ASSESSING THE EFFECTIVENESS OF PHONE-BASED GPS FOR CAPTURING HORIZONTAL AND VERTICAL CHARACTERISTICS OF HIKING TRAILS

Doc. dr. Klemen Prah[1], prof. dr. Ashton M. Shortridge[2]
[1]Fakulteta za logistiko, Univerza v Mariboru, Mariborska cesta 7, 3000 Celje, Slovenija
[2] Department of Geography, Environment, and Spatial Sciences, Michigan State University, 673 Auditorium Road, East Lansing, MI 48824, USA
e-mail: e-mail: klemen.prah@um.si, ashton@msu.edu

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Abstract
Smartphone-based Global Positioning System (GPS) applications are widely used to record hiking and recreational activities, yet their effectiveness for capturing fine-scale geometric properties of trails remains uncertain. In particular, while horizontal (planar) positional accuracy of consumer-grade GPS has been extensively studied, vertical accuracy and its consequences for derived metrics such as elevation gain and trail length are less well understood. This study evaluates the horizontal and vertical consistency of six smartphone GPS tracks recorded simultaneously by hikers walking as a group along the same route on Miklavški Hill (Celje, Slovenia), using OpenStreetMap (OSM) trail geometry as a practical reference. Track alignment is assessed using a buffer-based method following Hunter and Goodchild, and point-to-line distances are used to characterize positional uncertainty along the trail. We further examine how these uncertainties propagate into commonly used derived measures, including total trail length, elevation gain, and measures of path complexity. Results indicate that phone-based GPS is sufficiently accurate for comparative and descriptive trail analysis, but not reliable for fine-scale geometric characterization below several meters, particularly in the vertical dimension. These findings highlight important limitations for quantitative analyses of hiking trail geometry based on consumer GPS data.

***Keywords**: Smartphone GPS, positional accuracy, vertical accuracy, hiking trails, error propagation*
JEL classification: O33, C18, R41

INTRODUCTION

Smartphones equipped with Global Navigation Satellite System (GNSS) receivers have become the dominant devices for recording outdoor recreational activities such as hiking, trail running, and cycling. Applications such as Strava enable users to generate detailed geographic tracks that are increasingly reused for scientific, planning, and environmental analyses of recreational activity patterns (Venter et al., 2023; Sun & Mobasheri, 2017). Despite their popularity, the positional accuracy of smartphone-based GPS data—particularly under variable terrain and forest canopy conditions—remains a matter of ongoing concern (Purfürst, 2022; Huang et al., 2022).

Horizontal positional accuracy of consumer-grade GPS is generally reported to be within a few meters under favorable, open-sky conditions (Zandbergen & Barbeau, 2011; *GPS Accuracy | GPS.Gov*, n.d.), while vertical accuracy is often substantially worse due to satellite geometry, atmospheric effects, and receiver limitations (Hofmann-Wellenhof et al., 2007; Purfürst, 2022). For many recreational applications this distinction is of little consequence; however, for quantitative analyses of trail geometry, elevation profiles, and derived metrics such as elevation gain or fractal dimension, the implications of positional uncertainty can be substantial (Goodchild & Hunter, 1997).

This paper addresses the following questions:

- How effective is phone-based GPS at capturing the horizontal geometry of hiking trails?
- How consistent are vertical measurements derived from smartphone GPS along the same trail?
- What is the magnitude and structure of uncertainty in planar and elevation estimates under typical hiking conditions?
- How does this uncertainty affect our ability to compute derived geometric metrics, such as trail length, elevation gain, and measures of path complexity?

To answer these questions, we analyze six smartphone GPS tracks recorded simultaneously by hikers walking as a group along the same route on Miklavški Hill, Slovenia. By comparing these tracks to a reference trail geometry derived from OpenStreetMap, we evaluate positional consistency and assess the consequences of GPS uncertainty for higher-order trail analysis.

