey grid system. The alignment axis can be indicated by survey stakes, ranging poles or pathways. Ranging poles and cloth tape will be used to place chaining arrows at the grid intersections.

The height of collimation method of recording will allow quick reduction of the DEM levels.

2.6.4 Orthogonal Grid Layout Methods

The requirement for a grid is that it should be orthogonal, i.e., the grid lines should be perpendicular to each other. How is this achieved?

3 – 4 – 5 triangle: The traditional technique is to use the dimensions of a plane right angle triangle as control. This method has been used since antiquity and continues today in the building industry. The best traditional triangle is the "3 – 4 – 5" triangle. 3 and 4 are the perpendicular axes and 5 is the length of the hypotenuse.

Establish the **grid origin** and lay out the extension of the main axis, marking it with stakes or ranging poles. Lay the tape on the ground from the origin. Place a survey pin at, say, 6.0m. From the origin lay a second tape at about right angles to the main axis. Measure down 8.0m. Check the diagonal from the 6m pin and adjust the 8m alignment until the diagonal distance reads 10.0m. Extend the alignment with a range pole and you have your main grid axes. It works with a 30m tape.

Optical square: It is a small hand instrument (Figure 2.25, Figure 2.26) used for laying off a right angle by means of two pentaprisms separated vertically by a small gap. The pentaprisms deflect the line of sight through the prism faces by 90º to the left and right.

If two range poles are coincident in the prisms, then a point also coincident through the gap is perpendicular to the line of the range poles (Figure 2.27). Hanging a plum bob from the prism allows a reasonable intersection.

Figure 2.25 Optical square.

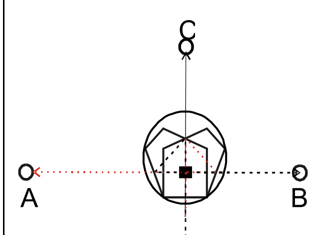


Figure 2.26 Optical path through square.

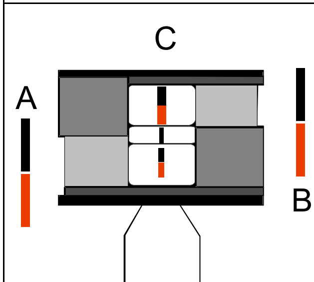


Figure 2.27 Aligning to perpendicular.

Grid orientation: Grid orientation may be calculated by measuring in from known points to a convenient integer co-ordinate, or by examination of a site plan. Often plans will be plotted over existing features that can be used as a base line.

2.6.5 Height from Vertical Inclination

Part of the practical tasks involves finding the height of trees using a tape and **clinometer**. The enclosed case clinometer comprises a pendulous calibrated wheel supported on dual sapphire bearings in a fluid filled capsule. The face of the wheel is graduated 0° to ±90° and is read against an index on the capsule. The periphery of the wheel, viewed through the magnifying eyepiece, shows elevation and depression from the horizon It is graduated in degrees (LHS) and percentage of horizontal distance (RHS) to the target. Typical performance is quoted as: accuracy ¼°, graduation 0.5°.

The illustration shows the simultaneous view using both eyes, reading to the top of a tree trunk The clinometer wheel is viewed with one eye, and the target with the other. (Tricky 'til you get the hang of it.) The elevation reading is 7° (about 12%).

The height of the tree, above the observer's eye, is the horizontal distance to target x tan(angle).

Assume H distance = 50m:

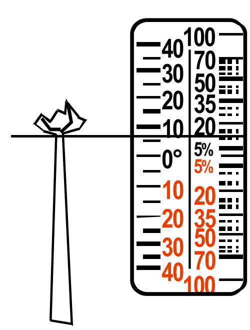
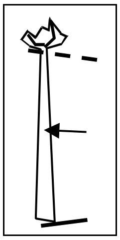


Figure 2.28 Tree elevation.

Ht = 50 tan(7°) = 6.1m (50 x 12% = 6).

