Comparison of Elevation in a straight line from Leveling with Level and Global Navigation Satellite Systems

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Abstract

Accurate elevation determination is essential in civil engineering for ensuring the structural integrity of constructed facilities. Traditional optical leveling, while highly precise, requires transferring elevation values from existing benchmarks, which can be time-consuming when the benchmarks are located far from the project area. Recent advances in Global Navigation Satellite Systems (GNSS) technology-especially using static surveying techniques with post-processing and geoid correction-have enabled the possibility of determining elevation data more efficiently. This study evaluates the accuracy of GNSS-based elevation measurements compared with conventional third-order leveling methods, focusing on a straight-line transect of 2,201 meters at the Agricultural Technology Research Institute, Rajamangala University of Technology Lanna. The GNSS survey was conducted using the static method, with observed data post-processed and converted from ellipsoidal to orthometric height using the Thailand Geoid Model 2017 (TGM2017). The optical leveling was performed to third-order standards using both aluminum and Invar leveling rods. Results show that the elevation difference obtained from GNSS measurements deviated by only 6 millimeters from the optical leveling result, which falls within the allowable error margin for third-order leveling standards. The findings confirm that GNSS, when used with a validated geoid model, is a viable alternative for elevation determination in engineering applications under the Thai vertical datum, particularly for establishing local control benchmarks with reduced fieldwork time and cost.

Keywords: GNSS, GNSS Leveling, Third-order Leveling, Elevation Survey.

1. Introduction

Leveling is a fundamental technique in civil engineering and surveying that ensures structures are positioned accurately in the vertical dimension. It involves measuring the elevation, or height above a reference surface, at specific points, or determining the elevation difference between two locations [1]. Elevation information is crucial because errors in vertical positioning can lead to serious structural and drainage problems. For example, if a building’s foundation is not properly leveled, it may experience uneven settlement, leading to cracks or even structural failure. In typical engineering projects, leveling is used during the design and construction phases to ensure that roads, bridges, buildings, and pipelines conform precisely to their design specifications. Normally, surveyors reference known elevation points, called benchmarks, to anchor their measurements. Traditional leveling methods often rely on optical instruments, such as automatic levels and leveling rods, which require setting up equipment along a line of sight between points. This method, although highly accurate, can be labor-intensive and time-consuming, especially when benchmarks are located far from the project site, requiring many intermediate measurements.

The Global Navigation Satellite System (GNSS) provides positioning data on the Earth’s surface, enabling the determination of both horizontal and vertical coordinates. Initially, vertical positioning obtained through GNSS exhibited significant errors, making it unsuitable for engineering applications. However, over the past several years, advancements in geoid modeling—especially the development of country-specific geoid models such as Thailand Geoid Model 2017 (TGM2017)-have substantially improved the accuracy of vertical coordinates, allowing for the conversion of ellipsoidal heights into orthometric heights with centimeter-level precision [2].

Consequently, GNSS technology is increasingly employed to obtain both horizontal and vertical positions [3], with vertical accuracies meeting the requirements of third-order leveling standards for engineering works [4]. Recent studies in Thailand have verified the reliability of combining GNSS static surveys with TGM2017 in real-world environments, especially in reducing time, labor, and cost associated with conventional optical leveling [5-6]. Recognizing these technological advancements, the researcher aims to evaluate whether GNSS-based leveling can achieve third-order accuracy suitable for engineering applications. If successful, this method could be used to establish local control benchmarks more efficiently, resulting in significant savings in both time and cost associated with traditional leveling methods.

2. Literature and Methodology

In the context of surveying, precise elevation data is typically obtained through leveling techniques defined by engineering standards [7]. Third-order leveling is widely accepted for engineering applications due to its balance of accuracy and field efficiency. Over the years, GNSS technologies have emerged as viable alternatives to traditional methods, offering potential benefits in reducing manpower, time, and accessibility constraints [8].

GNSS-based height determination relies on satellite observations to calculate ellipsoidal height, which must be converted to orthometric height for engineering applications. This conversion is performed using a geoid model that represents the shape of the Earth's gravity field. The precision of this conversion depends heavily on the accuracy and regional suitability ozf the geoid model in use [9]. Limitations of global geoid models such as EGM96 or EGM2008-particularly their coarse resolution-can introduce discrepancies when applied to local conditions [10]. Therefore, several countries, including Thailand, have developed high-resolution local geoid models.

