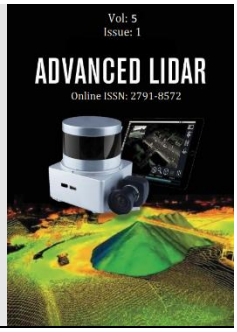
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# Wearable Mobile LiDAR Applications and Measurement Accuracy Assessment in Topographic Surveying

**Atila Karabacak** *
*Department of Architecture and Urban Planning, Mustafa Baysan Vocational School, Mersin University, Mersin, Türkiye,*
*e-mail:* atilakarabacak@mersin.edu.tr
* Correspondence: atilakarabacak@mersin.edu.tr

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## Abstract

Wearable mobile light detection and ranging offers a practical approach to three dimensional surveying where terrain, narrow passages, or complex surfaces restrict conventional access. Its usefulness depends on the accuracy of the final mapping product rather than point density alone. This narrative review examines applications in terrain mapping, slope documentation, excavation surveying, and geometrically complex environments using literature published before 2025. Evidence from wearable systems is distinguished from contextual studies using terrestrial scanners, aerial platforms, and photogrammetry. The synthesis identifies trajectory drift, incomplete surface visibility, ground classification, georeferencing, and surface interpolation as interacting sources of error. A reproducible assessment framework is proposed that separates independent coordinate accuracy, local surface agreement, repeatability, completeness, and uncertainty in derived terrain products. The framework combines distributed checkpoints, repeated survey routes, reference surface comparisons, and sensitivity analysis of filtering and grid resolution. The review supports conditional adoption of wearable systems for topographic surveying when independent validation demonstrates compliance with the intended tolerance. It does not establish a universal accuracy value or report a new field experiment.

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**Contribution to the field statement:**
This review links acquisition conditions to independent validation of terrain, slope, and volume products, while distinguishing wearable evidence from evidence obtained using other mapping platforms.

**Highlights:**
- Independent checkpoints separate georeferencing quality from internal agreement
- Slope and visibility affect the interpretation of residuals
- Product acceptance combines accuracy with completeness and uncertainty

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## 1. Introduction

Topographic surveying supplies the geometric information required for land management, infrastructure design, earthwork planning, and environmental monitoring. The surveyed landscape often contains abrupt slope changes, exposed rock faces, vegetation, retaining structures, and confined passages. Describing these features with a limited number of discrete observations can leave important geometric detail unresolved. Three dimensional point clouds provide a denser representation, but the transition from dense observations to dependable terrain information requires explicit control of measurement and processing errors.

Wearable mobile light detection and ranging (LiDAR) systems allow an operator to collect range observations while walking through a site. Sensors may be mounted on a backpack, a body harness, or another person carried configuration. In this article, wearable mobile LiDAR refers primarily to these pedestrian systems. Handheld and

smartphone scanners are discussed as related platforms with distinct sensor capabilities. Simultaneous localization and mapping (SLAM) estimates sensor motion and environmental geometry together, making data capture possible in settings where continuous Global Navigation Satellite System (GNSS) positioning is unavailable.

The central difficulty is that a visually convincing model can conceal systematic coordinate displacement, accumulated trajectory error, or missing ground observations. A cloud may reproduce a local wall accurately while misplacing the wider site. Conversely, a globally aligned cloud may still smooth a narrow breakline or misclassify low vegetation as terrain. Accuracy must therefore be defined in relation to the target product: a terrain model, a slope cross section, a measured distance, an excavation volume, or a change estimate.

This review examines how wearable mobile LiDAR can support mapping of terrain surfaces, slopes, and complex geometries. It addresses three questions: which survey tasks benefit most from pedestrian acquisition; which acquisition and processing factors control reliability; and how should accuracy be tested independently? The contribution is a structured assessment framework that connects field design, processing choices, validation metrics, and acceptance decisions. The article presents a narrative synthesis and a proposed evaluation protocol rather than a new experimental campaign.

## 2. Method

### 2.1 Review design and evidence boundaries

Direct wearable studies on Cambazlı Church and cadastral mapping provide application context [1, 2]. A contribution specifically addressing incorrect wearable use provides a complementary failure oriented perspective [3]. Indoor mobile mapping research informs the evaluation of pedestrian acquisition, while handheld LiDAR and inertial SLAM research explains trajectory estimation and loop constraints [4, 5]. These categories are related, but their reported performance is not treated as interchangeable.

A wide field of view mobile scanning study provides additional context for person carried acquisition [6]. Aerial LiDAR studies are retained to clarify platform dependent georeferencing and the distinction between absolute accuracy and precision [7, 8]. They do not constitute wearable accuracy benchmarks. Sources were synthesized by methodological relevance; no pooled accuracy estimate was calculated because the measurement targets, reference methods, and operating environments differ.

### 2.2 Mapping products and observation geometry

The survey objective should be stated before acquisition. A digital terrain model (DTM) represents bare earth, whereas a digital surface model includes vegetation and structures. A triangulated irregular network can preserve observed breaklines when the model explicitly incorporates them. A raster provides regular sampling for analysis, but interpolation can obscure abrupt changes. Work on terrain grid resolution motivates a sensitivity assessment of the delivered surface rather than acceptance based solely on the original cloud [9].

