Linking Persistent Scatterers with Urban Features Using LoD2 Building Models

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Abstract

Persistent Scatterer Interferometry (PSI) provides valuable information on ground and structural changes, particularly in dynamic urban environments. At the same time, urban digital twins (UDTs), as detailed three-dimensional (3D) representations of cities, are increasingly used for monitoring and analysis. However, the effective integration of results of PSI processing named Point Scatterers (PSs) into such frameworks remains challenging due to the limited positional accuracy of PSs, despite the high precision of displacement estimates. This study investigates a methodology for integrating PSI data from the European Ground Motion Service (EGMS) with airborne laser scanning (ALS) data and Level of Detail 2 (LoD2) building models to improve the connection of PSs with real-world objects. Three integration variants were analysed, differing in the reference datasets used for linking: (i) ALS point cloud, (ii) point cloud derived from LoD2 models and digital terrain model (DTM), and (iii) a combined approach integrating ALS and LoD2 representations. The results demonstrate that the combined approach yields the highest performance, achieving up to 88% of successfully linked PSs, compared to 70.4% and 80.3% for the ALS-only and LoD2-based approaches, respectively. The findings indicate that LoD2 models provide sufficient geometric detail for PS linking, despite lacking fine-scale building elements. Their use improves data completeness, particularly on building facades, where ALS data are often sparse or missing. The proposed methodology confirms the applicability of EGMS products as a valuable data source for 3D geoportals and urban digital twins, supporting advanced spatial analyses in complex environments.

1. Introduction

Effective management of cities, including the maintenance of infrastructure, operation of transportation systems, efficient energy use, environmental quality, public safety, and ongoing urban development, requires continuous monitoring of urban processes. Urban Digital Twins (UDTs) have emerged as an important tool that can support this task. By integrating data collected in smart cities and automatically incorporating them into digital city models and related systems, UDTs enable the creation of accurate digital representations of urban environments. These digital replicas can interact with the physical city and support better decision-making in urban management. UDTs can represent not only the physical structure of cities but also their social and economic aspects (Ferré-Bigorra et al., 2022). Through continuous data exchange between the physical and digital environments, they can support more efficient management and operation of urban infrastructure.

Within the DigiTwins4PEDs project (https://digitwins4peds.eu/), UDTs are used as digital representations of real cities that enable detailed modeling of urban energy behavior. As part of the project, a dedicated 3D visualization platform is being developed to provide residents and stakeholders with an interactive environment to exchange information and explore various Positive Energy District (PED) scenarios before they are implemented in the real world. The UDTs are being developed for several cities within the project, including Rotterdam (the Netherlands), Stuttgart (Germany), Vienna (Austria), and Wrocław (Poland).

However, monitoring energy systems is only one aspect of understanding how cities work. It is also important to observe how cities and districts evolve over time. Rapid urbanization, including the expansion of residential areas, may lead to ground deformation caused by intensive land use (Fotiou et al., 2022). In particular, extensive groundwater extraction and underground construction activities are recognized as major drivers of land subsidence in cities (Parsons et al., 2023; Saraswat et al., 2025). Such deformations may pose risks to newly constructed buildings even in the early stages of their lifecycle.

Remote sensing techniques can support this type of monitoring by providing large-scale observations of urban surface changes. One of the most suitable approaches is Interferometric Synthetic Aperture Radar (InSAR), which enables satellite-based monitoring of ground displacement with revisit intervals of several days. A commonly used technique in urban environments is Persistent Scatterer Interferometry (PSI), which allows the detection of ground and object displacement with millimeter-level precision (Crosetto et al., 2016). PSI exploits time series of synthetic aperture radar (SAR) images to identify stable radar targets, known as point scatterers (PSs), whose signal reflections remain coherent over time. Analyzing phase differences between acquisitions enables the estimation of displacement along the satellite line of sight (LOS). The technique is particularly effective in urban areas due to the abundance of stable reflectors, such as buildings and infrastructure(Ciampalini et al., 2014). Access to PSI data has recently become significantly easier thanks to the European Space Agency (ESA), which provides PSI products derived from the Sentinel-1 mission through the European Ground Motion Service (EGMS) (Crosetto et al., 2020). EGMS provides standardized, pan-European ground motion data with regular updates, ensuring temporal consistency of the observations. The service includes an online platform for data visualization and download, which supports efficient use of PSI data in further analyses and applications, e.g. in land subsidence monitoring related to landslides, mining activity, geodynamics, and tectonics, as well as monitoring of infrastructure, urban areas, and cultural heritage (Crosetto et al., 2025).

