Back to the Future: Revisiting Barometric Levelling

Gabriel Scarmana[1]

[1] School of Surveying and Built Environment, University of Southern Queensland, Australia - gabriel.scarmana@usq.edu.au

Keywords: Barometric Levelling, Altimetry, Levelling Techniques

Abstract

Barometric levelling, traditionally employed in aviation, parachute jumping, and mountain climbing, has undergone a transformative shift with the technological advancement of state-of-the-art atmospheric pressure sensors. This evolution has rendered these sensors more accurate and affordable, broadening their applications within the realm of Intelligent Systems. The integration of barometric altimeter modules into electronic devices, coupled with GNSS and mapping systems, has significantly enhanced their versatility, making them complementary components in various consumer electronics like smartphones, watches, sports bands, bicycle computers, and motor vehicle tracking devices. Moreover, they play a pivotal role in emerging technologies such as drone mapping projects and modelling. This because of their capabilities of measuring elevations in GNSS denied areas such as caves, canyons, and tunnels. The significance of barometric levelling lies in its capacity to determine relative elevation between two points through the measurement of atmospheric pressure. This technique leverages the fact that atmospheric pressure decreases with increasing altitude, enabling the calculation of elevation differences by comparing pressure readings at different locations.

In this study, 25 elevations within a 3 km radius were independently measured using barometric levelling, highlighting its practical usage. These elevations ranged from 2 m to 140 m. Readings of time of measurements, temperature, air pressure, and humidity were taken at each of these stations and were synchronized with the readings obtained from a fixed reference station of known elevation. The measurements at this reference station were carried out with an instrument with data logging capabilities, able to record relevant weather data at pre-established intervals of time without human intervention. The results of these measurements were compared to fixed reference stations of known elevation, and the subsequent differences were analysed. The study employed a portable weather monitoring instrumentation with data logging capabilities, emphasizing the importance of automated data collection practices. The comparison of the 25 elevation readings with true elevations, determined by conventional surveying methods, revealed an RMSE of +/- 0.49 meters, affirming the accuracy of barometric levelling.

Additionally, a distance-dependent test demonstrated a predictable decrease in positional accuracy as the distance from a reference base station increased, providing valuable insights into the system's limitations. The barometric levelling tests presented here offer results that can inform future applications. The conclusions and recommendations derived from this study provide guidance for optimizing the use of barometric levelling within the broader landscape of Intelligent Systems.

1. Introduction

Technological innovations in sensor technology, connectivity, miniaturization, data processing, and durability have collectively contributed to the significant improvement of portable weather stations. These enhancements have made them more accurate, versatile, user-friendly, and reliable tools for measuring environmental parameters, including altimetry, in a wide range of applications. Modern portable weather stations leverage advancements in these areas to provide precise and real-time data, making them necessary in both professional and amateur meteorological, geological, and environmental research.

In this context, barometric levelling, also known as barometric altimetry, relies on measuring atmospheric pressure to determine elevation differences between two or more points of interest. This method can be particularly useful in environments like tunnels, caves, or canyons where GPS/GNSS signals may be obstructed or unreliable due to the lack of direct line-of-sight to satellites (Ann et al., 2019). Barometric levelling offers a practical solution in these challenging environments by using atmospheric pressure changes to calculate elevation differences accurately.

Barometric levelling using portable weather stations involves the measurement of the weight of air converted into metres of altitude based on the instrument's graduations. This is possible because the weight of air above a point is inversely related to the point's elevation. As elevation rises, the amount and weight of air above that point decrease (Pırtı et al., 2019). However, several factors must be considered when applying this principle, particularly when observing changes in air pressure. These factors include temperature variations, humidity, and local weather conditions, which can all affect atmospheric pressure readings and, consequently, altitude calculations.

This levelling technique is generally employed in reconnaissance or exploratory surveys but can also serve in various surveying and mapping scenarios depending on accuracy requirements. For example, in a specific study, an overall and consistent elevation positional accuracy of +/- 0.49 meters was achieved within an area of approximately 10 km². This level of precision demonstrates the capability of barometric levelling to provide reliable elevation data in diverse applications, ranging from geological surveys to environmental monitoring.