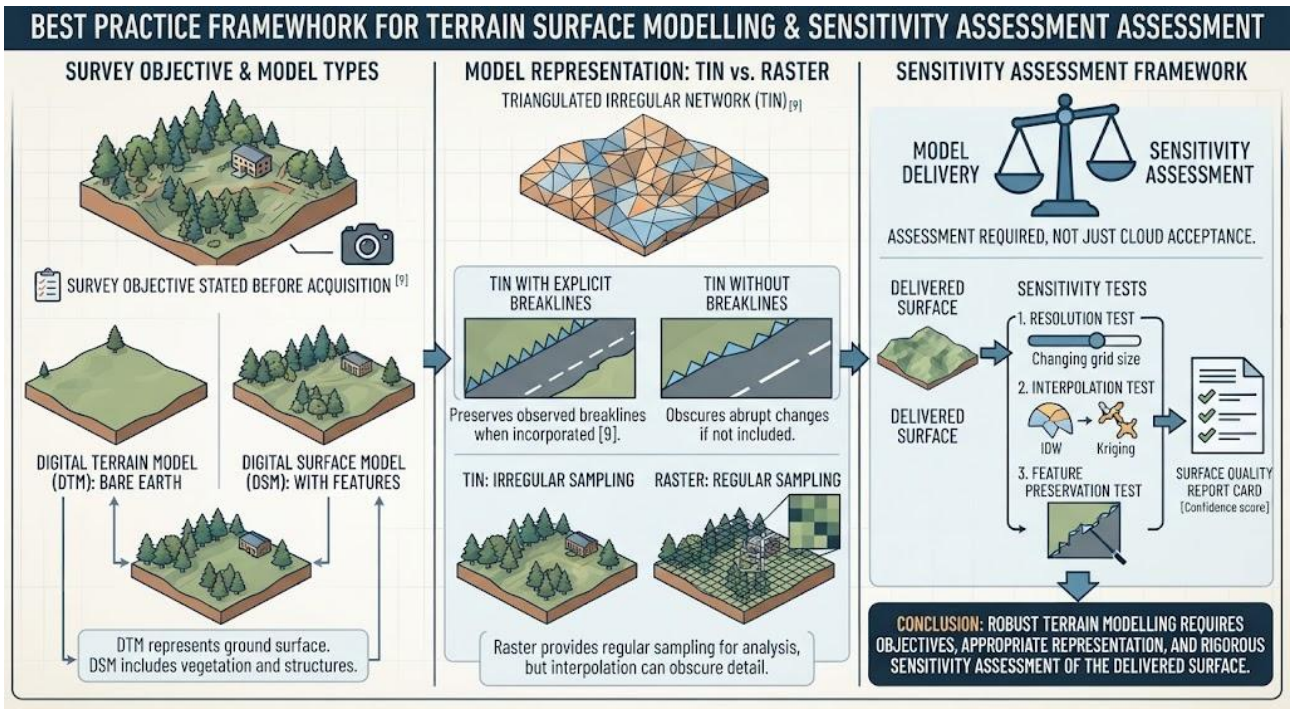



**Figure 1:** Best Practice Framework for Terrain Surface Modelling and Sensitivity Assessment

For a scanner observation q(t) expressed in the sensor frame, the mapped point is represented by Equation (1). The rigid transformation contains the sensor orientation R(t) and translation T(t). Calibration, time synchronization, and trajectory estimation therefore affect mapped coordinates even when an individual range observation is precise.

$$P(t) = R(t)q(t) + T(t) \quad (1)$$

This equation is an observation model, not a complete stochastic description. Range noise acts along the emitted beam, while an orientation error produces a displacement that generally grows with object distance. Pedestrian movement can change observation geometry rapidly. Opposing passes and revisits increase redundancy, but the benefit depends on whether the processing algorithm recognizes reliable correspondences.

### 2.3. Proposed field acquisition and reference design

The proposed protocol begins with a reconnaissance that separates open ground, vegetated ground, steep surfaces, confined passages, and areas of moving objects. Route planning should provide connected observations across these environments. Short loops and cross connections are preferable where they preserve stable geometric constraints. A loop should revisit recognizable, stationary surfaces, rather than merely return the operator to a nearby location. Weakly featured surfaces and long repetitive corridors require particular attention because geometric ambiguity can persist after an apparently successful closure.

A reference network should be surveyed independently using methods suitable for the site and required tolerance. GNSS may be appropriate in open areas, while a total station can extend control into obstructed locations. Reference uncertainty and coordinate datum must be documented. Control targets used during adjustment must be kept separate from checkpoints reserved for validation. Checkpoints should cover the perimeter, interior, elevation range, long route sections, and transitions between contrasting environments. Their number and distribution should reflect the project area and confidence required; a universal minimum is not prescribed here.