1. BACKGROUND AND RELATED WORK

GPS accuracy has been studied extensively since the widespread availability of civilian receivers (Kaplan, 2006). Numerous studies have documented that vertical accuracy is typically between two and three times worse than horizontal accuracy due to satellite constellation geometry and weaker vertical dilution of precision (Hofmann-Wellenhof et al., 2007; Purfürst, 2022). Research has also shown that consumer-grade devices, including smartphones, are more susceptible to signal multipath, obstruction, and algorithmic filtering than survey-grade equipment (Kaplan, 2006).

For linear geographic features such as roads, rivers, or trails, accuracy assessment presents specific challenges. Traditional point-by-point comparison methods require clearly identifiable corresponding points, which are often unavailable for paths recorded independently. To address this issue, Hunter and Goodchild (Goodchild & Hunter, 1997) proposed a buffer-based approach, in which positional agreement is assessed by measuring the proportion of a recorded line that falls within a specified distance of a reference feature. This method has since been widely adopted in GIS accuracy studies (Wing et al., 2005; Haklay, 2010).More recently, attention has turned to the reliability of derived metrics computed from GPS tracks, as small positional errors can propagate non-linearly into estimates of path length, elevation change, and application-specific measures such as energy expenditure (Minetti et al., 2002; Zandbergen & Barbeau, 2011).

Trail length, elevation gain, and slope are especially sensitive to positional noise and sampling resolution. Fractal dimension, frequently used to characterize path complexity and terrain roughness, is particularly sensitive to high-frequency positional variation and measurement noise. As a result, uncertainty in raw GPS measurements can substantially influence interpretations based on fractal analyses.

2. STUDY AREA AND DATA

2.1 STUDY AREA

Miklavški Hill is located near the town of Celje in eastern Slovenia. The hiking route analyzed in this study follows a well-established trail with moderate elevation gain and mixed terrain, including forested sections and open areas. The trail length is approximately 1.4–1.6 km with a net elevation gain of approximately 150 m.

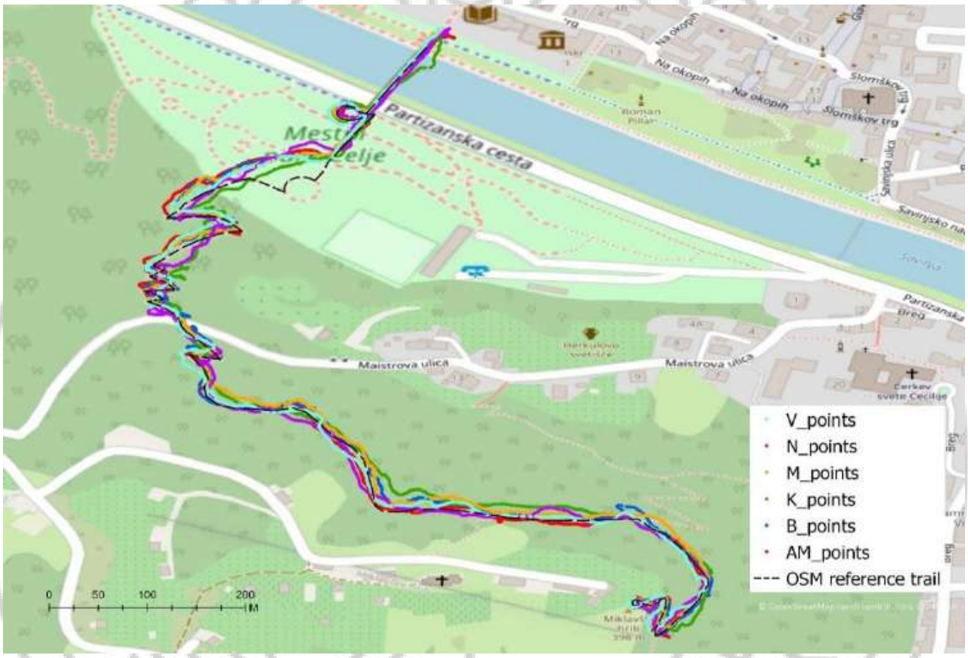

Figure 1. Location of Miklavški Hill (Slovenia) and six smartphone GPS tracks overlaid on the OpenStreetMap reference trail.