There are three evident advantages of barometric levelling. First, it allows for determining elevations in GNSS-denied places, making it invaluable in locations where satellite signals are obstructed. Second, the computations can be performed using conventional office software like Microsoft Excel©, which simplifies data processing and analysis. Third, terrain is not a major obstacle, enabling surveys in rugged or inaccessible areas without the need for extensive physical infrastructure.

Lastly, current state-of-the-art instrumentation is portable, cost-effective, and user-friendly, further enhancing the practicality of barometric levelling in field operations. Indeed, modern

This contribution has been peer-reviewed.
https://doi.org/10.5194/isprs-archives-XLVIII-4-2024-403-2024

barometric altimeters and weather data loggers are lightweight, compact, and easily transportable by field personnel or can be integrated or embedded into other measuring platforms such as GPS-enabled devices (Hajiyev et al., 2020). For instance, a drone equipped with a barometric altimeter can accurately measure altitude up to its maximum limits and beyond. It can also record both relative and absolute altitude, providing readings in Mean Sea Level (MSL) and Above Ground Level (AGL) units simultaneously as needed. This versatility allows for comprehensive altitude data collection in various operational contexts.

In stable weather conditions, barometric levelling can be more reliable and accurate than a navigational GPS receiver for measuring relative elevations between multiple points. Some handheld GPS receivers include built-in barometric altimeters and algorithms to fuse GPS and atmospheric pressure data, enhancing accuracy and reliability (Bi et al., 2013). This integration of technologies ensures that users can obtain precise elevation data even in the absence of optimal satellite signals.

It may be argued that global digital elevation data, like those generated using radar interferometry (e.g., SRTM), are free to use and globally available to the public. However, such data have limitations, primarily being outdated. Most accurate national DEM programs utilizing photogrammetry or LiDAR DEMs repeat their acquisition at regular intervals with associated costs and, in many instances, usage restrictions and limited coverage.

Global DEMs provide indicative elevations with vertical accuracy of around ±5 meters in flat or gentle terrains but may be less precise, approximately ±30 meters, in rugged or relief-rich areas (Schumann et al., 2018). Therefore, while global DEMs are useful for general purposes, barometric levelling offers a more precise and practical solution for specific, localized surveying needs, especially in environments where traditional methods face limitations.

2. Barometric levelling and sources of errors

As stated, barometric levelling operates based on the principle that air pressure changes in a predictable manner with elevation within a column of air. In terms of differences of elevations this relationship can be described mathematically as follows:

$$z = \left(\frac{R*T}{g*M}\right) * log_e * \left(\frac{Po}{P}\right) \quad (1)$$

The elevation difference (z) between two points is calculated using Equation 1, considering the following parameters: gas constant R (287 J/kg*k), average air temperature T (in Kelvin), acceleration due to gravity g (9.8 m/sec^2), molar mass of air M (28.965 g/mol), starting atmospheric pressure Po (mb), and measurement atmospheric pressure P (mb). This equation is implemented in electronic barometric altimeters, aiding elevation calculation based on pressure drifts (Lente and Osz, 2020; Jackson and Crocker, 1999, Bolanakis et al., 2015).

Equation 1 operates under the assumption that the barometric pressure sensor primarily reacts to pressure drifts, treating the other variables as constants. However, these variables are not truly constant, introducing elevation measurement errors due to their unpredictability. It's crucial to recognise that this work does not address construction-related errors specific to individual instruments. Instead, the focus is on recognizing the general principles used in the equation, rendering these errors significant and applicable across instruments in general.
Initially, it's assumed that gravitational acceleration (g) remains constant with both latitude and elevation, though in reality, it changes slightly. Between the Earth's equator and poles, g only varies by 1% (Deng et al., 2008). If manufacturers assumed a latitude of 45 degrees, using this value at a latitude of 52 degrees would introduce a mere 0.1% error. The correction for elevation is even smaller, at 0.03%. Thus, for most applications, errors stemming from g fluctuations may be ignored.