The Thailand Geoid Model 2017 (TGM2017) was developed using a combination of airborne and terrestrial gravimetric data, GNSS/leveling benchmarks, and advanced interpolation techniques [2], [11]. The model provides centimeter-level accuracy for converting ellipsoidal heights derived from GNSS to orthometric heights under the Thai vertical datum. It has become a standard reference model in Thai geodetic and engineering practice.

Studies in other regions, such as Nigeria, have similarly validated the use of GNSS-derived ellipsoidal heights combined with regional or global geoid models for determining orthometric elevations [12]. These findings reinforce the global applicability of satellite-based leveling methodologies when paired with a suitable geoid framework.

This study compares the elevation difference between two benchmarks measured using two methods: third-order optical leveling and GNSS static survey with post-processing. The study site is located at the Agricultural Technology Research Institute, Rajamangala University of Technology Lanna, Lampang Campus, as shown in Figure 1, which is situated in northern Thailand and serves as an ideal location for field-based geodetic studies due to its open terrain and controlled conditions.

Aerial imagery of the campus, as shown in Figure 2, displays the alignment of the measurement path along agricultural service roads and adjacent flat ground. Two benchmarks, BM4 and BM11, were selected along a straight transect of 2,201 meters, which were placed and referenced by the university’s surveying team (as shown in Figure 3).

The overall research design followed a stepwise protocol consisting of field reconnaissance, benchmark setup, GNSS observation using the static method, optical leveling using aluminum and Invar rods, data processing, and final comparison. A summarized flow of the methodology is illustrated in Figure 4.

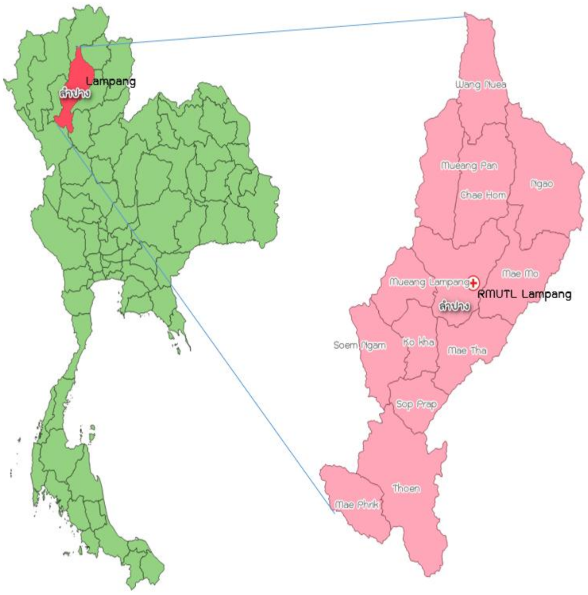

Figure 1 Location of Rajamangala University of Technology Lanna, Lampang Campus, Lampang Province.

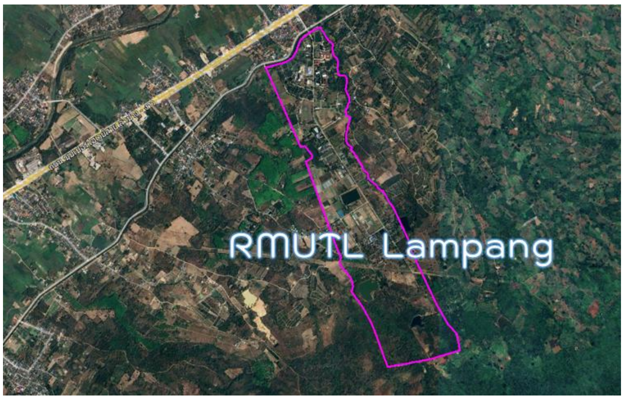

Figure 2 Aerial view of the Agricultural Technology Research Institute, Rajamangala University of Technology Lanna, Lampang Campus.

Figure 3 Locations of the benchmark points used for elevation testing.