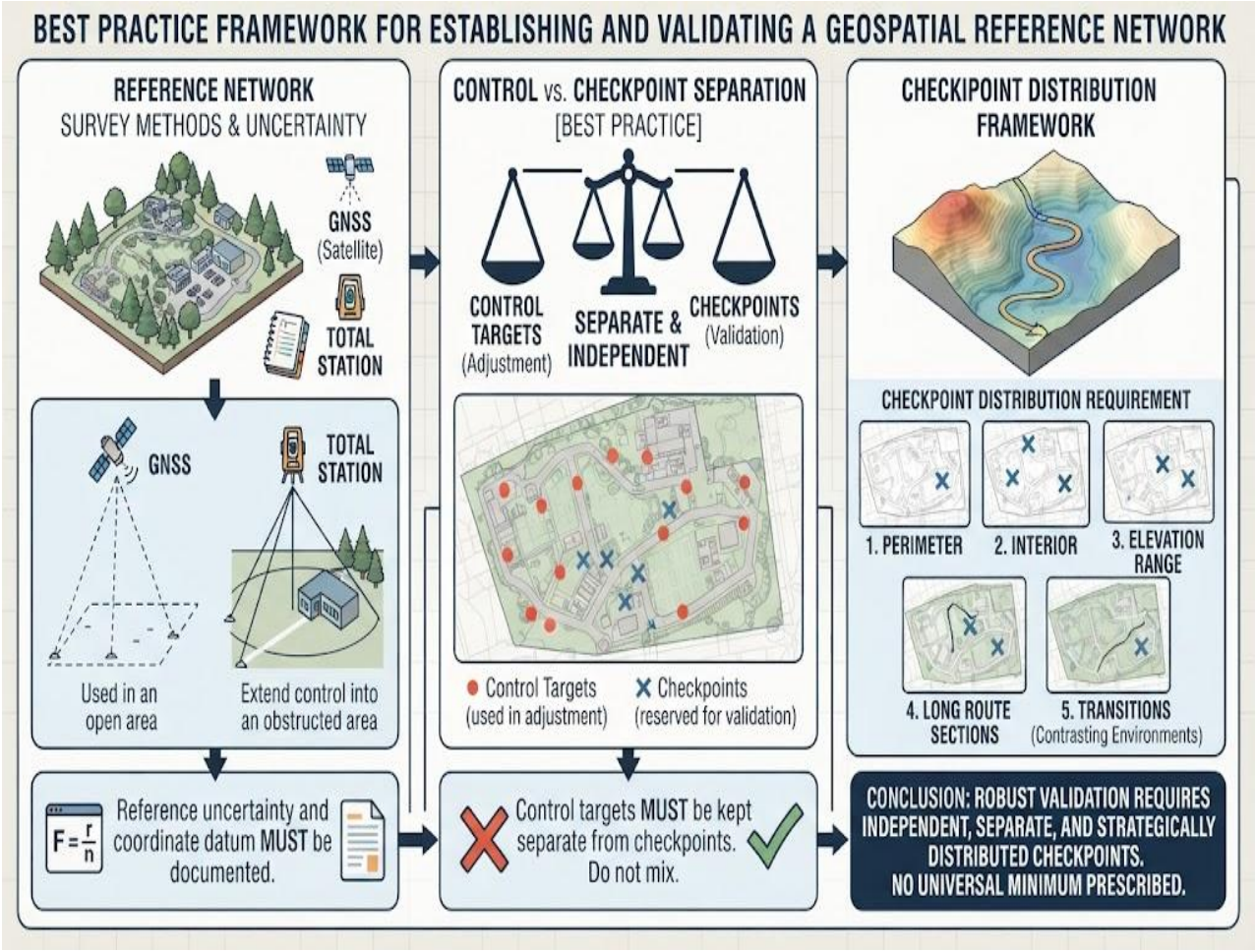



**Figure 2:** Best Practice Framework for Establishing and Validating a Geospatial Reference Network.

At least two independently initialized routes are proposed when repeatability matters. An opposing direction route can help reveal direction dependent effects. Raw trajectories, acquisition duration, walked distance, pauses, closure locations, and changes in scene conditions should be retained. Registration against a reference cloud must use designated stable surfaces. Testing the same surfaces used to optimize alignment would overstate independence, so separate surfaces or checkpoints should be withheld.

### 2.4. Coordinate and surface accuracy metrics

For checkpoint $i$, signed residuals are defined as $\Delta x_i = x_i - x_{i,ref}$, with equivalent definitions for $y$ and $z$. The number of independent checkpoints is $n$. Equations (2)–(4) describe root mean square error (RMSE), while Equation (5) describes mean signed vertical error. These quantities should be reported together, since RMSE combines systematic displacement with dispersion.

$$RMSE_x = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (\Delta x_i)^2} \quad (2)$$

$$RMSE_{horizontal} = \sqrt{RMSE_x^{\,2} + RMSE_y^{\,2}} \quad (3)$$

$$RMSE_{3D} = \sqrt{RMSE_x^{\,2} + RMSE_y^{\,2} + RMSE_z^{\,2}} \quad (4)$$

$$Bias_z = \frac{1}{n}\sum_{i=1}^{n} \Delta z_i \quad (5)$$

For each axis, dispersion around the mean should be provided alongside RMSE. A robust summary can use the median residual and normalized median absolute deviation, calculated as 1.4826 times the median absolute deviation from the median. The scaling gives a standard deviation equivalent under a normal error model; it does not make a non-normal distribution normal. Percentiles and spatial residual plots remain necessary where outliers or heterogeneous errors are present.

Surface assessment should use signed distances with a clearly defined reference direction. Nearest point distances are sensitive to sampling density and do not automatically represent displacement. Point to plane distances are useful on locally planar surfaces; rough or curved surfaces require a suitable local model and a stated comparison scale. Steep faces should be assessed in three dimensions because vertical differences alone can misrepresent surface agreement.




