A Densified Vertical Control Network to Support Groundwater Studies at Thirlmere Lakes

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ABSTRACT

Researchers in the Water Research Lab at the School of Civil and Environmental Engineering, UNSW, have been studying the unusual behaviour of the Thirlmere Lakes chain near Picton. Geologically these lakes were formerly part of a river system, which no longer flows due to local tectonics, causing the lakes to remain as an isolated and linked lake system. The water level of the lakes and the groundwater beneath recede and recharge with changing rainfall. The lake and groundwater levels are monitored using a network of piezometers housed inside PVC pipe. The problem, however, is that these pipes are connected to a thick, peat lakebed that itself moves considerably as the water level changes. How then can changes be monitored if both the water level and the piezometers are apparently moving? This was a perfect project for 4th year surveying students! Field Projects 2 is a capstone course within the UNSW surveying program. There are no lectures and no exams, just a challenging project that is effectively run by the students and guided by the lecturer. With 17 students enrolled, there was plenty of manpower to measure 5 lakes with around 4 piezometers in each. A day of reconnaissance revealed that leap-frog EDM height traversing would be the fastest and most accurate technique given the thick tree cover and dubious mobile phone connection. This was linked with a static Global Navigation Satellite System (GNSS) survey and simultaneous reciprocal trigonometric levelling to span the lakes. All lakes were flown with an Unmanned Aerial Vehicle (UAV) and drone-mounted Light Detection and Ranging (LiDAR). All the work was divided amongst students who also tried to adhere to ICSM's SP1 and Surveyor-General's Direction No. 12, used AUSPOS, GNSS baseline software and least squares network adjustment software, considered the Australian Vertical Working Surface (AVWS) and compared new UAV point clouds with previous recent flights. This paper outlines this challenging project, which also provided a rich education for everyone involved.

KEYWORDS: *Leap-frog EDM height traversing, GNSS, UAV, LiDAR, UNSW.*

1 INTRODUCTION

Every year, coordinators of the final year capstone course, Field Projects 2 (GMAT4150), seek out new and interesting projects to engage students with a challenging and hands-on exercise. A capstone course tries to encapsulate all that has been previously learnt in the Bachelor of Engineering (BE (Surveying)) program at the University of New South Wales (UNSW) and apply it to a problem. The year 2020 was particularly challenging, given that in term 2 no practical field exercises were allowed due to the COVID-19 pandemic, precluding any meaningful surveying project to be undertaken (Roberts and Harvey, 2019).

Fortunately, by September, university administrators indicated that outdoor field projects for small class sizes would be permitted. The year's cohort comprised a mixture of 17 Civil/Surveying students with various experience. Finding a project large enough to satisfy all students was concerning until a corridor conversation with researchers from the Water Research Lab within the School of Civil and Environmental Engineering (CVEN) revealed a potential project.

A/Prof Martin Andersen and Dr Christian Anibas have been engaged on a Department of Planning, Industry and Environment (DPIE) funded project investigating surface water–groundwater interactions, geological mapping and geophysical surveys of the Thirlmere Lakes area (DPIE, 2021). Water levels in Thirlmere Lakes have fluctuated over time, but some larger than usual declines in the last decade prompted significant concern by the local community and further investigation. A group of four independent scientists and a community representative were appointed by the NSW Government to evaluate possible causes for the low water levels in the lakes (Riley et al., 2012).

Researchers established a network of piezometers (an instrument for measuring the pressure and inferred depth of groundwater) to monitor the movement of groundwater and cross reference with rainfall and other parameters. There is a strong correlation between pressure and groundwater level, but the piezometers were mounted in PVC pipes driven into the deep peat soils in the lakebed. Fluctuating rainfall has the effect of swelling and contracting the peat lakebed significantly, introducing unmeasured biases into the Australian Height Datum (AHD) heights of the PVC-mounted piezometers. Providing a stable vertical control network separate from the piezometer network would enable researchers to account for these variabilities and in-so-doing determine more accurately the AHD height of the ground water interactions.

Further communication with the researchers indicated that they required sub-centimetre height accuracy on more than 20 piezometers spread across five lakes. This provided an excellent and challenging task for the final year students. This paper outlines the project, which provided a rich education for everyone involved.

2 THIRLMERE LAKES

Thirlmere Lakes National Park is located near Picton, south of Sydney. It comprises five lakes: Lake Gandangarra, Lake Werri Berri, Lake Couridjah, Lake Baraba and Lake Nerrigorang. At least four piezometers are located in each lake. The chain of lakes are girt by the Middleton Memorial Drive and Slades Road, providing a stable location for a vertical control network (Figure 1). This site was particularly suitable for 2020, where COVID-19 restrictions precluded an overnight camp, as multiple day trips from UNSW in Sydney were feasible for this project.