Take a second reading to the base of the tree, say –4°. Ht = –3.5.



Tree height = 6.1 – –3.5 = 9.6m.

Always measure from the longest possible distance away. The inclination angles are lower; the pointing errors associated targe definition are minimised. Read to both base and top, you are thus independent of eye height, especially on sloping ground.

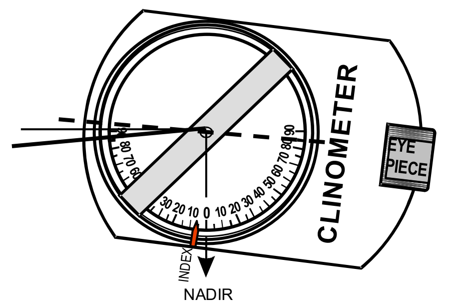


Figure 2.29 Clinometer measuring.

2.7 Errors in Levelling and Management Strategies

The best analytical discussion of errors in levelling is contained in Ghilani (chapter 9, pp151, *Error propagation in elevation determination*). As with any set of measurement observations, differential levelling is subject to three types of errors (i) systematic errors, (ii) random errors and (iii) blunders or mistakes and errors in datum total transfer.

2.7.1 Systematic Errors in Level Observations

1. Collimation errors, minimised by one of the rules of levelling:
   Back sight and foresight approximately equal:
   - an unbalance observation will introduce either a positive or negative systematic error depending on:

   a) collimation error,
      The Leica manufacturer’s max for example is 0.003 (3 mm) in 30 m = 0.0001 radians = 21" arc.

   b) difference between length of total back sights and total fore sights, error = distance x collimation error (radians).
      - max errors; 0.001m at 10m, 0.005 m at 50m.

   In an extended line levelling exercise, the difference in the sum of the distances covered as back sights and foresight may contribute to a significant systematic error.
2. Earth curvature and refraction, $\boldsymbol{h}_{\mathrm{CR}}$, minimised by one of the rules of levelling:
   Back sight and foresight approximately equal:
   - the staff reading error, in metres, combining curvature and refraction, is:
   - $\boldsymbol{h}_{\mathrm{CR}} = \mathrm{CR}\left(\frac{\mathrm{D}}{1000}\right)^2$, where CR = 0.0675 for, D, in metres.

   An unbalanced set of observations will introduce a positive systematic error, $\boldsymbol{e}_{\mathrm{CR}}$, that must be **subtracted** from the difference in elevation
   - $\boldsymbol{e}_{\mathrm{CR}} = \frac{\mathrm{CR}}{1000^2}\left(\Sigma \mathrm{D}_{\mathrm{BS}}^2 - \Sigma \mathrm{D}_{\mathrm{FS}}^2\right)$.

   CR is quoted as 0.0675 by Ghilani (2010). It is close to an empirical value of k=1/14 (0.07) developed by Bomford’s investigation of curvature and refraction of radio and light waves in EDM (e.g., Bomford, §3.5, (1.34), p52).

The effect is minimal, for example (Ghilani 2010, p147). Take transfer of levels on a sloping site, where BS/FS can vary in the ratio of 5:1. A 1:6 slope (9.5°), with a 5 m staff, has a BS = 8m and FS =21m. Over 150m traverse, say 5 x 30m bays.

- Σ_{BS} = 105, Σ_{FS} = 40. $dS^2 = (105^2 - 40^2) = 9{,}425$; $e_{CR} = 0.0675/10^6 \times 9425$m
- e_{CR} = 0.00064m, under 1mm.

3. Staff calibration and mechanical construction errors:
   It is generally assumed that staff markings have been manufactured accurately. They can be checked against a certified measuring tape ($100) or by a certified testing authority.
   Telescopic segmented staffs can suffer from worn locking mechanisms, especially over the base and 1st segment which are the most commonly extended sections. Use a tape cross the segment join to find any wear, making sure the staff is vertical to load the lock. (Figure 2.30).