2.2 GPS TRACK COLLECTION

In April 2025, six hikers simultaneously ascended Miklavški Hill while walking as a group and recorded their activity using the Strava application on their smartphones. Each hiker used a personal device, reflecting typical consumer use rather than controlled experimental conditions. The resulting GPS tracks were exported as spatial vector data and provided to the author for analysis.

2.3 REFERENCE DATA

The reference trail geometry was obtained from OpenStreetMap (*OSM*, 2025). While OSM data are not surveyed ground truth, they represent a widely used and community-validated spatial representation of hiking trails. In this study, OSM is treated as a practical reference against which relative positional agreement can be assessed.

3. METHODS

3.1 PREPROCESSING AND ALIGNMENT

All GPS tracks were converted to point geometries with associated elevation information. The OSM trail was densified to a spatial resolution of 0.5 m to allow accurate nearest-point matching. For each GPS point, the nearest point on the densified OSM path was identified, and the planar distance between them was calculated.

3.2 HORIZONTAL ACCURACY ASSESSMENT

Horizontal positional accuracy was evaluated using a buffer-based method after Goodchild and Hunter (Goodchild & Hunter, 1997). Buffers of increasing radius (1–24 m) were constructed around the reference OSM trail, and the proportion of GPS track points falling within each buffer was calculated for individual tracks and for all tracks combined.
In addition to buffer analysis, point-to-line distances were used to compute mean and standard deviation of horizontal errors for each track. Along-track error profiles were generated to visualize how positional deviation varied with distance along the trail.

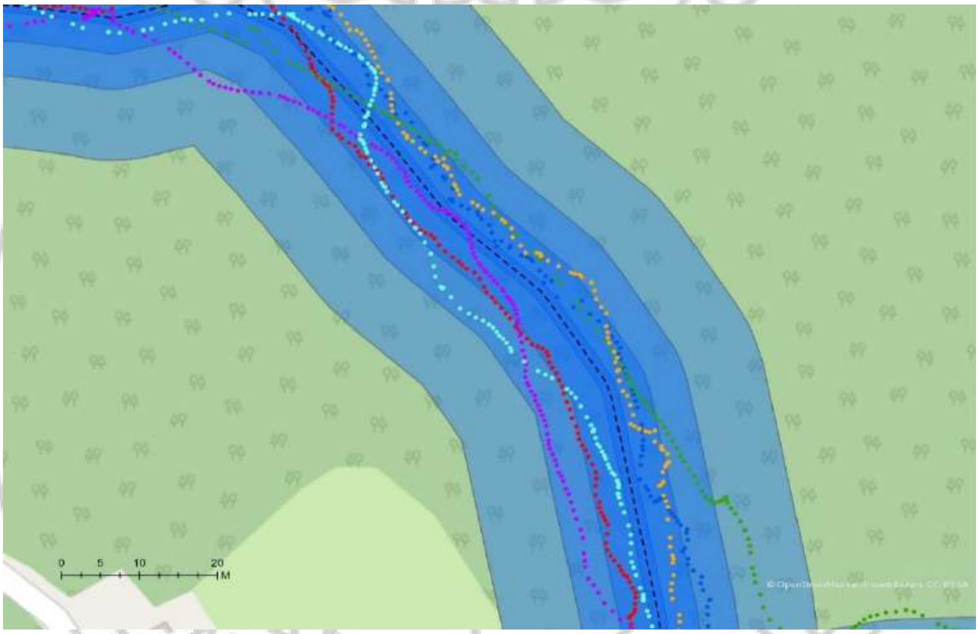

Figure 2. Conceptual illustration of the buffer-based method used for horizontal positional accuracy assessment. A reference trail geometry derived from OpenStreetMap (OSM) is surrounded by concentric buffer zones of increasing width (1 m, 5 m, 10 m and 20 m). GPS track points fall inside or outside each buffer.