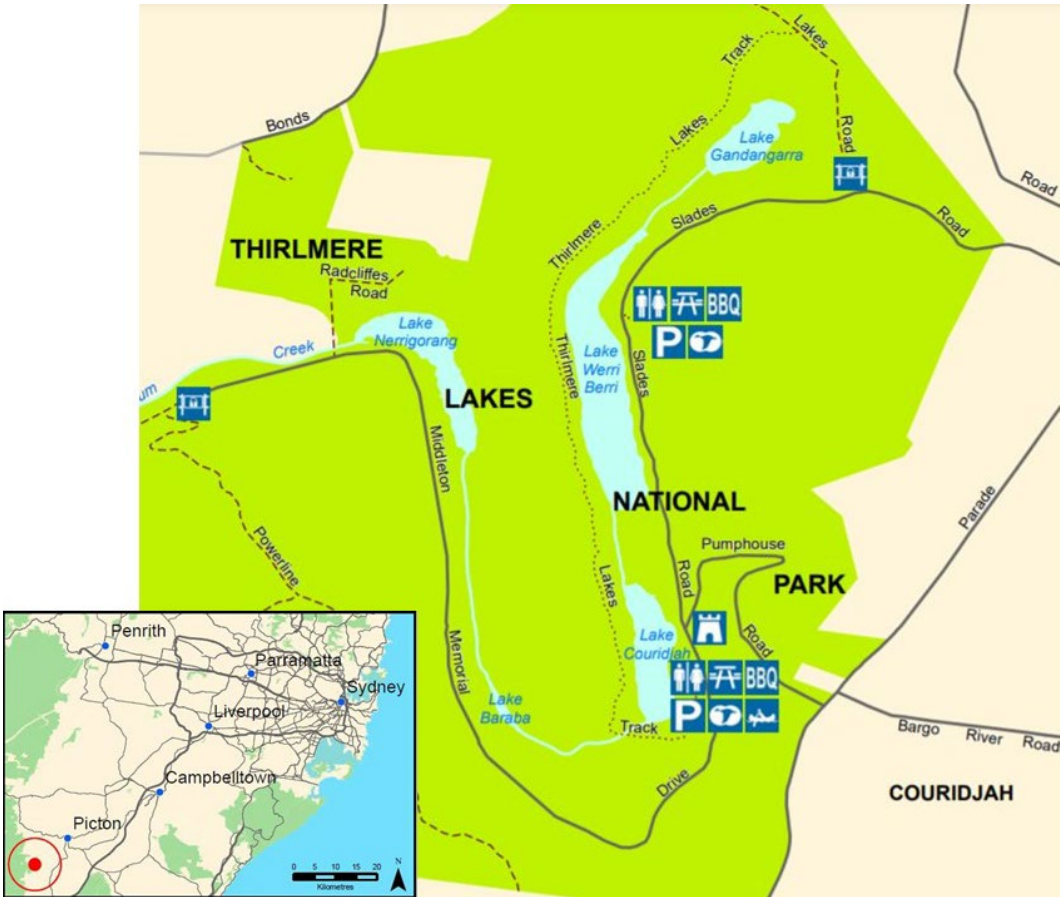

Figure 1: Location of Thirlmere Lakes National Park (NSW National Parks, 2021).

3 PROJECT DESIGN

The teaching year at UNSW now comprises 3 x 10-week terms. This term 3 project therefore had to accommodate the project brief, project design, literature review, instrument testing, reconnaissance, field work, computations, data analysis and final report writing in a 10-week period. The team was split into five groups of three students to cover each lake with two extra students acting as the specialist Global Navigation Satellite System (GNSS) surveyors. The whole group elected a Managing Director (MD) to coordinate all the activities and, given the logistics for this project, two other students stepped up to assist. These executive roles were additional to their group activities.

It was decided to visit the site for reconnaissance in week 3 with a view to returning for the bulk of the field work in weeks 5 and 6, depending on the weather. Weekly meetings were held on campus and due to the smaller class size, students could attend in person in accordance with COVID-19 guidelines. Later in the project, these weekly meetings combined in-classroom students with online students using an external microphone/video pointed at the whiteboard. This worked well.

The MD chaired the meeting, a secretary took minutes and the team collectively developed action items for all the student groups to address. The course coordinator (author) acted as a client and provided guidance and extra information where required. All students were required to keep a log of their hours worked on the project. This is seen as training for future work as a graduate surveyor.

The initial design of the project was discussed in extended Friday whiteboard sessions, agreed upon by all students and consequently plans were drafted. This was also an opportunity to allocate (by self-selection) students to undertake a literature review of anticipated techniques and concepts that would be required for the project. This drew upon the knowledge already gained in the BE (Surveying) program and newer techniques that may require further investigation. These included leap-frog EDM height traversing, digital levelling, classic and rapid static GNSS, trigonometric heighting, simultaneous reciprocal trigonometric levelling (SRTL), Australian Vertical Working Surface (AVWS) vs. AHD, modernised datums, Unmanned Aerial Vehicle (UAV) photogrammetry, UAV-based Light Detection and Ranging (LiDAR), post-processed kinematic (PPK) GNSS, AUSPOS and virtual RINEX.

The field reconnaissance in week 3 was crucial to the final design of the project. After experiencing the size and shape of the project and location of the piezometers (Figure 2), a more feasible project plan was developed in preparation for the first field day in week 5.