Secondly, the assumption holds that air composition remains steady, implying an unchanging apparent molecular weight. However, air composition does vary, primarily due to water vapour. Assuming the barometric altimeter calibrates for 50% relative humidity in the air, the correction for compositional alterations remains under 0.3% if the average air temperature doesn't exceed 13°C change between start and measure points. Beyond 13°C, the air's capacity to absorb water vapour significantly affects this correction (Halit, 2005).

A third potential error source in barometric levelling pertains to temperature. Temperature and atmospheric pressure share a close link. Rising temperature energizes air molecules, causing increased pressure. Conversely, lower temperature results in pressure reduction. The interchange between temperature and atmospheric pressure stands as a fundamental principle in meteorology, thus crucial in barometric levelling (WMO, 2021).

Employing suitable correction techniques, like temperature sensors, gradient analysis, and time synchronization, becomes vital to mitigate temperature effects, thus enabling more precise and reliable barometric levelling outcomes (Kellie et al., 1986). Additionally, it's crucial to acknowledge the constraints imposed by swift temperature changes and localized weather conditions to preserve the integrity of the levelling process.

A fourth source of error relates to instrumental drift. The net effect of this error can be illustrated by the fact that two instruments having equal readings simultaneously occupying the same station, might read differently if both were simultaneously moved to a second station. The result is that in moving from one station to another, the two instruments have drifted apart.

This drift can be evaluated by periodically reading the instruments simultaneously at the same station. The drifts, for times other than those at which the instruments are read together, are determined by interpolating with respect to time. However, it is worth noting that progresses in digital barometric instrument technology have led to improved accuracy and reduced drift compared to previous altimeter models (Matyja et al., 2022), even though regular calibration and maintenance are still relevant to ensure the reliability of the measurements.

Table 1 shows values of the resulting elevation drift, which is typical for many winters sunny days during the year on the Gold Coast (Queensland, Australia). As the altimeter is at a fixed location, the elevation or elevation changes represent pressure changes that have occurred in that location. Of course, this drift cannot be continuously monitored during a field survey; the best an observer or a surveyor can achieve is to rely of several points at convenient places where a feature or permanent survey mark can be accurately associated with an elevation.

Alternatively, a reference station (RS) can be considered where pressure measurements can be logged at specified time intervals so that pressure data can be properly synchronised with that obtained at a given measuring station (MS). In the example of Table 1, the elevations were calculated using equation 1 and they relate to readings of air pressures (converted to elevations) and temperatures taken between 6:00 a.m. and 6 p.m. (at 2 hours intervals) on 21/06/2023 at a fixed location of elevation 46.96 m (S -27.932915 and E 153.324371).

6 am	8 am	10 am	12 pm	2 pm	4 pm	6 pm
47.3 m	64.2 m	69.9 m	51.1 m	26.6 m	29.9	38.6

Table 1. Difference of elevations recorded at a fixed location every two hours during a 12-hour period. The large changes in elevation reflect on the difference of barometric pressures that occurred during that period.

Equation 1 was used for all calculations of *z* in the ensuing sections. In addition, this experiment (including those presented in the subsequent sections) the Kestrel DROP D3 data logger was used. This instrument is a compact environmental monitoring device that tracks temperature, humidity, heat index, dew point, barometric pressure, air density, altitude, and pressure trends. It is designed to be small, accurate, rugged, and waterproof and it meets military and international standards for durability (IP-67 and MIL-STD-810G). See kestrelmeters.com for specific product information.

A fifth source of error can be associated to map errors whereby the elevation for the start of a survey will usually be obtained from a surveying benchmark or an elevation contour on a map. Using reliable elevation sources will obviously have positive effect on the overall surveying measurements, thus avoiding error propagation effects (Nathanson et al., 2017).