Despite the high measurement precision of PSI, the measurement points, called PSs, often have limited geolocation accuracy (Dheenathayalan et al., 2016). This makes it difficult to associate them with specific real-world objects, such as buildings or infrastructure elements (Dheenathayalan et al., 2018; Yang et al.,

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2020). Several studies have used PSI data to analyze slow, long-term subsidence related to urban development patterns (Ciampalini et al., 2019; Saraswat et al., 2025). However, such processes are usually complex and result from multiple factors, for example, changes in groundwater levels combined with urban construction activities (Liu et al., 2018). Therefore, accurate spatial localization of PSs is essential for identifying the possible causes of observed deformations.

One approach to address this problem was proposed by Van Natijne et al. (2018), who linked PSI points to the nearest point in an airborne laser scanning (ALS) point cloud using a positional error ellipsoid. This approach was later extended by Wielgocka et al. (2025), who introduced a refined linking strategy. In their approach, candidate ALS points are first pre-selected based on return number, classification, and geometric features in order to reduce ambiguity in the matching process. This guarantees that linking occurs solely with points representing objects capable of realistically serving as PSs. The linking is then performed in two steps. First, the PS dataset is aligned with the ALS geometry using the Iterative Closest Point (ICP) algorithm. Second, for each PS, the nearest ALS point is identified within its positional error ellipsoid. This approach significantly improves the linking results, allowing more than 80% of Sentinel-1 PS points to be correctly linked with ALS data. However, an important limitation remains. ALS point clouds often lack sufficient coverage on building façades, which makes it difficult to assign PS points to specific structures, particularly in dense urban areas and narrow streets.

In this context, Urban Digital Twins offer a promising alternative. They increasingly incorporate detailed 3D building models that explicitly represent the geometry of urban structures, including façades and roofs. Such models provide a consistent and complete spatial representation of buildings, potentially supporting more accurate linking of PSI observations to real-world objects. However, their potential for improving the spatial localisation of PSI measurements has not yet been sufficiently explored.

Therefore, this study examines whether 3D building models derived from Urban Digital Twins platforms can be used as a reference for linking PSI points to urban structures. In particular, the study evaluates the use of LoD2 building models and digital terrain models (DTM) for this purpose. The novelty of this approach lies, firstly, in the use of building models as a reference dataset for PS linking, enabling improved geometric positioning of PSI points through integration with Urban Digital Twin data. This enhanced localization facilitates their incorporation into 3D visualization environments and supports further spatial analyses within UDT frameworks. Moreover, the study demonstrates how an openly accessible PSI data source, such as EGMS, can be effectively integrated into Urban Digital Twins. Several linking strategies are tested and compared, including a classical ALS-based approach, a model-based approach using Urban Digital Twin data, and a combined approach integrating both data sources.

The remainder of this paper is organized as follows. Section 2 describes the datasets and the PS linking methods. Section 3 presents the results. Section 4 discusses the results and provides conclusions and recommendations for future research.

2. Data & Methods

2.1 Study area

One of the areas for which a UDT has been developed within the DigiTwins4PEDs project is the Kleczków district in Wrocław, a city located in south-western Poland. In general, the city is not affected by significant regular ground deformations caused by natural or anthropogenic factors. However, in highly urbanized areas where new residential developments and other buildings are being constructed, local ground displacements have been observed.