Figure 2: Google Earth overlay showing the location of piezometers (LG = Lake Gandangarra, LW = Lake Werri Berri, LC = Lake Couridjah, LB = Lake Baraba, LN = Lake Nerrigorang, GW and BG are additional boreholes).

For assessment purposes, a project team planning report was required by the end of week 4 as a way of requiring students to both document what they had learnt from their literature review and to outline their team plans for the first field day in week 5.

3.1 Project Plan

Thirlmere Lakes National Park is a difficult environment for surveying. Mobile phone coverage is unreliable, inhibiting homogeneous GNSS Real Time Kinematic (GNSS RTK) techniques at all sites. Additionally, there is heavy tree cover along the road that was planned for the vertical control network. The road extends around 6 km, so each group would therefore have to propagate levels over more than one kilometre at better than 10 mm accuracy. Some piezometers were located underwater in the lake and some on the opposite side of the lake at a distance of over 100 m. The project design had to incorporate both a stable vertical control network and a means of measuring all the piezometers whilst equitably dividing the work amongst all student groups.

AHD control had been previously established in the national park in 2019 when DPIE engaged their in-house surveyor, Steve Holtznagel, to measure the height of all the piezometers. He did this using a combination of GNSS RTK, PPK and static GNSS surveying. It should be noted that at the time of this survey, the lakes were all dry due to an ongoing drought enabling easier access to the piezometers. Subsequently, substantial rain in February 2020 filled the lakes and it is anticipated that the AHD heights on the piezometers have most likely changed.

Surveyor Holtznagel recently established three high-quality permanent marks within the national park (PM170113, PM170114 and PM170115), but in the Survey Information Management System (SCIMS) these marks are currently allocated class D and have a Positional Uncertainty (PU) of about 0.19 m for the GNSS-derived AHD height. However, nearby were two levelled marks (SS24663 and SS24664) with class LB (levelled). It was decided to conduct a 2 x 4 hr session, GNSS rapid static survey using the full multi-GNSS constellation and AUSGeoid2020 to bring AHD control into the project.

Given the length of the level runs for the various groups, the time constraints and the vegetation coverage, it was decided to use leap-frog EDM height traversing to propagate AHD height throughout the network. 400 mm star droppers were placed as the survey marks (C100, C101 etc. in Figure 3) and distributed predominantly along the road in the vicinity of piezometers and as link points between adjacent groups. This enabled checks to be made between groups. Moreover, these link points were incorporated into the GNSS rapid static survey campaign as an extra check.

Figure 3: Google Earth overlay of control marks and existing SCIMS control (points C102, C117, C107 and C112 were link points between the adjacent student groups).

The survey was designed such that all piezometers could be measured using terrestrial surveying techniques to preserve the cm-level requirement of this survey. Piezometers located across the other side of the lakes were measured using simultaneous reciprocal trigonometric levelling and some marks were checked with digital levelling. A session plan and allocation of equipment was prepared by the GNSS team for the rapid static campaign. Planning for all tasks was conducted in the field during reconnaissance and in later class planning sessions.

It was anticipated that most of the levelling tasks and GNSS would be completed during the first field day in week 5. As GMAT4150 is primarily an educational exercise, UAV photogrammetry was also included in the project. Each group planned to have their lake flown by Dr Yincai Zhou (UAV pilot in CVEN) and consequently student groups were required to identify and measure suitable locations for Ground Control Points (GCPs) that had to be visible from the air and required mobile phone coverage for GNSS RTK. James Linke from Linke & Linke Surveys kindly offered to fly all five lakes with UAV LiDAR in week 6. The GCPs were therefore used for both UAV photogrammetry and UAV LiDAR surveys.

4 FIELD WORK

4.1 Leap-Frog EDM Height Traversing (LFHT)

Students used Sokkia 530RK3 total stations with two prism poles. Sight lengths of up to 100 m enabled fast progress. FL-FR-FR-FL observations were carefully taken and double runs with even bay numbers (2 poles) were performed to provide statistics on the quality of the level runs (Rüeger and Brunner, 1981; Ceylan and Baykal, 2006). Each group connected to their adjacent group's link station (see Figures 3 & 6).

4.2 Simultaneous Reciprocal Trigonometric Levelling

Spanning the lakes presented a wonderful opportunity to utilise the rarely used SRTL technique (Cannings, 2008). Two Sokkia 530RK3 instruments were used on either side of the lake with prism poles and bipods (Figure 4). Radios were used to ensure simultaneous observations to cancel the effects of refraction and earth curvature. All students reported mm-level precision for this technique.