3.3 VERTICAL PROFILES AND METRICS

Elevation profiles were extracted from each GPS track and plotted against both cumulative distance and proportional distance along the route. Total elevation gain, loss, and net elevation change were computed. Differences between tracks were used to assess vertical consistency.

3.4 DERIVED METRICS

Trail length was computed in both two-dimensional (planar) and three-dimensional (including elevation) form. The variation among tracks was quantified as a proportion of the mean. While full fractal-dimension estimation is beyond the scope of this paper, we discuss the implications of observed positional noise for higher-order geometric measures of path complexity, including fractal descriptors, drawing on the well-established sensitivity of such measures to spatial resolution and measurement noise.

4. RESULTS

4.1 HORIZONTAL POSITIONAL ACCURACY

Mean horizontal offsets from the reference trail ranged from approximately 3.6 m to 5.6 m across the six GPS tracks, with standard deviations of comparable magnitude. Buffer-based analysis indicated that the majority of recorded points fell within 5–10 m of the reference path, reflecting substantial spatial variability in horizontal error along the trail.

Along-track error profiles revealed segments with systematically larger deviations, which are consistent with localized canopy cover or terrain-related signal obstruction. Despite these localized effects, the overall horizontal alignment of the tracks remained broadly consistent.

While Table 1 summarizes mean horizontal offsets and variability, Figure 3 illustrates how positional agreement evolves across a range of buffer distances, providing a more detailed view of the distribution of horizontal error.

Table 1. Summary statistics describing horizontal positional uncertainty and derived trail length metrics for six smartphone GPS tracks. Reported values include the mean point-to-line distance from the reference trail geometry, the standard deviation of horizontal error, and total trail length computed in both planar (2D) and three-dimensional (3D) form.

trail ID	mean error (m)	SD (m)	2D length (m)	3D length (m)
AM_points	3.65	4.28	1506.60	1530.08
B_points	4.03	4.06	1612.45	1633.69
K_points	5.64	4.53	1369.43	1412.77
M_points	4.30	4.45	1473.93	1497.61
N_points	3.81	4.31	1345.11	1392.86
V_points	3.81	3.46	1410.89	1439.05

Across all tracks, the proportion of points increased gradually with buffer distance, indicating that horizontal accuracy is characterized by substantial spatial variability rather than a fixed lateral displacement.