A similar situation occurs in the Kleczków district. The area has a various building stock, ranging from historic tenement houses to modern residential developments, as well as municipal buildings, industrial sites, and public facilities. In particular, ground displacements have been observed in newly developed residential areas (shown in purple in Figure 1), where construction started after 2010. In these locations, the observed displacement reaches values of up to approximately 1 cm per year. The majority of these displacements occur during the initial years following construction, after which the ground motion stabilizes and becomes negligible.

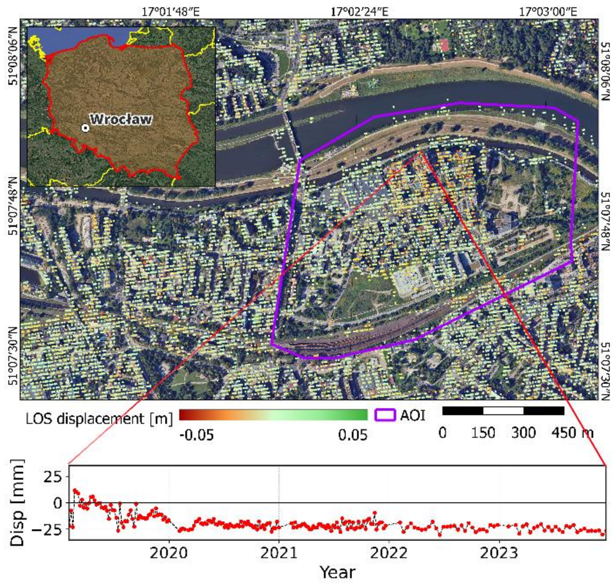

Figure 1. Location of the study area: Kleczków district in Wrocław (purple rectangle). The map presents EGMS PSI-derived ground displacement in line of sight direction, along with a time series for a selected building, highlighting the detected deformation.

2.2 Data

For the selected study area, publicly available PSI, ALS point clouds, LoD2 building models, and DTMs were used. PSI data for the Kleczków area covering the period from January 2019 to December 2023 were obtained from the European Ground Motion Service (EGMS) portal (https://egms.land.copernicus.eu/). In this study, data from ascending orbit 73 were used. The calibrated product was selected, in which deformations in the line of sight direction (LOS) are referenced to a model derived from GNSS observations (Dehls et al., 2022), providing absolute deformation values rather than relative measurements.

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As a reference representation of objects in 3D for the linking procedure, two data sources were selected. The first consisted of datasets available within the UDT platform. Data available within the DigiTwins4PEDs platform includes LoD2 building models and DTM (Figure 2a). The LoD2 building models, representing building geometry at the level of roofs and basic structures, were created by Zielonka et al. (2026) and uploaded publicly via Zenodo. It was constructed using publicly available spatial and geodetic datasets, including a DTM, Digital Surface Model (DSM), orthomosaics (ORTO), Topographic Object Database (BDOT10k), and cadastral data (EGiB). These data were integrated and processed to reconstruct 3D building models in accordance with the CityGML LoD2 specification (Gröger and Plümer, 2012). The integration of multiple data sources enabled the development of topologically consistent three-dimensional models enriched with semantic attributes. To ensure high geometric and semantic quality, the CityDoctor tool (https://transfer.hft-stuttgart.de/gitlab/citydoctor/) was employed for validation. The verification process included detecting topological errors and assessing compliance with the CityGML schema. Additionally, the DTM, with a spatial resolution of 1 m and an average vertical accuracy of 0.08 m, was obtained from the national geoportal (https://geoportal.gov.pl/), where data are provided by the Polish Head Office of Geodesy and Cartography (GUGiK).

Additionally, ALS data from the same source (GUGiK) were used as an independent reference dataset (Figure 2 c,d). The ALS point cloud, acquired in 2024, has a minimum density of 12 points/m². The dataset is classified according to the ASPRS classification scheme (https://github.com/ASPRSorg/LAS), including classes such as Unclassified Points, Ground, Low, Medium, and High Vegetation, Buildings, Water, Low Points, and Overlap Points. All datasets are referenced to the PL-EVRF2007-NH height system.