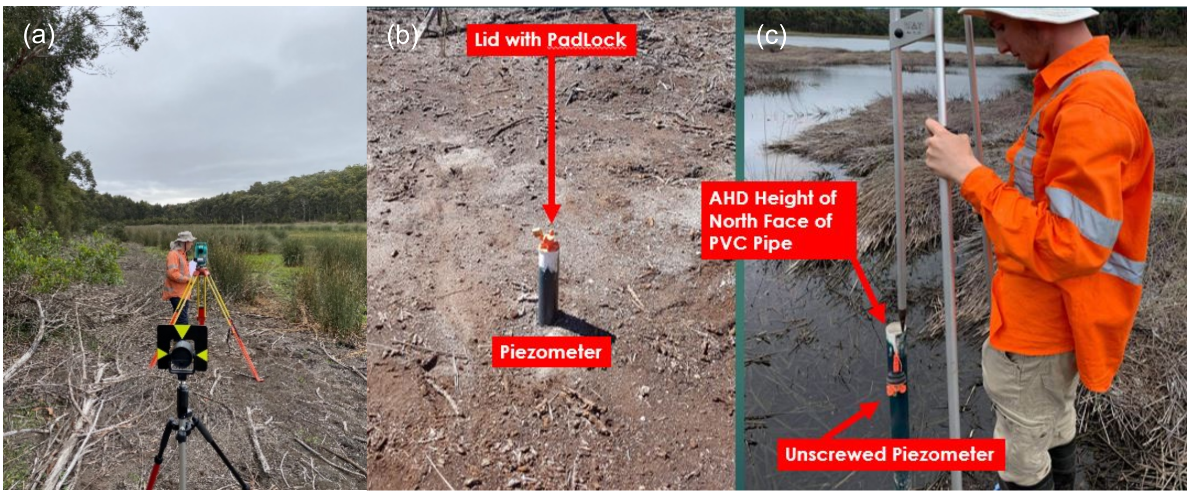

Figure 4: (a) Simultaneous reciprocal trigonometric levelling, (b) PVC housing for piezometer, and (c) trigonometric heighting of PVC pipe.

4.3 Digital Levelling

Trimble DiNi levels (0.7 mm double-run precision) were used with fibreglass staffs to check important level runs. Double runs were always measured.

4.4 GNSS Surveying

Eight Leica Viva GNSS receivers were available for the GNSS campaign survey. All were configured to measure multi-GNSS at a 10-second sampling rate for the planned 2 x 4 hr sessions. The nearest Continuously Operating Reference Stations (CORS) belonging to CORSnet-NSW (Janssen et al., 2016; DCS Spatial Services, 2021) were Picton (PCTN, 9 km NE), Cordeaux (CRDX, 24 km ESE) and Menangle (MENA, 21 km NE). RINEX data from these stations was collected for processing. GNSS RTK, using SmartNet and Network RTK (NRTK), was used for UAV GCPs (double occupation) and PPK was used where mobile phone coverage was unreliable. GNSS static RINEX data was processed using AUSPOS (GA, 2021) and CSRS-PPP (NRCan, 2021) to provide further checks.

5 RESULTS

5.1 Levelling Results

With six field parties operating for two full field days there was a large amount of data to organise and collate. Students created templates for Excel spreadsheets to ensure all calculations were performed identically, enabling direct comparisons of data quality between the lakes. All levelling results from leap-frog EDM height traversing, digital levelling and SRTL were listed on these templates (Table 1). Following ICSM guidelines (ICSM, 2020), second order $6\sqrt{k}$ tolerances would ensure the 10 mm level precision for the project would be achieved between adjacent control marks. Of the 46 double-run levelling sections, only two violated the tolerance limit as part of the direct control run and four more side runs to piezometers violated the second order tolerance, but never by more than 2 mm. Full results can be viewed in Roberts (2020a).

Table 1: Example of template data from the levelling data for Lake Gandangarra.

From →	To	Forward H Difference minus Backward H Difference (mm)	Section Length (m)	Tolerance (mm)
C116	C102	0.33	39.08	✓ 1.2
C102	C101	1.00	461.29	✓ 4.1
C101	C100	1.70	712.98	✓ 5.1
C100	LGP4	1.70	151.65	✓ 2.3
C101	LGP3	1.20	159.60	✓ 2.4
C101	LGP1	1.40	178.59	✓ 2.5
C101	LGP2	1.30	249.80	✓ 3.0
GW075411.1.1	C100	2.20	328.51	✓ 3.4

5.2 GNSS Results

Figure 5 shows the results of the week 5 field campaign using eight Leica Viva GNSS receivers. This data was combined with CORS data from PCTN, CRDX and MENA. Data processing used the Leica Infinity v3.1 GNSS baseline processing software. Despite the relatively long sessions, close geometry and use of all constellations, the baseline results were quite poor.

Phase-fixed solutions were achieved but they did not accord well with the leap-frog EDM height traversing results, largely due to the very heavily vegetated environment. It was very difficult to situate control marks in suitable locations with a reasonable sky view. Instead, it was assumed that taking more data and utilising all GNSS constellations would still achieve acceptable results.