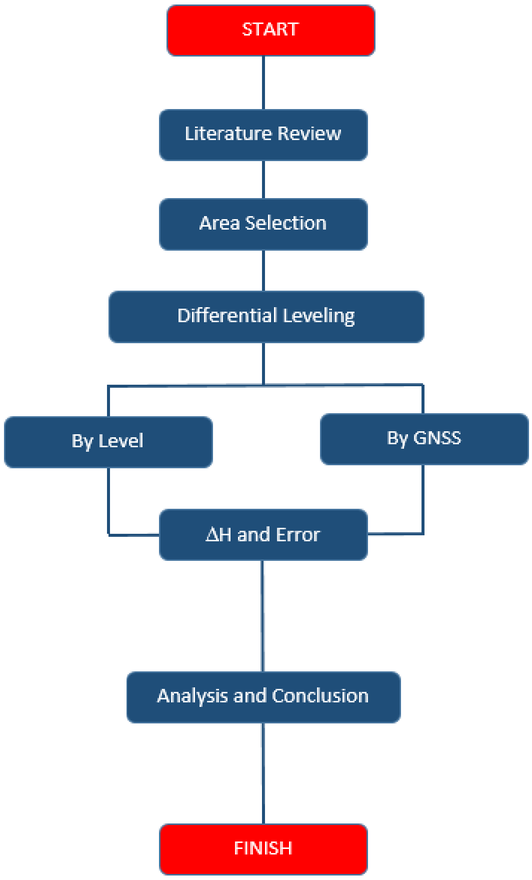

Figure 4 Flowchart of the research methodology.

2.1 Instruments and Equipment

The instruments and equipment used in this research are listed below and illustrated in Figures 5-7.

1) Sokkia C31 automatic level and tripod (Figure 5)
2) Folding aluminum leveling rod (Figure 5)
3) Invar leveling rod (Figure 6)
4) Foot plate (Figure 6)
5) Measuring tape (Figure 6)
6) GNSS Trimble R8s dual-frequency receiver (Figure 7)

Figure 5 Leveling instrument: Sokkia C31 with tripod.

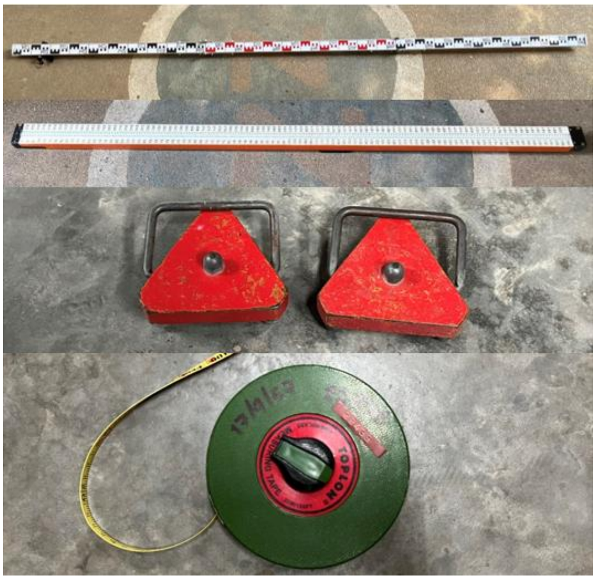

Figure 6 Aluminum folding Staff, Invar Staff, foot plate and measuring tape.

Figure 7 GNSS receiver Trimble R8s and supporting accessories

2.2 Fieldwork Procedures

After selecting the study area, a detailed evaluation of the terrain was conducted to determine the longest possible straight-line segment available within the site. This selection process is crucial because a straight-line layout minimizes errors associated with changes in direction and simplifies the comparison of elevation data collected by different methods. The chosen transect not only needed to maximize distance but also maintain direct line-of-sight and stable ground conditions suitable for accurate surveying. By ensuring the area of interest was as linear and uniform as possible, both GNSS and traditional optical leveling techniques could be applied under controlled and comparable conditions, strengthening the validity of the resulting analysis.

Figure 8 RTSD control point A100358

The GNSS survey was conducted using the static method, which involves placing dual-frequency GNSS receivers at both known and unknown stations. Initially, a receiver was installed and configured at the military geodetic control point A100358 (as shown in Figure 8), and additional GNSS units were deployed at the two benchmark locations, BM4 and BM11. Observations were conducted simultaneously and continuously for 1 hour and 30 minutes at each station. This extended observation duration helped improve positional accuracy by mitigating atmospheric disturbances and satellite geometry fluctuations. The base station was initialized at BM4 using known reference coordinates, while the rover receiver was positioned at BM11. During the observation period, field personnel monitored satellite geometry and signal obstructions to ensure data quality. Upon completion, RINEX data from the receivers were transferred to Trimble Business Center software for post-processing, which provided precise ellipsoidal coordinates. The orthometric heights (elevations above the geoid) were subsequently calculated using the TGM2017 geoid model, allowing an accurate determination of the elevation difference between BM4 and BM11.