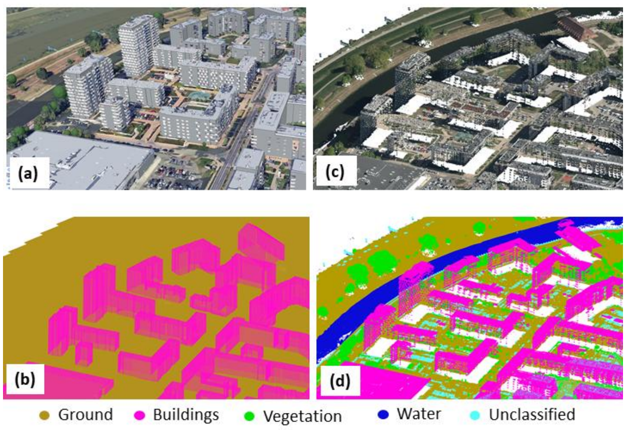

Figure 2. Data used: (a) DigiTwins4PEDs 3D platform; (b) synthetic point cloud generated from LoD2 (pink points) and DTM (brown points); (c) ALS point cloud in RGB; (d) ALS point cloud classes.

2.3 Linking procedure

The linking procedure aims to enhance the positional accuracy of PSs by associating them with their corresponding real-world objects. This is achieved by assigning each PS to the most likely candidate point extracted from reference datasets. For this purpose, the approach proposed by Wielgocka et al. (2025) was used. The entire workflow was implemented in Python, utilizing libraries such as NumPy, GeoPandas, Open3D, PCL, and LasPy. Figure 3 presents the workflow applied in this study.

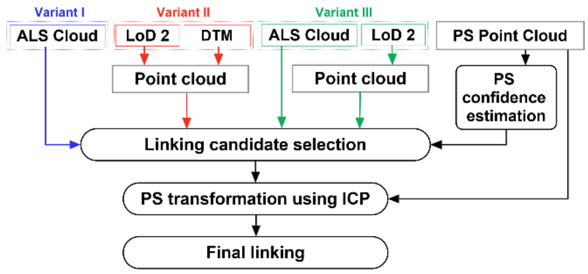

Figure 3. Linking workflow for three variants: ALS-based (blue), LoD2 + DTM (green), and combined approach (red).

The linking process consists of two main steps. First, global transformation parameters between datasets are estimated using the ICP algorithm, which aligns the PSI point cloud to the reference data. A point-to-plane ICP variant, implemented using the Open3D library (Zhou et al., 2018) is applied to minimize the distance between points and locally fitted planes, thereby improving alignment in structured urban environments. Both translation and rotation parameters are estimated during this process. Matching was performed only for points within a distance threshold corresponding to the spatial resolution of Sentinel-1 data (14 m in azimuth and 2 m in range direction).

In the second step, linking is performed within the positional error ellipsoid defined for each PS point. The ellipsoid parameters are derived from the variance–covariance matrix in the radar coordinate system, following the approach proposed by Dheenathayalan et al. (2018) and implemented by Van Natijne et al. (2018). In this system, the position of a scatterer is defined by range (r), azimuth (a), and cross-range (c) coordinates, where range corresponds to the radar line of sight, azimuth to the satellite flight direction, and cross-range is perpendicular to both.

Within each ellipsoid, the nearest suitable candidate point is selected. Candidate points are identified based on the selection procedure proposed by Wielgocka et al. (2025), which considers point classification, geometric features derived from principal component analysis (PCA), and surface normals. Within this framework, three variants of the linking procedure were tested using different reference datasets, which determine the approach for linking candidate selection:

- *Variant I: ALS-based approach*

The first variant follows the previously proposed approach and uses the ALS point cloud as the reference dataset. Before linking, the point cloud is filtered to retain only relevant candidate points. This includes selecting ground and building points, removing irrelevant classes such as vegetation, water, and low points, and filtering out unsuitable objects from the unclassified class using PCA. In addition, only points visible from the LOS are retained, based on surface normal analysis.