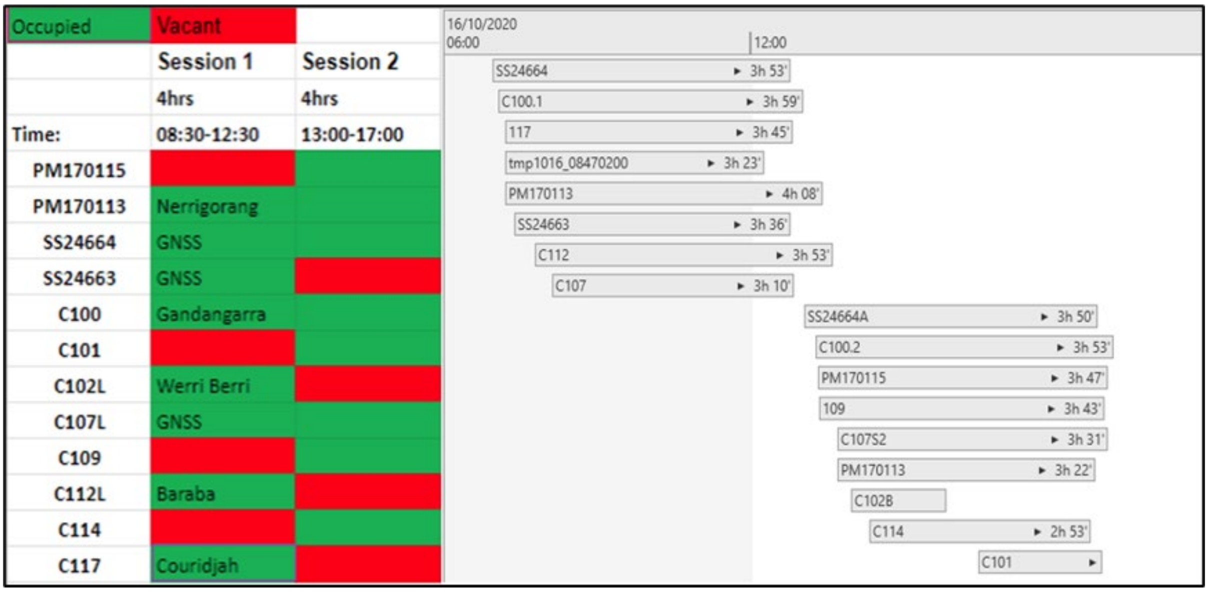

Figure 5: GNSS session plan and imported static data in Leica Infinity.

Examining Figure 5, some emphasis was placed on SS24664 and SS24663 to propagate the class LB AHD heights from these high-quality SCIMS marks. Further processing using single baselines from PCTN CORS (considered stable) revealed that these SCIMS marks had both subsided over time by 11 and 13 cm respectively and were no longer suitable to propagate AHD levels into the project. This hypothesis was confirmed by recent survey reports from DCS Spatial Services investigating the sinking of survey control in the region due to underground longwall coal mining (adjustment IDs 237896, 237897 & 238371).

Computing the baseline from PCTN CORS to PM170113 agreed to within 4 mm and indicated that this newly placed PM was indeed stable. Adjustment 237896 also showed that subsidence was restricted to east of the Thirlmere Lakes National Park, adding weight to the hypothesis that PM170113 was stable. Personal consultation with Surveyor Holtznagel confirmed that considerable data had been observed at this station, providing good confidence in its computed height.

One of the main tasks of this project was to compare the AHD heights of the piezometers (using conventional terrestrial surveying techniques) with the heights derived by GNSS techniques from Surveyor Holtznagel in 2019. Therefore, it was decided to use the GNSS-derived AHD height of PM170113 from SCIMS as control, although connection to a stable levelled mark would have been preferable. It is believed that the quality of its AHD height is better than that published in SCIMS (class D and AHD-PU of 0.19 m).

5.3 Network Adjustment

Having processed the GNSS baselines in Leica Infinity, it was decided to investigate the survey using the network adjustment functionality offered as part of this software. However, combining height difference data manually and with GNSS baseline data proved to be very time consuming and awkward. Due to time constraints, this option was no longer pursued.

Instead it was decided to use FIXIT4, an education-based least squares network adjustment package for survey observations (Harvey, 2021). It computes all adjustments on a plane and is therefore not suited to larger surveys. However, for this task it is only required to adjust heights so was considered suitable. Students are very familiar with this software. All data was checked by the groups for gross errors and internal consistency between forward and reverse levelling runs for each lake separately and provided in a standard template to one student who collated and adjusted the data. A specific point-numbering strategy was implemented for clarity. All data was found to be of good quality with expected standard deviations of 1-2 mm and a few instances of up to 3 mm in areas of unstable terrain (Roberts, 2020a).

PM170113 was held fixed and all AHD heights were propagated from this stable benchmark (see section 3.1). Checks on the link points using heights from the GNSS rapid static campaign were unreliable due to heavy tree cover. This rendered the leap-frog level run essentially a double-run hanging traverse from PM170113, running SW through link stations C112, C107, C117, C102 and closing on C100 (Figure 6).