With reference to Table 1, it can be inferred that the use of one barometric instrument is not recommended for any type of barometric levelling survey. As shown, the use of one instrument only can accumulate errors of several tens of metres or even more. Hence, at least two instruments (ideally of the same model) should be used concurrently (i.e., one at the RS and one at the MS) if an acceptable result is to be expected (Gruendler et al. 1972).

3. Techniques

By applying suitable measuring techniques, barometric levelling can produce reliable differences in elevation between points (or relative to a single point) within an area where weather conditions may be similar (Hu et al., 2013). This work adopted a technique referred to in the literature as the single base method (Kahmen et al, 1988). In this method, a weather data logger is stationed at a selected RS, which is a station of known elevation (i.e., a permanent survey mark).

A second portable barometric instrument, known as the rover, begins by reading alongside the RS barometer and then proceeds to the stations where elevations are wanted. The last reading made by the rover should in principle once again made alongside the RS.

Simultaneous measurements occur at both the MS (using a Kestrel 2500 portable weather station) and RS. This can be achieved through different methods. For instance, all readings (pressure, temperature, and humidity) can be pre-scheduled, or RS readings can be logged at predetermined intervals and then interpolated based on observation times (Gruendler et al., 1970). In this study, the RS instrument, a data logger (kestrel DROP D3), was programmed to record weather data every 5 minutes.

This single base approach assumes pressure changes at the RS mirror those at the MS. To maintain this assumption, elevations from any RS should ideally be determined within a radius of a few kilometres. It also assumes linear drift between the RS and the MS instruments from the survey's start to end.

The MS-RS separation varies based on factors like barometric instrument accuracy, local weather, and desired precision. Generally, a closer MS-RS proximity yields a more accurate elevation difference estimate (Zhengqun et al., 2020). If the distance is substantial, atmospheric pressure unpredictability due to weather conditions introduce errors in elevation estimation.

Preferably, barometric levelling surveys should be made on days when there is not much variation in barometric pressure. For instance, windy days when detached clouds are traveling rapidly should be avoided because alternating sunlight and shade over the survey area can cause instrument readings variations. Steady barometric pressures generally occur on days with gentle winds and an overcast or clear sky.

The recommended time for observations is 2 to 4 hours after sunrise and 2 to 4 hours before sunset. Midday observation should be prevented if feasible. The recording instrument should be in the shade, and abrupt vibrations of the instrument during its transfer from one station to another should be avoided.

A variation of the single base method is referred to as the leapfrog technique. In this instance, the two instruments are initially read together at the RS. The rover then moves to the first MS and synchronised readings are taken with the RS. The rover moves to the MS and the RS instrument moves to the MS the rover just left. This procedure is continued which keeps the barometric instruments close together.

This helps the assumption of equal air pressure variations a much better one (Kahmen et al., 1988). It is from this movement that the term leapfrog is taken. By bringing the two instruments together more often in this manner, the drift is better controlled (Minchin, 2016). Clearly, this requires at least two operators to work together for this method to take effect. Further methods intrinsically involve the use of more control RSs in the measuring network system.

4. Materials and methods

A first barometric levelling survey was carried out within a suburb of the Gold Coast (Queensland, Australia) referred to as Pacific Pines (central coordinates E 153.326238 and S -27.936753) during a sunny morning (06/07/2023) characterised by a mild wind (i.e., between 2 and 4 km/h) with temperatures ranging between 17^0C and 20^0C. The 25 stations at which barometric observations were taken were arbitrarily selected points spaced at an average distance of 0.6 km from each other and distributed in a random manner as illustrated in Figure 1.

The RS in the configuration was located at shown in Figure 1 (true elevation 46.967 m). All other MSs were referred to by numbers. The elevations of all 25 MSs, which ranged from approximately 2 m at MS-1 to 140 m at MS-25, were permanent survey marks (PSM) estimated by differential levelling to an estimated accuracy +/- 0.02 metres.