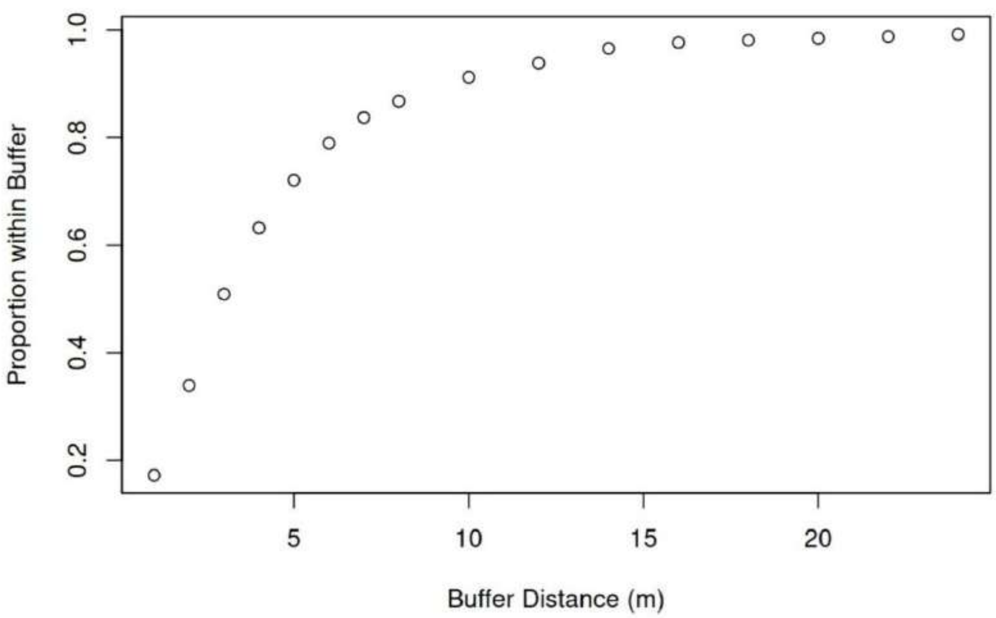

Figure 3. Proportion of GPS points within increasing buffer distances.

4.2 VERTICAL CONSISTENCY

Elevation profiles showed similar overall shapes across tracks but differed in fine-scale variation.

Vertical consistency was examined using elevation profiles plotted against both cumulative and proportional distance (Figures 4 and 5). Profiles referenced to cumulative distance (Figure 4) illustrate the real-world terrain progression, while also revealing varying degrees of local elevation noise among tracks. When normalized by proportional distance (Figure 5), differences in total track length are removed; under this representation, the overall structure remains largely aligned, but small-scale discrepancies become more apparent, highlighting variability in vertical measurements.

Summary statistics of elevation gain, loss, net elevation change, and average slope are reported in Table 2. Cumulative elevation gain varied by less than approximately 5 % across tracks, while net elevation change showed even lower relative variation (≈ 4 %), indicating strong agreement in overall vertical displacement. In contrast, elevation loss exhibited somewhat greater variability, reflecting the sensitivity of downhill segments to short-scale elevation noise and sampling differences. Mean percent grades were broadly consistent across tracks, varying within a narrow range, and reflect similar average slope estimates.

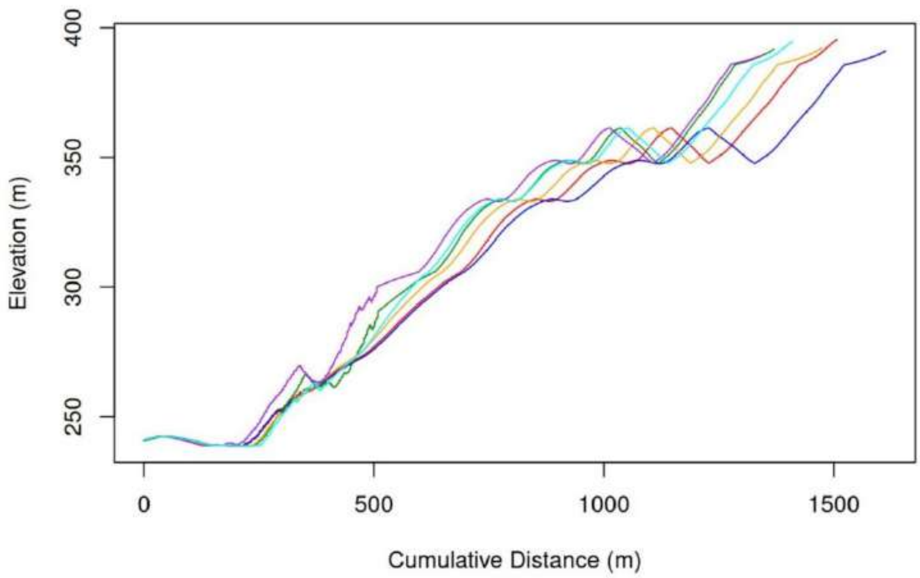

Figure 4. Elevation profiles of six smartphone GPS tracks plotted against cumulative horizontal distance along the hiking route. Profiles reflect the recorded elevation at each point as a function of traveled distance, illustrating both the overall terrain structure and differences in vertical noise among tracks under identical hiking conditions.