**Figure 3:** Best Practice Framework for Geospatial Surface Assessment.

### 2.5 Product level uncertainty and acceptance

The protocol evaluates terrain products after filtering and interpolation, using checkpoints that were not used in model construction. Filtering parameters, grid size, interpolation method, and breakline treatment should be varied within defensible ranges. Completeness should be expressed relative to a defined target surface or map area, with inaccessible and unobserved regions reported explicitly. A low residual over the observed area does not justify treating a hidden region as measured.

For elevation based volume calculation, cell differences $\Delta z_j$ and cell areas $A_j$ give $V = \sum_j A_j \Delta z_j$. Under a linear uncertainty model, the variance is $A^T C_{\Delta z} A$, where $C_{\Delta z}$ is the covariance matrix of elevation differences. Ignoring off diagonal terms assumes independence and can underestimate uncertainty when registration errors are spatially correlated. Overhangs require an appropriate three dimensional solid or surface approach because a single elevation per horizontal location cannot represent them.

For two independent epochs, a simplified normal direction detection threshold can be written as $LoD_{95} = 1.96\sqrt{{u_1}^2 + {u_2}^2 + {u_{reg}}^2}$, where $u_1$ and $u_2$ are standard uncertainties of the local surface estimates and $u_{reg}$ is an additional, independent registration uncertainty. The expression assumes approximately normal errors and excludes double counting of registration terms already present in $u_1$ or $u_2$. Correlated epochs require covariance terms. This proposed threshold is a decision aid, not evidence that an unmeasured change has occurred.

## 3. RESULTS

### 3.1 Terrain surfaces and exposed slopes

The synthesis identifies a distinction between capturing surface geometry and validating a terrain interpretation. Earlier work on earth pillar erosion and sea cliff modelling establishes the relevance of dense geometric observations for irregular natural surfaces [10, 11]. For wearable surveys, accessible benches, paths,

and slope toes can provide useful observation routes. The resulting cloud should nevertheless distinguish exposed ground from vegetation and areas hidden by terrain. A route confined to the slope toe can leave upper surfaces inadequately observed.

Photogrammetric landslide studies provide context for terrain coverage and regional representation [12, 13]. Oblique stereo imaging of outcrops also addresses the relation between accessibility, observation scale, and reconstructed geometry [14]. These studies support complementary acquisition planning, but they do not establish the accuracy of a wearable scanner. The proposed interpretation is to use pedestrian data for accessible detail and complementary observations where upper faces or broad context remain missing.

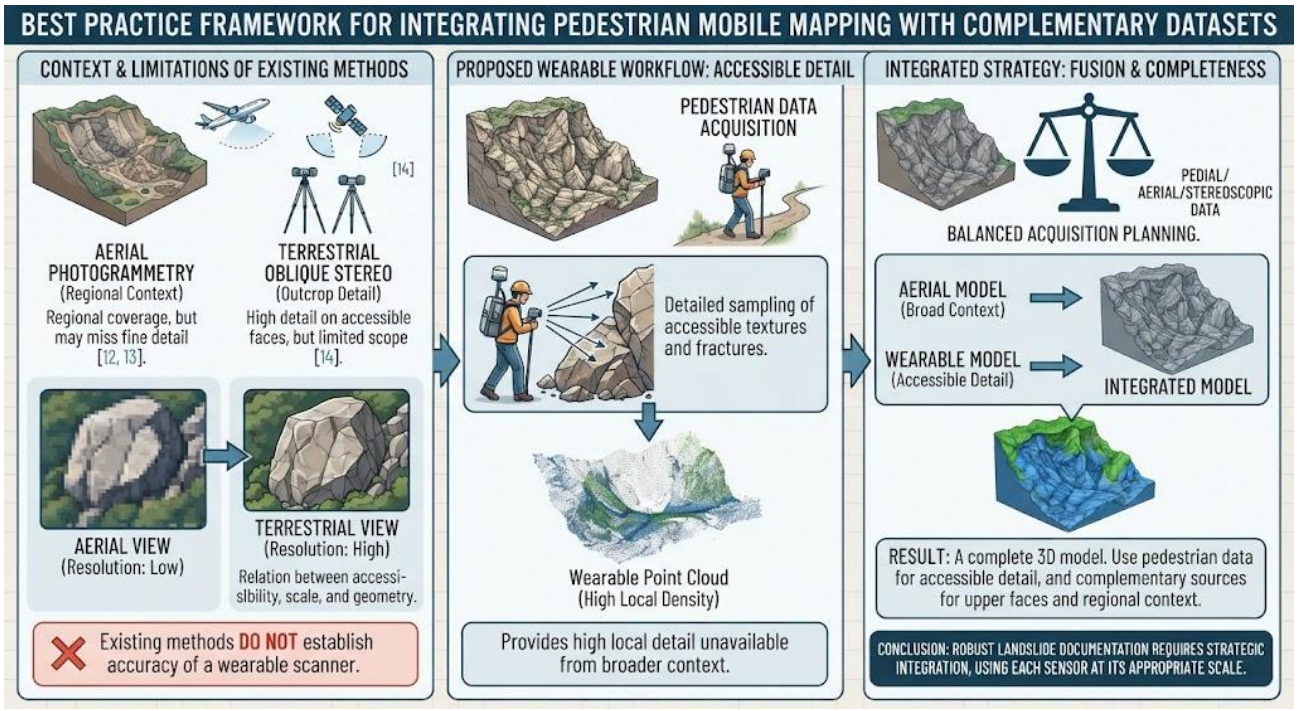



**Figure 4:** Best Practice Framework for Terrain Product Validation and Volume Uncertainty Analysis

The Gümüşhane-Trabzon slope study uses photogrammetrically generated geometry as input to stability analysis [15]. Its role in this review is to illustrate a downstream use of point cloud derived sections. It is not evidence of wearable LiDAR performance, and geometric accuracy alone cannot validate a stability model whose material parameters or boundary conditions remain uncertain. Table 1 connects mapping tasks to the validation quantities that would be required.