- *Variant II: modified LoD2 + DTM approach*

In the second variant, reference data are derived from the UDT platform. Building geometry is represented using LoD2 models, while terrain is described using the DTM. Based on these datasets, a synthetic point cloud with a regular spacing of 0.5 m is generated and divided into two classes: Buildings (derived from LoD2 models) and Ground (derived from the DTM) (Figure 1b). The point cloud generation procedure was carried out using FME software. In this variant, filtering is limited to the removal of points not visible to the radar LOS. DTM points corresponding to areas under buildings were kept unchanged. No additional classification-based filtering is applied.

- *Variant III: Combined approach*

The third variant combines ALS data with LoD2-based models. In this approach, building points from the ALS point cloud are replaced with a synthetic point cloud generated from LoD2 models, while the remaining ALS-derived points are retained. The same filtering strategy as in Variant I is applied, including candidate selection based on classification, geometric features, and LOS visibility as in Variant II.

The output of the linking procedure is an enhanced PS dataset that contains corrected PS coordinates from linking, the assigned class for the linked reference point, and variance data in the radar geometry. PSs that could not be linked remain without updated coordinates and classification.

The effectiveness of the linking procedure was evaluated by the percentage of successfully linked PS points and by visual inspection of the 3D linking results.

3. Results

3.1 Comparison between ALS point cloud and LoD2

Because the LoD2 models were created by integrating multiple data sources, including spatial and cadastral datasets, they were first compared with the ALS point cloud. Figure 4 presents an example of one of the buildings located in the northern part of the study area, in the vicinity of the point for which the time series is shown in Figure 1. To enable a more comprehensive analysis, cross-sections through the building were generated for both the point cloud and the model.

As the roofs of this building, as well as most buildings in the area, are flat, their representation in the LoD2 model does not differ significantly from the point cloud. The point cloud, however, captures additional roof elements such as hatches, chimneys, and antennas. Apart from these differences, both datasets remain largely consistent. The most pronounced discrepancies are observed on building facades. In these areas, the ALS point cloud is either sparse or exhibits significant deviations from the LoD2 outlines. This is primarily due to the representation of protruding balconies in the ALS data, which does not correspond to the simplified facade geometry in the LoD2 model. The LoD2 models are based on EGiB building footprints, with walls created by extrusion, which means that details such as balconies are not represented. Nevertheless, the models and the point cloud show good agreement on building facades.

For the ground surface, the point cloud exhibits considerably higher noise levels than the terrain model. Despite these differences, the datasets are overall consistent, and the LoD2 model serves as a reliable reference for data integration, particularly in facade areas where ALS data are largely missing.

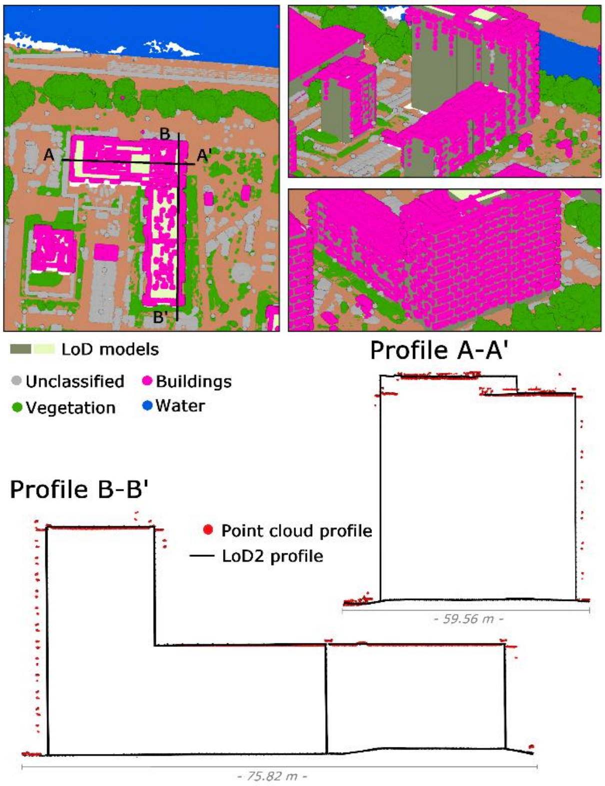

Figure 4. Comparison of the ALS point cloud and the LoD2 model for a representative building and its surroundings. Cross-sections A–A′ and B–B′ are shown below. The point cloud is in red, and the solid black line represents the LoD2 model and DTM surface.