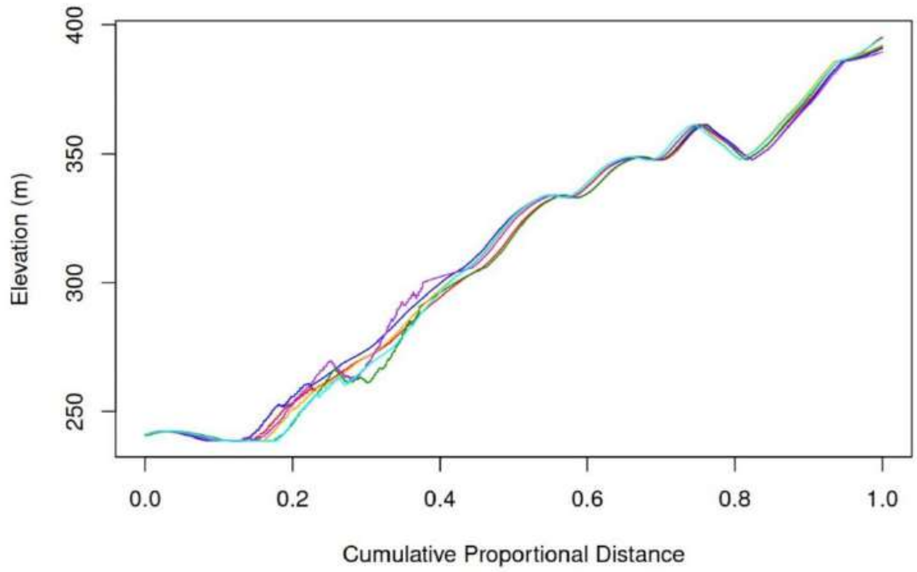

Figure 5. Elevation profiles of the same six GPS tracks plotted against proportional (normalized) distance along the route. Normalization removes differences in total track length, enabling direct comparison of profile shape and highlighting variability in vertical measurements attributable to GPS noise rather than differences in path geometry.

Table 2. Summary of elevation gain, loss, and average slope metrics.

trail ID	gain	loss	net change	percent grade
AM_points	181	26.7	154.3	13.8
B_points	175.1	25.1	150	12.4
K_points	183.4	32.4	151	15.8
M_points	174.6	23.5	151.1	13.4
N_points	183	34.4	148.6	16.2
V_points	179.5	25.7	153.8	14.5

4.3 DERIVED METRICS AND VARIABILITY

Two-dimensional trail length varied by approximately 18 % relative to the mean, reflecting the sensitivity of path length estimation to horizontal positional noise and recording resolution. In contrast, net elevation change exhibited much lower proportional variation, indicating greater robustness of integrated vertical metrics.

These results suggest that while cumulative measures derived from GPS tracks can be relatively stable, fine-scale derived metrics—such as local slope variation or measures of path complexity—may be highly sensitive to positional noise, particularly in the vertical dimension. To examine how horizontal positional error propagates along the trail independent of total track length, along-track offsets were plotted as a function of proportional distance (Figure 6).