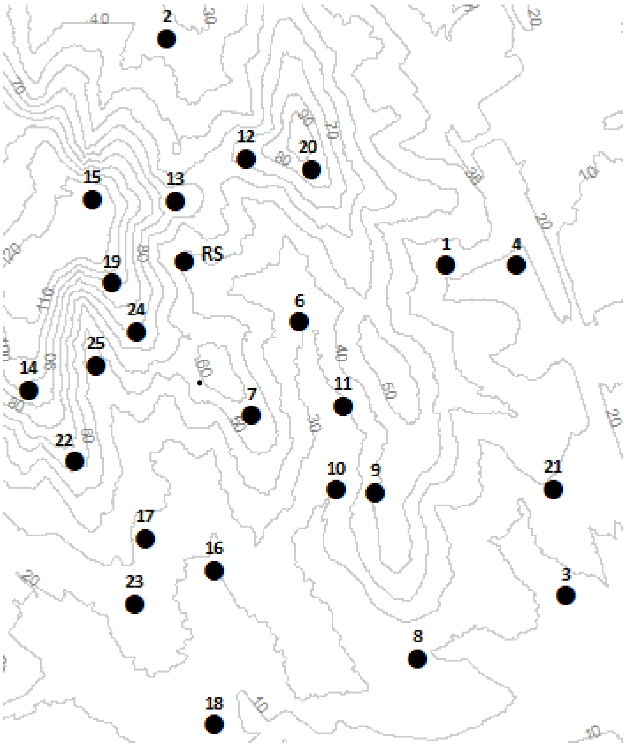

Figure 1. Map showing the 25 MSs (circles) where barometric observations were taken in succession. The location of the RS is also shown (elevation 46.97 m). For scale purposes the distance between station 18 and station 8 is 1 km.

These relatively precise elevations were considered as nominal or true reference values thus allowing the determination of the true error of each MS. All measurements were carried out by one observer using the Kestrel 2500 hand-held weather station as the rover and a Kestrel DROP D3 data logger that could be customized to capture data at any logging rate.

Apart from many other functionalities, the Kestrel 2500 can store barometric pressure readings to the second decimal place and can record time, air pressure, temperature, wind speed and humidity of a given location. A Bluetooth connectivity is also available for easy data transfer to mobile devices (i.e., mobile phones, tablets) and/or PC as needed for further data processing.

The whole task of surveying the 25 MSs was completed in 2.5 hours approximately. During the time of the survey the data logger instrument was permanently located at the RS (and shaded), and it was set to obtain readings of time, pressure (mb), temperature (Cº) and humidity (%) at 5-min intervals prior to the start of the survey. The Kestrel 2500 was transported by car by one observer and readings were taken in succession at each MS. Before taking any readings one or two minutes were allowed for the instrument to “settle” at each MS.

Note that humidity was recorded during the observations to ensure the integrity of the measurements, but it did not affect the calculation of elevation differences. Recording humidity helped with checking the consistency in weather conditions throughout the data collection process, serving as a reference to confirm stable atmospheric conditions and thereby supporting the reliability of the barometric readings.

Each reading was recorded with the instrument placed over the MS on an elevated (10 cm timber platform). Instrument drift was evaluated by simultaneously comparing the information of the data logger at the RS with each MS readings. Since the readings at the MS needed to be synchronized with the reading at the RS, an interpolation method with respect to time (i.e., 2nd degree polynomial) was used to estimate the correct pressure value to be used in the computations. Note that a difference of 0.1 mb corresponds to a difference of elevation of approximately 0.82 m.

As the elevations of all stations were already known, the absolute error could be calculated for each MS. The RMSE of the differences was +/- 0.49 m. It should be noted that the two instruments employed in this task could estimate the air pressure (i.e., millibars) to two decimal figures, thus estimating an elevation to a relative submeter accuracy was theoretically feasible. This would seem to indicate that perhaps a finer graduation on the handheld instrument might be warranted so to minimise rounding errors. Table 2 is a statistical summary of the differences between the nominal/true elevations and the computed ones via barometric levelling.

Min.	Max.	Mean	Med.	Var.	RMSE
-0.65 m	0.68 m	0.48 m	0.37 m	0.24 m	+/- 0.49 m

Table 2. Statistical summary of the differences between the nominal/true elevations and the computed ones for the processed 25 stations.