The second method involved conducting a traditional elevation survey using a Sokkia C31 automatic level and two types of leveling rods: a 3-meter aluminum rod and a 3-meter Invar rod. The elevation of BM4, obtained from the GNSS survey, was adopted as the starting reference elevation. The leveling operation proceeded along the same straight-line transect, with intermediate checkpoints established every 500 meters to monitor cumulative error. In each segment, the leveling path was divided into distances not exceeding 40 meters and measured in alternating forward and backward directions using a leapfrog pattern. This approach allowed for systematic error detection and comparison between rod materials, including evaluating the influence of thermal expansion. Observations were conducted to comply with third-order leveling standards, applying a maximum allowable misclosure of $\pm 12\sqrt{K}$ mm, where K is the total distance in kilometers. All elevation differences were recorded in field notebooks and later compiled into a leveling loop adjustment table to compute the net elevation change between BM4 and BM11. By employing both GNSS-based static surveying and precise third-order optical leveling, this study ensured a robust comparative methodology. The use of intermediate checkpoints and dual rod types added redundancy and enhanced the reliability of the optical leveling results, while the extended GNSS observation time and rigorous data processing minimized positioning error. Together, the two approaches enabled a comprehensive evaluation of whether GNSS with geoid correction could reliably substitute traditional leveling techniques for engineering applications, especially in establishing third-order leveling benchmarks

3. Results and Discussion

3.1 GNSS Elevation Results

GNSS observations at BM4 and BM11 were post-processed using Trimble Business Center software. The data from the static survey was converted from ellipsoidal height to orthometric height using the TGM2017 geoid model. The orthometric height values are shown in Table 1.

Table 1 Orthometric heights from GNSS measurements using TGM2017

Benchmark	Ellipsoidal Height (m)	Geoid Undulation (m)	Orthometric Height (m)
BM4	222.562	-37.269	**259.831**
BM11	256.356	-37.228	**293.593**

The elevation difference between BM4 and BM11, as obtained from the GNSS survey, was calculated to be 33.762 meters. The location of the GNSS setup at points BM4 and BM11, as shown in Figure 9 and Figure 10.

Figure 9 GNSS receiver setup at point BM4

Figure 10 GNSS receiver setup at point BM11

Figure 11 Survey line from point BM4 to point BM11

Figure 12 Leveling procedure using an automatic level

3.2 Optical Leveling Results

The optical leveling survey was conducted along the same transect using a Sokkia C31 automatic level, with aluminum and Invar leveling rods used during the forward and return runs, respectively. Intermediate checkpoints were established every 500 meters, and segment lengths were kept under 40 meters to maintain third-order accuracy. The leveling path is depicted in Figure 11.

Leveling was performed over the entire 2,201-meter transect to determine the elevation difference, as shown in Figure 12.

A sample of leveling survey data is shown in Table 2, illustrating the detailed field observations recorded during the optical leveling process. This includes back sight (BS), fore sight (FS), intermediate readings, distances, and computed elevations at each checkpoint, which were used to verify measurement consistency and ensure compliance with third-order leveling standards.

Table 2 Example of leveling data collected during the survey

Target	BS	INT	Dist	FS	INT	Dist	HI	Elve
BM4	1.566						261.273	259.831
	1.442	0.124						
	1.318	0.124						
		24.8	24.8					
TP1	1.385			1.599			261.059	259.799
	1.2605	0.1245		1.4745	0.1245			
	1.136	0.1245		1.35	0.1245			
		24.9	49.7		24.9	24.9		
TP2	1.46			1.402			261.116	259.782
	1.334	0.126		1.277	0.125			
	1.208	0.126		1.152	0.125			
		25.2	74.9		25	49.9		
TP3	1.332			1.39			261.054	259.852
	1.202	0.13		1.2645	0.1255			
	1.072	0.13		1.139	0.1255			
		26	100.9		25.1	75		
TP4	2.125			1.446			261.733	259.733
	2	0.125		1.321	0.125			
	1.875	0.125		1.196	0.125			
		25	125.9		25	100		
TP5	1.411			1.431			261.714	260.379
	1.335	0.076		1.3535	0.0775			
	1.259	0.076		1.276	0.0775			
		15.2			15.5			
TP6	1.385			0.95			262.13	260.87
	1.2605	0.1245		0.8445	0.1055			
	1.136	0.1245		0.739	0.1055			
		24.9			21.1			
TP7	1.47			0.448			263.153	261.808
	1.3455	0.1245		0.3225	0.1255			
	1.221	0.1245		0.197	0.1255			
		24.9	150.8		25.1	125.1		

Table 3 shows the computed elevation values from the leveling data, highlighting the differences observed between aluminum folding and Invar rods. These values support the evaluation of rod performance under third-order leveling standards.