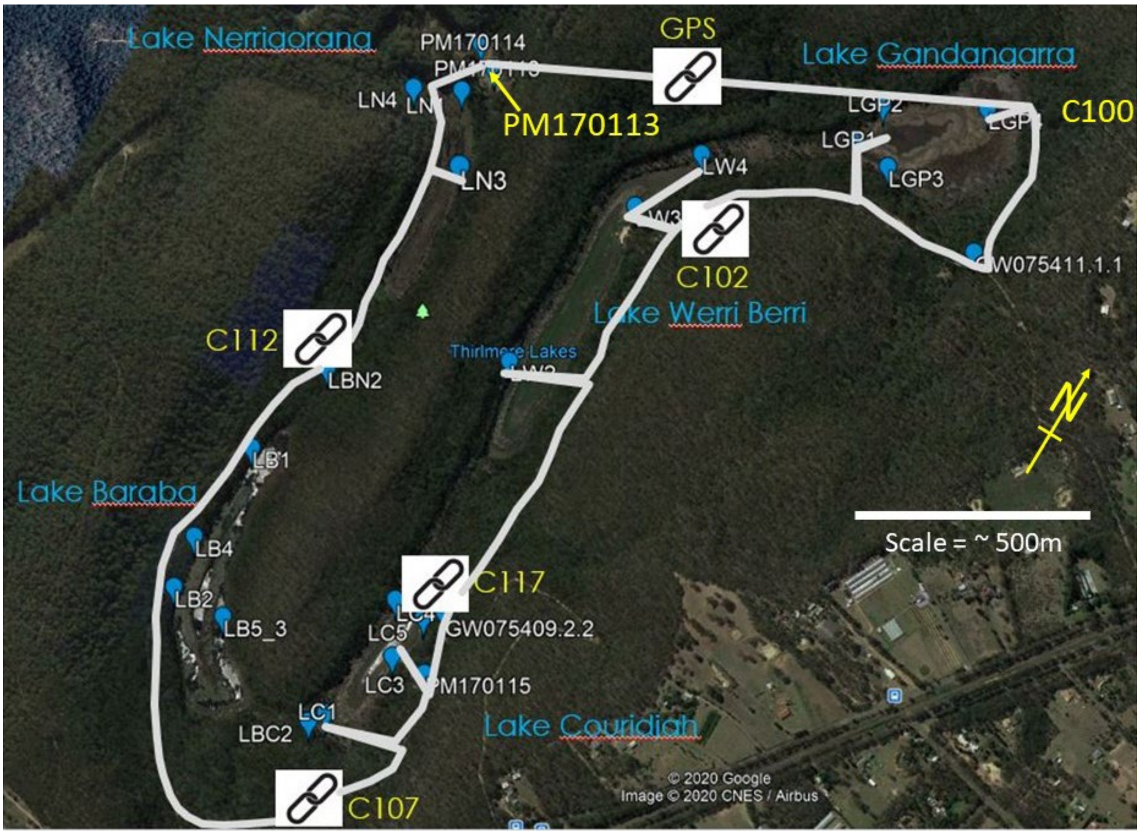

Figure 6: Network adjusted level run using FIXIT4 and showing GNSS baseline check from PM170113 to C100.

The final network adjustment, using only the levelling data propagating over the 6 km, U-shaped run, yielded AHD heights with a 95% confidence interval of no more than 9 mm at the Lake Gandangarra sites. As a sanity check, C100 and C102 provided a relatively clear sky view compared to all other control points. GNSS baselines between PM170113 and C100 and C102 showed discrepancies of 22 and 26 mm respectively, which provided some confidence in the quality of the leap-frog EDM levelling results. A complete table of results is listed in Roberts (2020a).

6 POINT CLOUD DATA

Increasingly surveyors use point cloud data in their work, derived from UAV photogrammetry, laser scanning or satellite imagery. Students have studied photogrammetry and carried out some image processing, but GMAT4150 enables practical application and exposure to these latest technologies.

6.1 UAV Photogrammetry

A DJI Phantom 4 RTK drone was used for this project. It can connect to CORSnet-NSW but only where mobile phone coverage was stable. Once airborne, the connection was much more robust than on the ground. CVEN drone pilot Dr Yincai Zhou discussed flight planning and logistics with the student group during Friday planning sessions (Zhou and Roberts, 2018).

The DJI Phantom 4 RTK was chosen because it enabled direct georeferencing. Direct georeferencing implies that no ground control is required to produce a Digital Surface Model (DSM) which, depending on conditions, can achieve up to 50 mm height accuracy. Indirect georeferencing is the preferred method of DSM generation and requires GCPs placed geometrically around the area to be captured (Figure 7). The ability to lock a processed DSM to ground control ensures a more reliable and higher-accuracy result.