On the other hand, Table 3 outlines the irregular distribution of the differences between the true elevations and the measured ones.

MS	True elev.	Bar. Elev.	Diff.	Dist. from True
1	22.265	21.86	0.41	1.73
2	32.951	32.50	0.45	1.61
3	5.726	6.28	-0.55	2.42
4	15.56	15.11	0.45	1.92
RS	46.967	46.95	0.02	0.00
6	31.772	32.34	-0.57	1.36
7	57.537	57.16	0.38	1.46
8	11.472	11.082	0.39	2.27
9	38.959	38.28	0.68	1.83
10	22.473	23.03	-0.56	1.75
11	28.167	28.32	-0.15	1.59
12	71.754	72.17	-0.42	1.33
13	71.787	71.38	0.41	1.17
14	94.288	93.84	0.45	1.56
15	121.549	121.13	0.42	1.3
16	19.603	18.99	0.61	1.85
17	26.478	26.86	-0.38	1.77
18	15.411	16.06	-0.65	2.28
19	100.753	100.38	0.37	1.21
20	90.967	90.42	0.55	1.43
21	16.739	16.31	0.43	2.19
22	62.392	62.95	-0.56	1.63
23	26.76	27.31	-0.55	1.95
25	45.652	46.12	-0.47	1.38

Table 3. Values showing the difference of elevation between the nominal or true elevations and those computed via barometric levelling.

https://doi.org/10.5194/isprs-archives-XLVIII-4-2024-403-2024

By way of example, the difference of elevation for MS No. 15 from the RS was determined using equation 1 with the following data:

Time of synchronised measurements: 9:32 am.
Barometric pressure measured at RS: 1017.61 mb.
True elevation of MS No. 15: 121.549 m.
Barometric pressure at MS No. 15: 1.003.19 mb.
Calculated elevation at MS No. 15: 121.13 m.
Difference from nominal elevation: 0.42 m.
Average temperature: 17.2 C^0.

A t-test using a one-tailed hypothesis at the significance level of 0.05 was conducted so to compare the nominal elevation values with those computed via barometric levelling. The results determined a t-value 0.009 for a p-value of 0.496. Hence, the outcome was not significant at $p < 0.05$.

5. The effect of distance from the base station

A second test was carried out to consider the influence that distances from a given RS may have on the accuracy of the elevation of an MS. For this purpose, this exercise used as the RS an established permanent survey mark (elevation = 4 m). Distances of the MSs to the RS ranged between about 2 km and 14 km whereas the elevations ranged between approximately 2 m and 140 m. A statistical summary of the differences between the nominal/true elevations and the computed ones is shown in Table 4.

Min.	Max.	Sum	Mean	Med.	RMSE
-0.98 m	1.17 m	2.26 m	0.69 m	0.57 m	+/- 0.78 m

Table 4**.** Statistical summary of the differences between the nominal/true elevations and the computed ones. Note how the maximum and minimum values correspond to the last two MSs further away from the RS. The number of stations was 12.

From Table 5 below it may be discerned that the computed elevations are much better at the first few stations, which where nearest the RS, than the elevations determined at the reminder of the route. The errors tend to increase as the rover moved away from the RS until, at station 12, a maximum was reached. Station 12 is the furthest station from the RS.

MS No.	True elev. m	Bar. Elev.	Diff.	Dist. fr. RS
1	2.93	3.36	-0.4	2.12
2	2.16	2.61	-0.45	2.61
3	15.1	14.54	0.56	3.59
4	12.27	12.88	-0.61	4.14
5	5.2	4.62	0.58	5.48
6	7.29	6.59	0.7	7.12
7	19.36	20.04	-0.68	8.18
8	10.36	11.36	-1	9.63
9	47.48	48.65	-0.98	10.67
10	71.7	70.8	0.96	12.22
11	90.45	89.3	1.15	13.26
12	140.8	142	1.17	14.19

Table 5. Distribution of the differences of elevation between the nominal/true elevations (m) and the elevations of the MSs (m) for the same points determined by barometric levelling. Distances (km) from the MSs to the RS are also included.