**Table 1.** Application specific products and proposed independent checks

| Application | Delivered product | Primary validation | Main limitation |
|---|---|---|---|
| Open or gently sloping terrain | DTM and contours | Withheld elevation and planimetric checkpoints | Interpolation across gaps |
| Rock face or steep slope | 3D mesh and sections | Normal distances and surveyed breaklines | Occlusion and orientation error |
| Excavation and stockpile | Surface and volume | Independent surfaces and volume sensitivity | Boundary and base definition |
| Confined or complex geometry | Connected 3D model | Distributed checkpoints and repeat routes | Trajectory drift and ambiguity |
| Repeated monitoring | Surface change map | Stable reference zones and local detection limits | Registration and temporal changes |

### 3.2. Ground extraction and terrain representation

Ground classification is a separate source of uncertainty from coordinate measurement. Airborne LiDAR filtering studies show that cloth simulation filtering responds to slope, vegetation, and parameter selection [16, 17]. These findings justify testing parameter sensitivity in a wearable workflow, but airborne defaults should not be transferred automatically. Pedestrian data have different viewing directions, point distributions, and occlusions. A parameter set that retains a steep ground face may also retain low vegetation or built structures.

The Skopje study compares filtered terrain models with a manually constructed reference and demonstrates parameter dependent volume differences [18]. This is model agreement evidence; it should not be interpreted as independent geodetic accuracy. For topographic products, manual cleaning must be logged, and difficult locations should retain uncertainty labels. A terrain model produced after extensive editing can be useful, but reproducibility requires the edits and their effects to be documented.