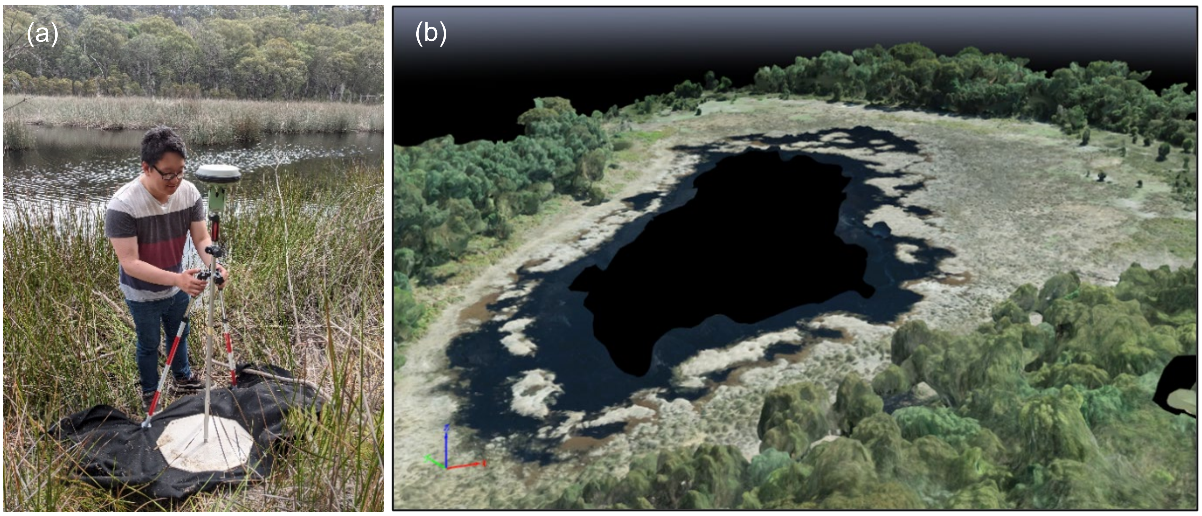

Figure 7: (a) NRTK of GCPs, and (b) the DSM from UAV photogrammetry of Lake Gandangarra.

All student groups established four GCPs around their lake and double-occupied these control marks (see section 4.4). This meant that if indirect georeferencing was not possible, then direct georeferencing (i.e. without control) would still be an option. All student groups processed their image files by direct and indirect georeferencing (where possible) using Pix4D software. Image processing prompted some interesting questions. The Pix4D software used the GDA94 datum, yet GCPs were captured in GDA2020 – were they compatible? Furthermore, which geoid model should be used in the software: AUSGeoid09, AUSGeoid2020 or EGM96? These questions provided excellent revision for 3rd year geodesy courses (Roberts, 2020b).

Students performed visual checks on points with levelled heights vs. the equivalent pixel on their DSM model. Using the software Cloud Compare (2021), they compared their direct and indirect generated DSM models for compatibility.

6.2 UAV LiDAR

Aerial LiDAR surveys were performed by James Linke at Thirlmere Lakes to produce point clouds of the five lakes. The raw data comprised two main file types:

- .nav describes the flight path taken and includes GPS coordinates as well as data from the Inertial Measurement Unit (IMU) which details the vehicle's attitude (yaw, pitch and roll) at a given time.
- .ldr contains LiDAR information such as the azimuth and zenith angle of the laser and range for each pulse at a given time.

Due to the complicated nature of this procedure and the limited student resources, the processing was allocated to two students and performed under the guidance of Peter Mumford from the UNSW Surveying and Geospatial Engineering group, following his guide on processing the Phoenix LiDAR (Mumford, 2019). Figure 8 describes the overall methodology, which can be separated into two main parts: processing the navigation file to obtain an accurate trajectory and then combining it with the raw LiDAR data to create a point cloud.

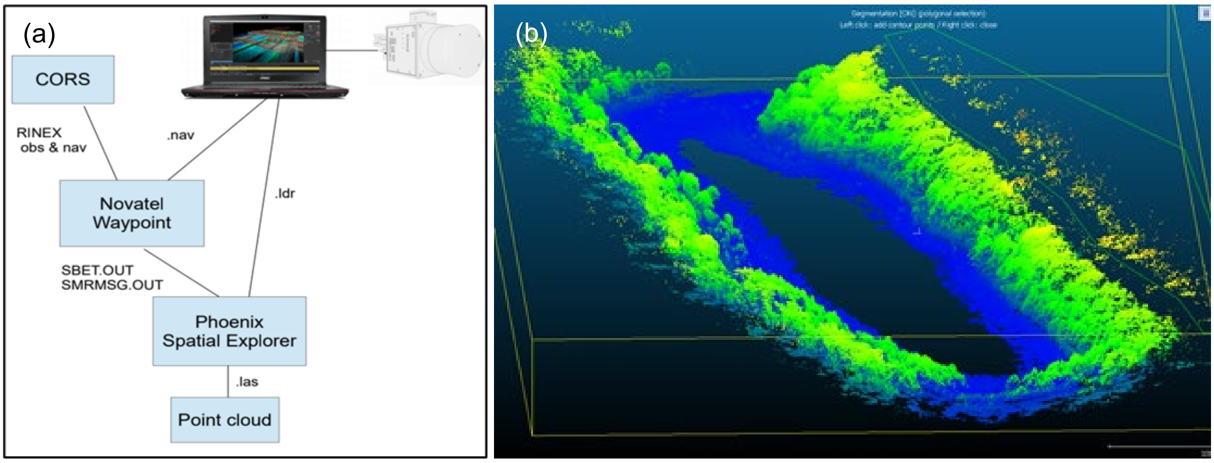

Figure 8: (a) Phoenix LiDAR processing flow chart (Mumford, 2019), and (b) example raw LiDAR file.