Readings of the rover instrument (Kestrel 2500) were taken at the RS so to synchronise with the RS reading of the Kestrel D3 prior to the start of the survey. That is, and like in the previous experiment, pressure, altitude, temperature, time and % of humidity readings were synchronised with the RS. Readings at the RS and MSs and subsequent computations follow the same process as per the previous section.

However, in this instance, readings were made forward and back, and the two elevation results for each MS were averaged accordingly. The total time for the survey was in the vicinity of 3 hours (7:25 a.m. to 10:33 a.m., 07/07/2023). For consistency of measurements the task was completed under similar weather conditions as per Section 4. That is, a sunny day with temperature differences ranging to approximately 4 C^o between the start and the end of the survey.

6. Conclusions and discussion

Barometric levelling is a technique used to determine the relative elevation between two points by measuring the atmospheric pressure at each location. It relies on the fact that atmospheric pressure decreases with increasing altitude, so by comparing pressure readings at different points, the elevation difference between them can be calculated. While barometric levelling can be a cost-effective and practical method for obtaining elevation data, it is essential to consider certain factors and sources of errors that can affect its accuracy.

It was found that one of the main challenges with barometric levelling is its sensitivity to changes in atmospheric conditions. Variations in weather patterns and local weather phenomena can introduce errors in the readings, leading to inaccuracies in the elevation measurements. To mitigate these issues, this work used two portable and synchronised barometric instruments.

By employing two instruments simultaneously, any sudden fluctuations in atmospheric pressure were detected, mitigated, and cross-verified, thus improving the reliability of the results obtained. Likewise, the use of two barometric instruments allowed for the elimination of systematic errors that could have affected each individual device differently. By synchronising the readings from both instruments, the impact of instrument-specific biases was reduced, enhancing the overall accuracy of the results.

In addition to using multiple instruments, the integration of barometric data with other measurement techniques can further enhance accuracy. For instance, combining barometric levelling with GNSS data, when available, can provide a more robust elevation profile by cross-referencing data from both sources. This hybrid approach leverages the strengths of each method, compensating for the weaknesses inherent in using a single technique. Furthermore, implementing advanced atmospheric correction models that account for temperature, humidity, and other meteorological variables can significantly reduce errors introduced by environmental changes.

Future research endeavours in barometric levelling should focus on improving atmospheric correction models, developing more accurate and stable barometric instruments, using a denser network of reference stations, exploring data fusion with other elevation measurement techniques, and considering a broader range of environmental factors (i.e., measuring on days of adverse weather conditions). Innovations in sensor technology, such as real-time data logging and remote monitoring capabilities, could also streamline the barometric levelling process, making it more efficient and less susceptible to human error.

In summary, by leveraging barometric levelling in environments where GPS or GNSS signals are not feasible, engineers and surveyors can acquire valuable elevation data essential for various applications. However, achieving accurate results requires an understanding of the method's limitations, rigorous calibration procedures, and diligent application of correction techniques to account for environmental variables. These approaches will collectively contribute to overcoming the limitations of barometric levelling, making it an even more valuable tool for elevation data in various surveying and mapping applications.

By continuously advancing the technology and methodologies used in barometric levelling, its application can be broadened to include more diverse and challenging environments. This will not only enhance the precision of elevation measurements but also expand the usability of barometric techniques in fields such as environmental monitoring, geological surveying, and infrastructure development, ultimately contributing to more accurate and reliable data collection in critical areas.

References

Ann A., Ahmed A., Soh G. S. and Foong S., 2019. Barometer Assisted GPS Denied Trilateration Algorithm for Traversing Vertical Three-Dimensional Spaces, *Proceedings of the ION 2019 Pacific PNT Meeting*, Honolulu, Hawaii, pp. 171-184. https://doi.org/10.33012 /2019.16802.