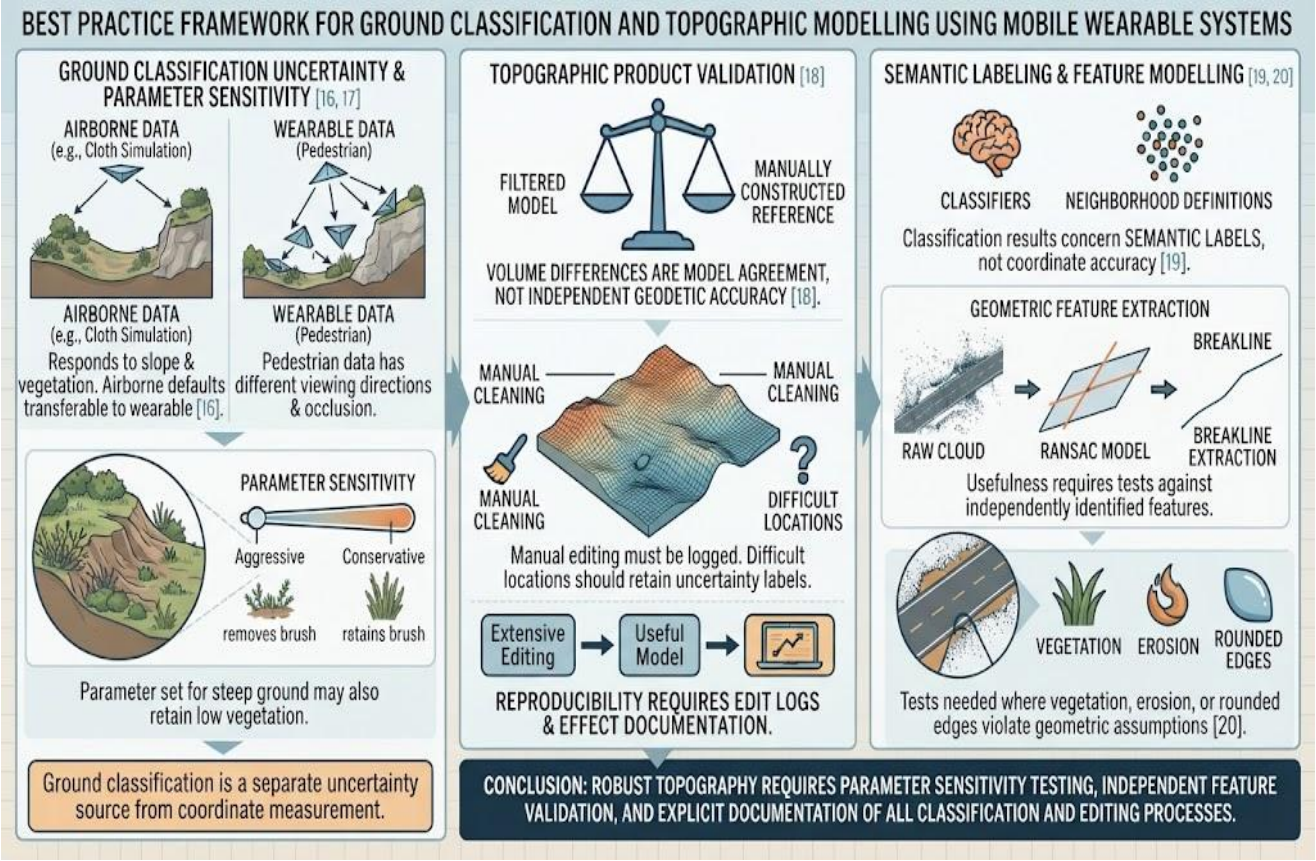



**Figure 5:** Best Practice Framework for Integrating Pedestrian Mobile Mapping with Complementary Datasets.

The mobile point cloud classification study by Mohamed and colleagues compares classifiers and neighborhood definitions [19]. Its classification results concern semantic labels rather than coordinate accuracy. Geometric feature extraction and Random Sample Consensus methods can support plane and line modelling [20]. Their usefulness for breakline extraction still requires tests against independently identified features, especially where vegetation, erosion, or rounded edges violate simple geometric assumptions.

### 3.3. Excavation volumes and complex geometries

Photogrammetric excavation volume work provides a relevant precedent for assessing derived quantities against survey based alternatives [21]. The transferable issue is that volume depends on the reconstructed surface and its integration boundary. A small consistent elevation bias over a large area can produce a substantial volume difference even when local roughness appears satisfactory. For wearable acquisition, uncertainty in the reference base, incomplete sidewall coverage, and the treatment of voids should be investigated separately from point coordinate RMSE.

Affordable cave scanning research illustrates the construction of complex underground models from sequential profiles, while reporting gaps between profiles and sidewall representation limitations [22]. This is evidence from a modified two dimensional scanning approach, not a wearable SLAM accuracy trial. It nevertheless

highlights a general validation requirement: cross sections can describe passages without capturing all intervening geometry. Meshing must not silently turn unobserved areas into apparently measured surfaces.

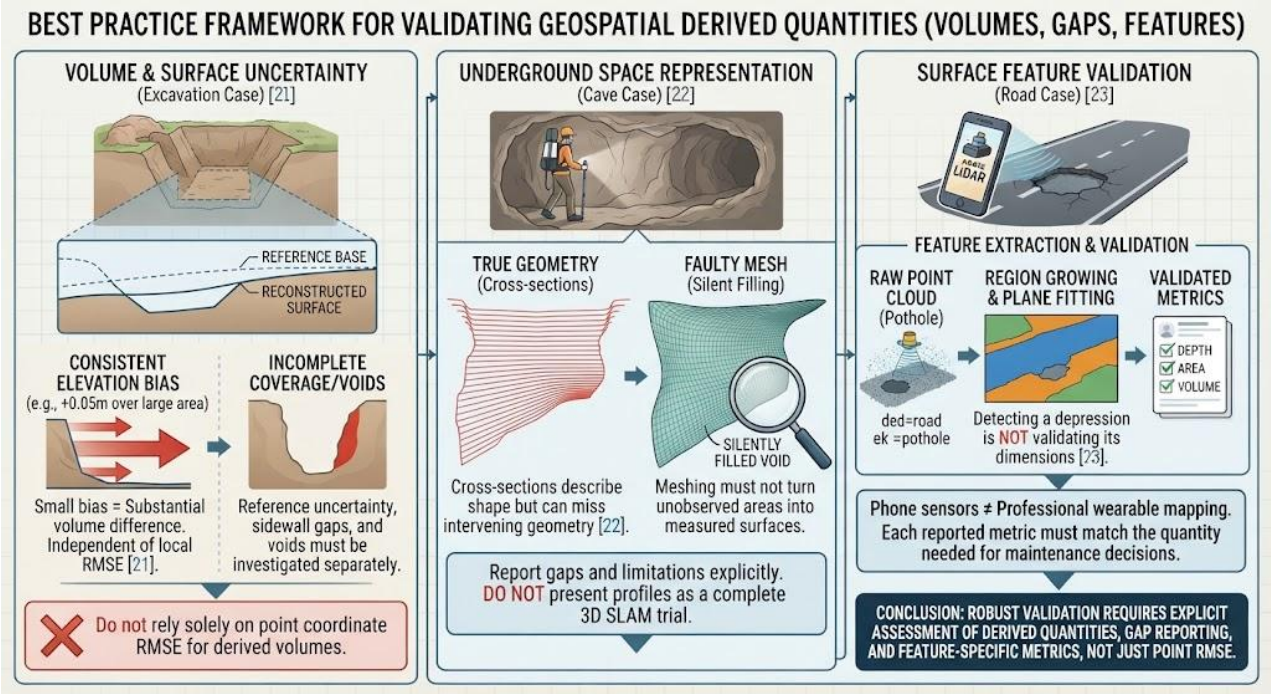



**Figure 6:** Best Practice Framework for Validating Geospatial Derived Quantities (Volumes, Gaps, Features).

Road distress work using mobile phone LiDAR demonstrates local surface feature extraction with region growing and plane fitting [23]. This is a useful comparison for small surface defects, but phone sensors and wearable mapping systems differ in range, tracking, and data quality. Detecting a depression is also a different task from validating its depth, area, or volume. Each reported metric should match the quantity used for maintenance or engineering decisions.