3.2 Linking results

The integration of PSI processing results obtained from the EGMS service was performed in three variants, depending on the reference data used for linking. Example cross-sections of the resulting point clouds for each variant, after applying candidate selection for linking, are presented in Figure 5.

In Variant I, the ALS point cloud was used and filtered to identify suitable candidates for linking PSs. As a result, the modified point cloud includes buildings (excluding walls in shadow relative to the satellite line of sight), ground surface, and filtered stable scatterers from the unclassified category, such as poles and railway traction elements (Figure 5a). In Variant II, a regular grid point cloud was generated based on the LoD2 model and terrain derived from the DTM (Figure 5b). Variant III represents a combined approach, in which buildings from the ALS data were replaced with those from the LoD2 model (Figure 5c).

The comparison of cross-sections indicates that the combined approach preserves complete building geometries while also capturing additional infrastructure elements suitable for PS generation (brown rectangles in Figure 5). However, this approach also results in the absence of certain building elements (pink rectangles) and entire structures for which no LoD2 models are available. An example includes above-ground elements of underground parking facilities (yellow rectangles in Figure 5), which were classified as buildings in the ALS data but replaced by LoD2 models that do not represent such objects.

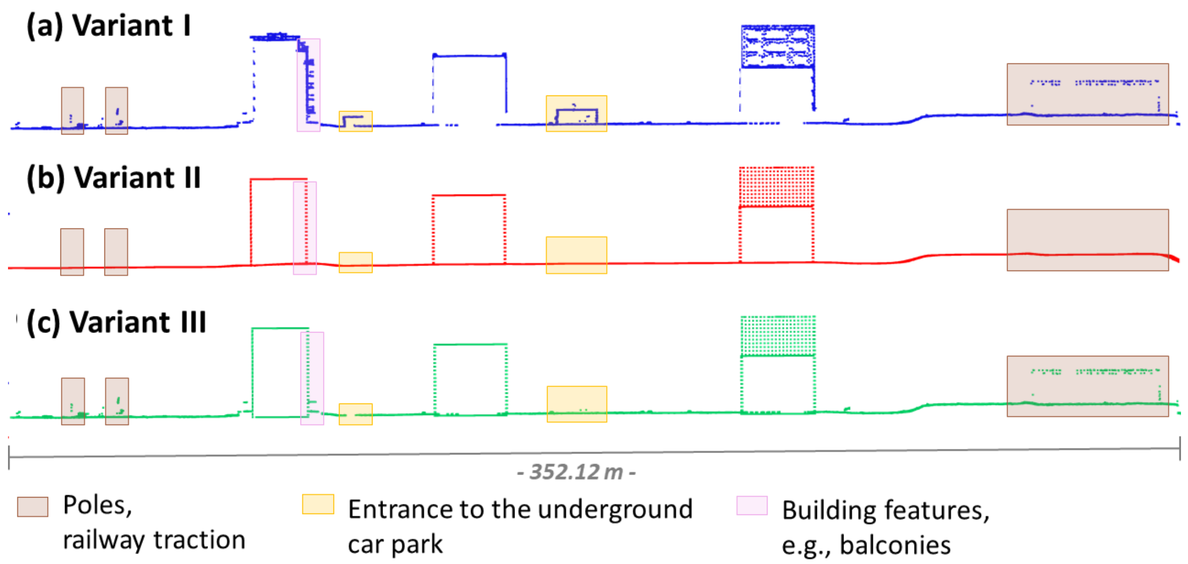

Figure 5. Comparison of filtered point clouds used for PSs linking. Colored rectangles highlight characteristic objects that are either present or absent in individual variants.