Bolanakis D. Kotis, K. and Laoupoulos T., 2015. Temperature influence on differential barometric altitude measurements. IEEE *Int. Conf. Intelligent Data Acquisition and Advanced Computing Systems: Technology and Applications, Warsaw, Poland.*

Deng, Y., Ridley, A. J., and Wang, W., 2008. Effect of the altitudinal variation of the gravitational acceleration on the thermosphere. *Simulation, Journal of Geophysics Res., 113, A09302*, Doi: 10.1029/2008JA013081.

Gruendler D., Thomack F., and Clapp J., 1972. Barometric Levelling Analysis. *Journal of the Surveying and Mapping Division.* Proceedings of the American Society of Civil Engineering. Vol. 98. Issue 1. ISSN: 0569-8073.

Gruendler J. Clapp J. and Wolf P., 1970. Evaluation of Barometric Levelling**.** *Journal of the Surveying and Mapping*. Volume 96, Issue 1. https://doi.org/10.1061/JSUEAX. 0000325.

Hajiyev C. Hacizade U. and Demet C. G., 2020. Integration of barometric and GPS altimeters via adaptive data fusion algorithm. *International Journal of Adaptive Control and Signal Processing*. 35. 10.1002/acs.3184.

Hu Z., Zhang L., Shi H., Pei J. and Wang X., 2012. RSSI system based on differential barometric altimetry: Research and analysis, Lecture Notes in Electrical Engineering volume 159, 2012, pp 559-568.

Jackson G and Crocker C., 1999. The use of in height measurement. The data base of the British and Irish Hills. http://www.hills-database.co.uk/art.

Kahmen H., and Faig, W., 1988. Surveying. Berlin, Boston: De Gruyter Publication. Chapter 11. https://doi.org/ 10.1515/ 9783110845716.

Kellie A. Young F., 1986. Accuracies and instrumentation in barometric elevation. Australian Surveyor, 33:3, 245-251. DOI:10.1080/ 00050326. 1986.10438892.

Lente, G. and Osz, K., 2020. Barometric formulas: various derivations and comparisons to environmentally relevant observations. ChemTexts 6, 13 https://doi.org/10.1007/s40828-020-0111-6.

Li B., Harvey B. and Gallagher T., 2013. Using Barometers to Determine the Elevation for Indoor Positioning. *International Conference on Indoor Positioning and Indoor Navigation*. Montbéliard-Belfort, France. Doi: 10.1109/ IPIN.2013.6817923.

Matyja T., Kubik, A., Stanik Z., 2022. The MEMS-based barometric altimeter inaccuracy and drift phenomenon. *Scientific Journal of Silesian University of Technology. Series Transport*. 2022, 116, 141-162. ISSN: 0209-3324. DOI: https://doi.org/10.20858/sjsutst.2022.116.9

Minchin M., 2016. Introduction to Surveying. 2nd Edition. Western Australia Department of Training and Workforce Development 2016. ISBN 0 7307 9218 8.

Nathanson J, Lanzafama M., and Kissam P., 2017. Surveying Fundamentals and Practices. 7th edition. ISBN: 9780134414430. Pearson. 368 pages.

Pırtı, A. and Hoşbaş R., 2019. Evaluation of some levelling techniques in surveying application. *Geodesy and Cartography*; vol. 68; No 2; 361-373. doi.org/10.24425/gac.2019.128463.

Schumann J. and Bates D. 2018. The Need for a High-Accuracy, Open-Access Global DEM. Front. Earth Sci., 04 December 2018. Sec. Hydrosphere Vol. 6 - 2018. doi.org/ 10.3389/feart.2018.00225.

WMO, 2021. World Meteorological Organization, Guide to Instruments and Methods of Observation Volume I, Measurement of Meteorological Variables. ISBN 978-92-63-10008-5.

Zhengqun H., Lirong Z. and Yuanfa J., 2020. Applications of differential barometric altimeter in ground cellular communication positioning network. *IET Science, Measurement & Technology*. ISSN 1751-8822 Doi: 10.1049/ iet-smt.2018.5316.