### 3.4. Built and heritage environments as methodological comparators

The wearable survey of Mufti Abdullah Sıddık Mosque provides a directly relevant example of pedestrian acquisition for connected structure modelling [24]. Earlier laser scanner performance work on historical ruins offers a static acquisition comparison [25]. Together with the Cambazlı study, these sources show why confined and irregular sites are important application settings. Their architectural targets do not by themselves establish the reliability of bare earth terrain extraction.

Alyilmaz, Alyilmaz, and Yakar's Qobustan study documents petroglyphs using close range photogrammetry [26]. It is included as a precedent for detailed recording of irregular rock surfaces, with an explicit distinction between image based documentation and mobile ranging. Fine engravings can demand greater spatial detail than a terrain mapping specification. A wearable model of the surrounding rock setting may therefore need supplementary close range imagery or higher resolution static measurements to document the engravings themselves.

Studies integrating terrestrial scanning and photogrammetry for historical artifacts and heritage surveys provide context for complementary observations [27, 28]. The Burdur Station study applies that combination to material deterioration [29]. For the present framework, these contributions support separating geometric surface capture from visual interpretation. Surface discoloration or deterioration should not be inferred solely from geometric residuals, and adding photographic texture does not independently improve the coordinates of an incorrectly registered cloud.

A comparison of terrestrial scanning and UAV photogrammetry at archaeological excavation sites provides a further example of complementary coverage [30]. Its relevance to excavation mapping is the comparison of acquisition geometries, rather than evidence that both platforms have identical accuracy. A wearable survey should preserve the same distinction when integrating ground level and aerial observations.

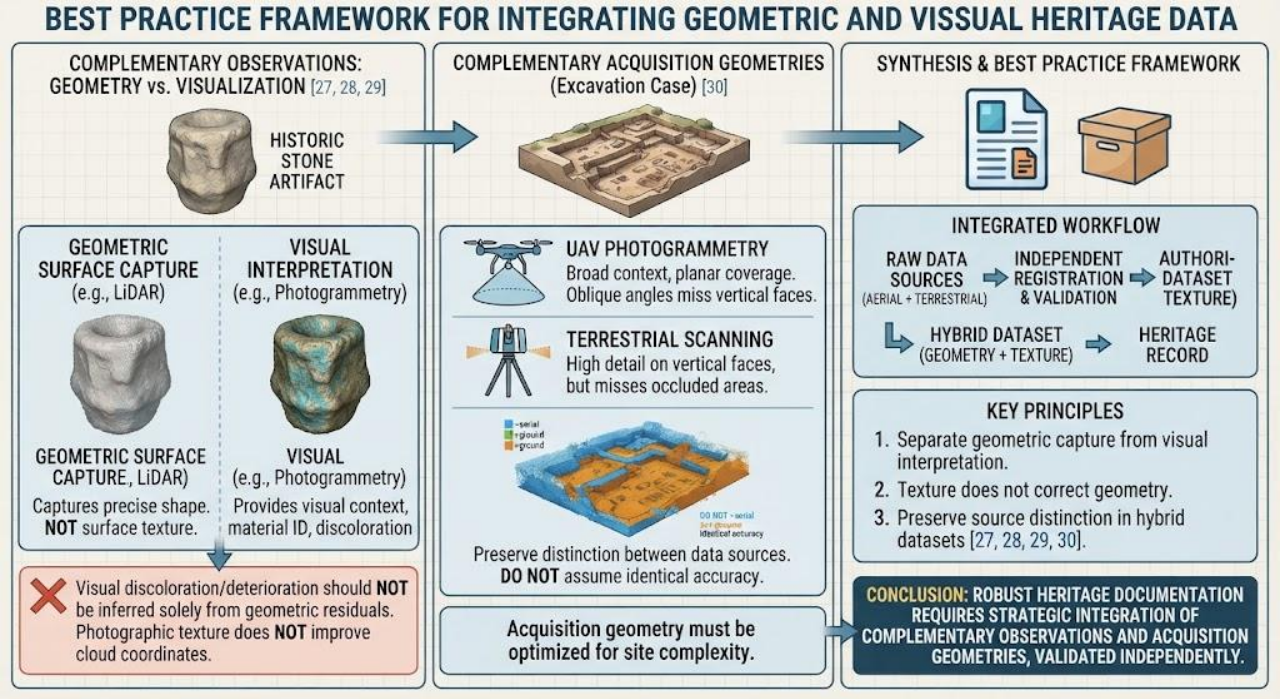



**Figure 7:** Best Practice Framework for Integrating Geometric and Visual Heritage Data.

## 4. Discussion

### 4.1 Accuracy is a chain of dependent decisions

The review supports evaluating wearable mapping as a sequence from observation to trajectory estimation, coordinate referencing, classification, modelling, and extraction. Construction point cloud reviews distinguish acquisition from subsequent processing and application [31, 32]. The proposed framework extends that distinction to terrain products. A low scanner range uncertainty cannot compensate for poor trajectory geometry; accurate coordinates cannot compensate for incorrect ground classification; and a valid ground cloud can still yield misleading contours if interpolation crosses a data gap.