Table 3 Elevation results from third-order optical leveling survey

Staff	BM4 (m)	BM11 (m)	BM4 (m)	Error (m)
Folding	259.831	293.597	259.828	-0.003
Inva	259.831	293.598	259.834	+0.003

The total elevation difference from BM4 to BM11 obtained from optical leveling was 33.766 meters. The misclosure between forward and return runs was within 3 mm, which complies with the allowable error for third-order leveling (±12√K mm, where K = 2.201 km ≈ ±17.7 mm).

3.3 Comparative Analysis

Before conducting the main comparison between GNSS-based elevation measurements and traditional optical leveling, this study initially evaluated the performance of two types of leveling rods: aluminum folding rods and Invar rods. The objective was to determine whether the more portable aluminum rod could satisfy the accuracy requirements of third-order leveling standards. As shown in Table 4, the elevation difference obtained using the aluminum rod was 33.768 meters, while the Invar rod yielded 33.765 meters. The discrepancy between the two was only 1 millimeter, well within the allowable error margin for third-order leveling (±12√K mm). These results confirm that aluminum folding rods, despite being more susceptible to thermal expansion, can be reliably used in third-order leveling applications when proper procedures are followed. This validation supports their practical use in field conditions, offering greater convenience without compromising accuracy. Following this confirmation, the study proceeded to compare GNSS-derived elevations with those obtained from optical leveling.

The difference between the GNSS-derived elevation difference and that from optical leveling was 0.006 meters (6 mm), well within the acceptable range for third-order leveling precision. This indicates that GNSS static surveying when paired with post-processing and geoid correction is capable of producing reliable vertical measurements.

Table 4 compares the elevation differences obtained from each method and also includes measurements using different rod types.

Staff	BM4 (m)	BM11 (m)	BM4 (m)	ΔH (m)
Folding	259.831	293.599	259.831	33.768
Inva	259.831	293.596	259.831	33.765

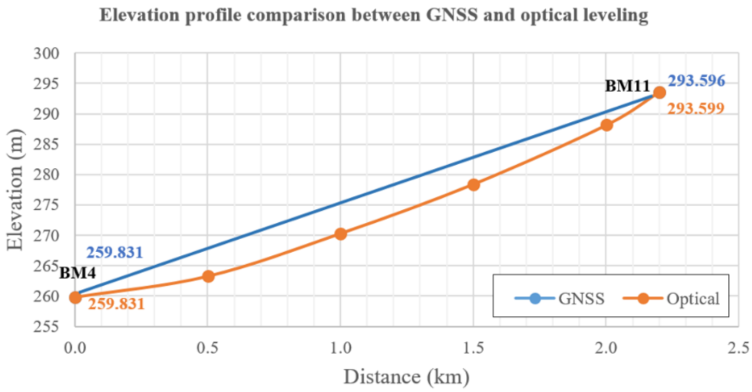

Figure 13 Elevation profile comparison between GNSS and optical leveling

3.4 Elevation Profile and Interpretation

Figure 13 illustrates the elevation profile along the transect, based on both GNSS and leveling observations. The plotted profiles show excellent alignment, with only minor deviations at checkpoint locations. These variations may be attributed to local surface irregularities or minor observational noise, but do not significantly affect the overall accuracy.

These results confirm the practicality of GNSS-based leveling for engineering applications under the Thai vertical datum. With proper observation time, equipment calibration, and reliable geoid models such as TGM2017, GNSS offers a time- and labor-efficient alternative to traditional leveling methods, especially for establishing third-order benchmarks in field environments.

4. Conclusions

This study presented a comparative evaluation of two elevation determination techniques-GNSS static surveying with geoid correction and conventional third-order optical leveling-conducted over a 2.201 km straight-line transect located within a controlled research area. The GNSS method, using post-processed data and the TGM2017 geoid model, produced an elevation difference of 33.762 meters between benchmarks BM4 and BM11. The corresponding elevation difference obtained via optical leveling was 33.762 meters. The observed discrepancy of 6 millimeters between the two methods falls well within the permissible tolerance for third-order leveling ($\pm 12\sqrt{K}$ mm), thereby confirming the reliability and consistency of both approaches.

The results validate that GNSS-based surveying, when combined with an appropriate local geoid model and sufficient observation duration, can serve as an efficient and accurate alternative to optical leveling, particularly for establishing elevation benchmarks under the Thai vertical datum. The advantages in operational time, reduced manpower, and flexibility in field conditions underscore its potential for broader engineering applications.

5. Acknowledgment

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