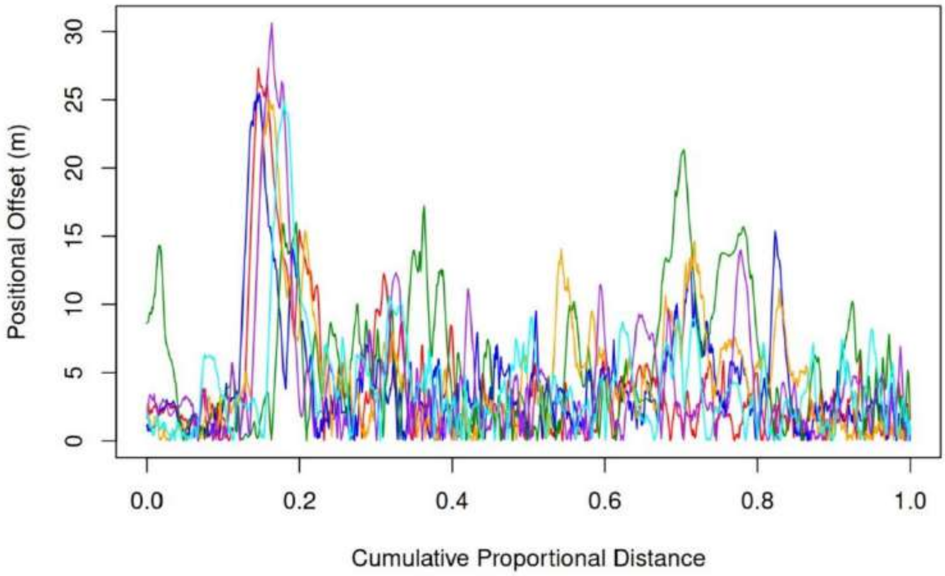

Figure 6. Along-track horizontal positional error plotted against proportional distance along the hiking route. Normalization by proportional distance enables direct comparison of error patterns among tracks of differing lengths and highlights systematic versus localized contributions to horizontal error propagation.

5. DISCUSSION

The results demonstrate that smartphone-based GPS provides sufficient accuracy for comparative trail analysis and general descriptive purposes. Horizontal positional accuracy on the order of a few meters (Table 1), together with the buffer-based agreement patterns shown in Figure 3, indicates that smartphone GPS data allow reliable identification of trail corridors and relative path alignment. Standard deviations of similar magnitude to mean offsets (Table 1) further suggest that horizontal error is characterized by substantial spatial variability rather than a uniform lateral displacement, as also reflected in the along-track error patterns (Figure 6).

Vertical measurements were found to be noisier at fine spatial scales, yet cumulative metrics remained comparatively stable. Elevation profiles plotted against both cumulative and proportional distance (Figures 4 and 5) showed consistent overall terrain structure across tracks, while Table 2 indicates that net elevation change and mean slope varied only modestly among devices. These findings suggest that vertical noise tends to average out in integrated metrics such as net elevation change, even when local elevation fluctuations are pronounced.

However, the results also highlight clear limitations of consumer-grade GPS data. Fine-scale geometric features below several meters cannot be reliably captured, particularly in the vertical dimension (Figures 4–6). This has important implications for analyses aiming to characterize trail roughness, micro-topography, or higher-order measures of path complexity, for which short-wavelength positional variability can strongly influence derived estimates.

Several limitations of the present study should be noted. OpenStreetMap data were treated as a practical reference rather than surveyed ground truth, and the Strava platform applies undocumented processing steps to recorded GPS tracks, particularly for elevation. Consequently, the results reflect realistic consumer usage conditions rather than controlled GNSS accuracy testing. While this constrains strict error attribution, it also strengthens the relevance of the findings for real-world recreational tracking applications.

CONCLUSIONS

This study evaluated the effectiveness of smartphone-based GPS for capturing horizontal and vertical characteristics of a hiking trail using six GPS tracks recorded simultaneously during a group hike on Miklavški Hill. The findings support the following conclusions:

• Smartphone GPS provides sufficient accuracy for comparative analysis of hiking trails and for descriptive metrics such as overall path geometry and integrated elevation measures.

• Horizontal positional uncertainty on the order of several meters results in substantial variability in derived quantities such as estimated trail length.

• Vertical measurements exhibit greater fine-scale noise, limiting their suitability for detailed slope analysis and characterization of local terrain variability.

• Fine-scale geometric descriptors and other higher-order measures of path complexity cannot be reliably derived at spatial scales below several meters from consumer-grade GPS data, particularly in the vertical dimension.

Overall, smartphone GPS data are best suited to relative and comparative analyses of hiking trails rather than precise geometric characterization at fine spatial scales.

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