This dependence makes a single global RMSE insufficient as the sole acceptance criterion. Residuals should be grouped by terrain class, slope, route segment, and distance from control. An overall statistic weighted by many easy checkpoints can conceal a small but important failure zone. Where suitable sample sizes are available, confidence intervals should be based on independent spatial units or survey repeats rather than treating every adjacent cloud point as an independent replicate.

Table 2 distinguishes error mechanisms and diagnostic evidence. The diagnostics are proposed checks. They should not be reported as observed findings until they have been applied to a measured dataset.

**Table 2.** Error mechanisms and proposed diagnostic tests

| Mechanism | Expected diagnostic pattern | Required check |
|---|---|---|
| Trajectory drift | Residual trends along route or disagreement at revisits | Withheld targets along long sections and independent repeat routes |
| Rigid datum error | Consistent translation or rotation against independent control | Check coordinate reference system and distributed checkpoints |
| Surface visibility | Missing upper faces, ground patches, or backs of objects | Coverage map and observations from another viewpoint |
| Ground misclassification | Local terrain bias near vegetation or structures | Manually labelled validation samples by terrain class |
| Interpolation and smoothing | Rounded breaklines or artificial surfaces across voids | Grid sensitivity and independent profiles |

| Mechanism | Expected diagnostic pattern | Required check |
|---|---|---|
| Temporal scene changes | Localized differences at moving or altered objects | Acquisition notes and stable reference surfaces |

### 4.2. Choosing complementary survey methods

Reviews of building reality capture and scanning to building information modelling show that the capture method should be chosen in relation to the intended representation [33, 34]. Integrated scanning, photogrammetry, and modelling workflows provide further context for combining observation types [35]. For topography, a wearable system is most useful where pedestrian movement improves access and observation continuity. Static scanning remains relevant for stable high detail views; aerial observations can improve coverage of upper surfaces. Instrument choice should follow the required uncertainty, visibility, and operating conditions.

Integration requires more than merging dense clouds. Each dataset should have a documented datum, epoch, reference uncertainty, and processing history. The combined product should be tested independently after alignment. A surface used to fit a transformation cannot also serve as independent evidence that the same transformation is accurate. If an aerial cloud supplies the only observations of an upper face, that face should retain its source identity rather than inherit the validation statistics of lower wearable observations.

### 4.3. Survey efficiency and fitness for purpose

Acquisition speed should be assessed with the complete workflow: reconnaissance, control establishment, field capture, processing, editing, validation, and remeasurement. Indoor mobile scanning research motivates time savings as an application question, but those savings must be evaluated alongside product suitability [4]. A short walk that requires extensive correction may not reduce the total cost. Conversely, a system with moderate coordinate accuracy may be entirely adequate for reconnaissance or contextual visualization when its limitations are disclosed.

A proposed acceptance rule combines four conditions. Independent coordinate and surface errors must meet the project tolerance; coverage must be adequate for the defined target; repeated observations must show acceptable consistency; and derived quantities must have uncertainty appropriate to their use. Tolerances should be agreed before inspecting the result. Exclusions should be based on physical reasons, documented consistently, and accompanied by the proportion of the target area that remains unvalidated.

### 4.4. Limitations and research priorities

The source set is purposive and includes conference contributions as well as journal articles. Some references provide contextual evidence from terrestrial scanning, photogrammetry, aerial LiDAR, or smartphone sensors. Their inclusion supports methodological comparison, while limiting any inference about a particular wearable device. The review does not establish a pooled accuracy, rank commercial instruments, or claim that architectural validation transfers directly to natural terrain.

A next empirical study should compare independently initialized wearable routes across open ground, vegetated slopes, steep exposed faces, and confined passages. The same withheld checkpoints and reference surfaces should be applied to all routes. Raw and adjusted trajectories should be retained where available, and filtering and interpolation settings should be varied systematically. Reporting should distinguish reference uncertainty, checkpoint residuals, surface distances, completeness, and uncertainty of the final product. Shared benchmark datasets containing both successful surveys and trajectory failures would make comparisons more informative.

## 5. Conclusion

Wearable mobile LiDAR provides a practical means of collecting three dimensional observations along pedestrian routes and in geometrically complex environments. Its principal surveying value lies in access, connected observation, and the possibility of dense surface representation. These benefits become dependable mapping capabilities only when the final product is independently validated.

The proposed framework separates coordinate accuracy, local surface agreement, repeatability, completeness, and uncertainty in derived products. Distributed checkpoints and withheld reference surfaces are necessary to distinguish independent accuracy from adjustment quality. Terrain filtering, breakline representation, and interpolation should be tested because they can alter the usefulness of a correctly positioned

point cloud. Steep and overhanging surfaces require a three dimensional assessment rather than reliance on elevation differences alone.

No universal accuracy level can be assigned to wearable mobile LiDAR from the heterogeneous evidence reviewed. Suitability depends on the sensor configuration, trajectory constraints, surface visibility, reference network, and required product. Future field evaluations should apply reproducible acquisition routes and independent controls, retain unobserved areas explicitly, and report uncertainties that correspond to the engineering or environmental decision being made.

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**Data Availability Statement**
No new field measurements or experimental datasets were generated. The literature used in the narrative synthesis is identified in the reference list.

**Institutional Review Board Statement**
Not applicable. This review does not involve human participants or animal experiments.

**Credit Author Statement**
Author contribution roles will be confirmed by Atilla Karabacak and Murat Yakar before submission.

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