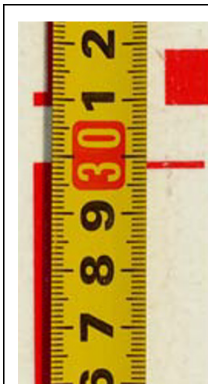


Figure 2.30 Worn staff.

4. If using two staffs, make sure they have similar base segment lengths, a worn staff foot could introduce a systematic error between staves, a staff datum error. Complete each pair of level bays by leapfrogging staves. Ensure an even number of bays.
5. Temperature expansion: staffs should be manufactured at a standard temperature, about 25°C,
   - a fibreglass staff has a temperature coefficient of about 10 ppm/°C
   - an aluminium staff has a temperature coefficient of about 25
   - ppm/°C

   At 35°C, δT = 10, over a height difference of 50 m there would be an error of:
   - 0.013 m using an aluminium staff ((50(dH) x $25/10^6$) x 10 (δT) =0.0125) and
   - 0.005 m using a fibreglass staff.

2.7.2 Random Errors in Level Observations

1. Observer reading errors:
   single reading error:
   ±1.2 mm/30 m = 0.00004 radians = 8" arc
2. Instrument level error: usually expressed as the:
   - standard deviation in mm per km of double run levelling:
     - ±2 mm/km = 2.0^{-6} radians = 0.4" arc

   this value is in agreement with the declared compensator settling accuracy
3. Staff verticality, staff bubble error, **δ**
   may be of the order of 5′ arc, (Ghilani 2010, p149)
   $e_{LS} = \frac{h}{2}\sin^2\delta$, at h = 5m e_{LS} = 0.005**mm**
   - (1/200mm).
   when δ = 1.5°, at h = 5m then $e_{LS} \approx \pm 0.002$m
   - **(2mm).**

   The analysis (Figure 2.31) shows that a staff bubble should be used for all observations. But at normal observation levels, where h = 2m, a non-verticality of 2.5° is needed to produce a 2mm error.

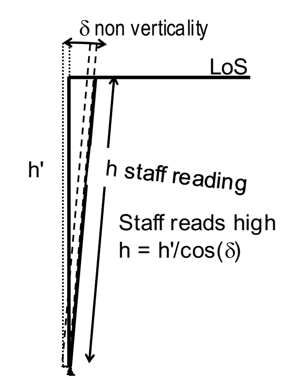


Figure 2.31 Verticality.

4. Lack of a staff bubble can be overcome by rocking the vertical staff slowly backwards and forwards, and reading the minimum height value on the mid wire. (Also, check verticality against vertical cross hair).

2.7.3 Observation Blunders and Mistakes

Likely sources of error in observations will come from:

1. Gross reading error of centre wire
   - read and record top and bottom stadia wires,
     - check mean.
2. Reading top or bottom stadia wire instead of centre wire.
3. Parallax in reading staff,
   - check reticule and object focus.
4. Unstable change points
5. Staff section not extended, or not locked (Figure 2.32).
6. Incorrect recording of Bench Mark data
7. Not using BM correctly
   - ensure correct reference surface (Figure 2.33).
8. Transcription errors in field book
   - poor character formation, printing, transposition.

Figure 2.32 Section error.

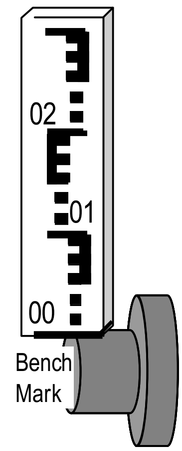


Figure 2.33 Bench mark reference

2.8 Concluding Remarks

This chapter has introduced you to levelling, i.e., the surveying procedure used to determine elevation differences. Arguably, most tasks that you will undertake in civil engineering and mining operations will require some sort of height (elevation) information. In the chapters ahead, we will see how this information becomes vital for the design/construction projects.

2.9 References to Chapter 2

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