Despite the mentioned differences, the results demonstrate that the highest number of links to real-world objects was achieved for the combined Variant III (Figure 6), with 88% of points successfully linked. In comparison, Variants I and II achieved 70.4% and 80.3%, respectively.

For the best-performing variant, the majority of linked points correspond to the Building class (41.4%), which is the primary source of double-bounce reflections and is particularly suitable for stable scatterer generation. A similar pattern is observed in Variant II, which is based on the same building data, whereas Variant I shows significantly fewer links (21.4%), as building points are derived directly from ALS data. The reduced number of links in this case is mainly due to data gaps on building facades.

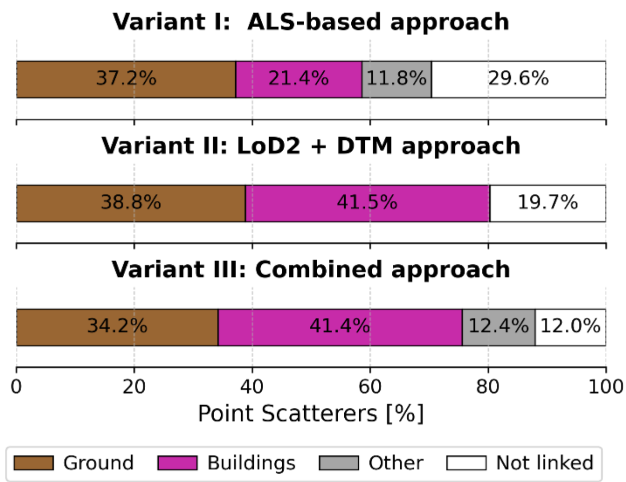

Figure 6. Percentage of linked PSs in different processing variants categorized into point classes according to the ALS data classification, and PSs that could not be linked.

Although LoD2 models do not include detailed building elements such as chimneys or balconies, they outperform raw ALS point clouds in this context. Given the relatively low positional accuracy of initial PS locations (on the order of several meters for Sentinel data), the level of geometric detail in building representation is of secondary importance.

For the second-most-frequent class (Ground), the results remain consistent. The number of links in Variant III is lower than in Variant I, primarily because more points are assigned to Buildings rather than to the Ground. The fewest links are observed for other classes (approximately 12%).

4. Conclusions

The results of this study demonstrate that the proposed methodology for integrating PSI data with ALS-derived datasets to improve the spatial positioning of persistent scatterers can be successfully applied to products provided within the EGMS service. This confirms their potential as a valuable data source for 3D geoportals and urban digital twins, as illustrated in this case study.

The incorporation of terrain and building models, commonly a core component of UDTs, significantly increases the number of successful links between PSs and real-world objects compared to approaches relying solely on ALS data. In particular, the proposed combined approach, integrating LoD2 building models with ALS data, yielded the highest performance, achieving up to 88% of points successfully linked.

The results indicate that the level of detail provided by LoD2 models is sufficient for this purpose. Despite the absence of detailed building features, such as chimneys or balconies, no reduction in accuracy was observed compared to ALS-based approaches. On the contrary, the use of LoD2 models improved data completeness by eliminating gaps, particularly on building facades, thereby enabling more consistent PS linking across entire surfaces.

Future research should assess whether the level of detail provided by LoD2 models remains sufficient when applied to higher-resolution SAR data, such as X-band systems, which offer improved positional accuracy compared to Sentinel-1 C-band data. In this context, it is important to determine whether more detailed building representations are required to fully exploit the increased precision of such datasets. Furthermore, an important direction for further work is the integration of EGMS data with urban digital twins to enable advanced analyses, including predictive modelling and simulation of ground deformation processes. This is particularly relevant in urban environments, where such deformations affect not only buildings but also technical infrastructure, including underground utility networks.

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