The UAV LiDAR device used GNSS RTK with the surrounding CORSnet-NSW control. Again, issues with mobile phone connectivity proved challenging but more robust when airborne. Post-processing ensured the quality of the GPS coordinates in the .nav file. Next, the improved GPS points were combined with the IMU data. The reason for this is because GPS coordinates are taken at slower, set intervals leading to gaps between each point. Higher-frequency data from the IMU can interpolate the path within these gaps to create an overall flight trajectory. The software can perform forward and backward trajectory processing, which is combined into a smooth best estimate trajectory file (.sbet).

Each group then used the Phoenix Spatial Explorer software to combine their .sbet file with their corresponding raw LiDAR file joined by common timestamps, and the results produced a point cloud file (.las). This gave all students the experience of dealing with UAV LiDAR data without having to undergo the more complicated navigation file processing. The expected accuracy can reach 10-20 cm, but this is dependent on many factors.

6.3 Aircraft LiDAR

Peter Mumford works with the UNSW School of Aviation and has access to an aircraft-mounted LiDAR device. Serendipitously, colleagues from the School of Aviation flew the Thirlmere

Lakes site three weeks after the UAV LiDAR capture. Students were therefore able to compare three different sources of point cloud data.

6.4 Cloud Compare

Cloud Compare (2021) is an open source 3D point cloud and mesh processing software. Data from different point clouds (i.e. UAV LiDAR and aircraft LiDAR) can be compared for differences. This can be useful to determine the quality of datasets and for checking height datum parameters, however there are some additional considerations. Aircraft LiDAR is known to have an approximate density of 10 points per square metre as opposed to UAV LiDAR and UAV photogrammetry with significantly higher point density. These differences are largely attributed to the variations in flying height where the former was performed at an altitude of 300 m and the latter at 50 m and 80 m respectively. Techniques such as nearest neighbour vs. 2D triangulation were investigated by all student groups who provided comparisons between the various datasets measured, processed and georeferenced at all five lakes. The interpretation of these datasets was challenging. Successful groups achieved comparisons between the various point clouds of around 0.2 m.

7 CONCLUDING REMARKS

The Thirlmere Lakes vertical control network project provided a diverse and engaging educational exercise for final year students. Students were exposed to a vast array of techniques and concepts including leap-frog EDM height traversing, digital levelling, GNSS static/rapid static/NRTK/PPK, trigonometric heighting, simultaneous reciprocal trigonometric levelling, AHD and geoid heights, modernised datums, UAV photogrammetry, UAV-based LiDAR, AUSPOS and PPP.

Students used a range of software including MS Excel, Leica Infinity, FIXIT4, Magnet Office, Pix4D, Phoenix Spatial Explorer, Cloud Compare and coordinated communications between the groups using Google docs and Facebook messenger groups. They also adhered to a range of documentation such as the GDA2020 Technical Manual, ICSM Guideline for Control Surveys by Differential Levelling, and NSW Surveyor-General's Direction No. 12 (Control Surveys and SCIMS).

The main goal was to establish a densified vertical control network in AHD on stable ground to 10 mm accuracy to support groundwater research studies at Thirlmere Lakes. This goal was achieved. However, perhaps the most valuable part of the project was the teamwork required to overcome tight time constraints, manage considerable logistics (transport, field work, Work Health and Safety, data collection) as well as coordinating and communicating all tasks amongst the groups, ensuring the work was distributed evenly amongst the team and no one was overburdened.

Assessment for the course comprised:

- Individual contributions to the project planning report (30%).
- Individual contributions to the final report (50%).
- Presentation of one aspect of the project (10%).
- Self-assessment (10%).

In week 10, all students from the group were asked to prepare a 3-5-minute presentation. The lecturer provided the topics and allocated students accordingly. The presentations were an opportunity for the whole group to reflect on what they had achieved and critically examine areas for improvement. The topics ranged from an overview of the project, design, details of techniques utilised, results of field work from each lake, network adjustment, point cloud comparisons, height comparisons and some conclusions. Researchers, other students and academics attended the presentations.

As part of the project, students were asked to 'cost' the job by keeping track of their hours worked. This was intended to better prepare students for work as future graduate surveyors. They were also asked to assess themselves and their performance during the project and give themselves a mark out of 100. This task is designed to force students to reflect on their own performance and rate themselves according to any criteria they choose. For students, it is an unusual task, however after completing such capstone courses, students are mature enough to provide useful insights and usually award themselves a mark very close to that of the lecturer. As future professional surveyors, this task can be sobering but this reflection offers deep learning and important skills for a future professional career.

In summary, the Thirlmere Lakes vertical control project provided a very rich education. It was intense, rewarding and thoroughly enjoyable.

ACKNOWLEDGEMENTS

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