

Mapping Uncertainty. Defining Spatial Accuracy of WWI Historical Sources in the Asiago Plateau (NE Italy)

Mappare l'incertezza. Un'analisi della spatial accuracy di fonti storiche della Prima guerra mondiale nell'Altopiano di Asiago

Leonardo Mora

University of Padua

E-mail: leonardo.mora@phd.unipd.it

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record.

Questo articolo è stato accettato per la pubblicazione e ha completato l'intero processo di revisione paritaria, ma non ha ancora attraversato le fasi di preparazione per la stampa, impaginazione, numerazione delle pagine e correzione di bozze, il che potrebbe comportare differenze tra questa versione e la versione definitiva.

Accepted: 2026-10-05 | DOI: 10.36253/bsgi-7670

Please cite this article as:

Mora, L. (2026). Mapping Uncertainty. Defining Spatial Accuracy of WWI Historical Sources in the Asiago Plateau (NE Italy). *Bollettino della Società Geografica Italiana*, Just Accepted.

Mapping Uncertainty. Defining Spatial Accuracy of WWI Historical Sources in the Asiago Plateau (NE Italy)

Mappare l'incertezza. Un'analisi della spatial accuracy di fonti storiche della Prima guerra mondiale nell'Altopiano di Asiago

LEONARDO MORA

University of Padua

E-mail: leonardo.mora@phd.unipd.it

Abstract. During World War I the landscapes of the Venetian Prealps were extensively transformed by defensive lines and field fortifications. Historical sources preserve evidence of these changes and allow past military systems to be reconstructed through Geographic Information Systems (GIS), yet the spatial accuracy of digitized features remains problematic: the same element, derived from different source types, may show discrepancies of tens of metres owing to scale constraints, survey methods lacking topographic precision, or the physical condition of the documents. Systematic approaches for assessing and comparing accuracy across heterogeneous datasets are still limited. This study examines the positional accuracy of WWI military features through a Historical GIS database developed for the Asiago Plateau, a representative sector of the Italian Front, comprising 60,300 features digitized from Austro-Hungarian, British and Italian sources. A qualitative and semi-quantitative analysis evaluates accuracy across five source types and defines a priority scale based on their reliability. Building on these results, the study introduces an Accuracy Level index, a semi-qualitative ordinal scale for estimating the topographic accuracy of digitized military features. The methodology represents a first step towards a replicable framework for evaluating spatial accuracy in Historical GIS databases.

Keywords: World War I, historical GIS, spatial accuracy, historical cartography, aerial photos

Riassunto. Durante la Prima guerra mondiale i paesaggi delle Prealpi Venete furono profondamente trasformati dalla costruzione di linee difensive e fortificazioni campali. Le fonti storiche conservano la memoria di tali trasformazioni e consentono di ricostruire i sistemi militari del passato tramite Sistemi Informativi Geografici (GIS), mentre l'accuratezza spaziale degli elementi digitalizzati rimane problematica: lo stesso elemento, digitalizzato da tipologie di fonti diverse, può presentare discrepanze di alcune decine di metri per limiti di scala, per metodi di rilievo privi di precisione topografica o per lo stato di conservazione dei documenti. Gli approcci sistematici per valutare e confrontare la *spatial accuracy* tra dataset eterogenei risultano ancora limitati. La ricerca analizza l'accuratezza posizionale degli elementi militari della Prima guerra mondiale attraverso un Historical GIS dell'Altopiano di Asiago, settore rappresentativo del fronte italiano, con 60.300 elementi digitalizzati da fonti austro-ungariche, britanniche e italiane. Un'analisi qualitativa e semi-quantitativa valuta l'accuratezza di cinque tipologie di fonti e definisce una scala di priorità fondata sulla loro affidabilità. A partire da questi risultati lo studio introduce un indice di *Accuracy Level*, scala ordinale semi-qualitativa per stimare l'accuratezza topografica degli elementi militari digitalizzati. La metodologia costituisce un primo passo verso un framework replicabile per la valutazione della *spatial accuracy* negli Historical GIS.

Parole chiave: Prima guerra mondiale, historical GIS, spatial accuracy, cartografia storica, foto aeree

1. Introduction

The landscapes of the Venetian Prealps underwent significant transformation during World War I (WWI) through the construction of defensive lines and field fortifications by the opposing armies (Isnenghi, Rochat 2014; Pirina 2020). Digitization of historical geospatial sources through

Geographic Information Systems (GIS), Historical GIS (HGIS) (Knowles, Hillier 2008) and geohistorical approaches (Piovan 2020) offers a primary means of analysing these changes, rendering at different scales the diachronic evolution of military structures and locating trenches and emplacements that have since disappeared. The accuracy of such data nonetheless remains limited: the same feature, digitized from different types of historical source, may vary in position by tens of metres, which complicates precise geospatial location. Such discrepancies derive from scale constraints, from survey methods lacking topographic precision, or from the material condition of the sources, which may be aged, damaged or distorted (Mora et al. 2026).

This research investigates the positional accuracy of military elements detectable from five types of historical source, taking a specific sector of the Venetian Prealps as a first testing area. The sources considered are aerial photos, military cartography, ground photos, panoramic drawings and written documents, the five principal categories from which geospatial features can be derived. Military elements comprise the relatively stable anthropic features of the landscape built or adapted for military purposes during the conflict: defensive lines (trenches, walkways and barbed wire), artillery and machine-gun emplacements, observation posts, shelters, dumps, barracks and military infrastructure. The term military feature designates, in the GIS context, an immobile or semi-mobile military element digitized from a specific type of historical source (Mora et al. 2026).

Georeferencing and digitization of WWI geospatial documentation, and the construction of GIS databases of military features, have been addressed from the perspectives of HGIS, military geography (Bondesan, Ehlen 2022) and conflict archaeology (Pollard, Barton 2013). The literature covers each of the five source categories, with aerial photos and military cartography the most extensively treated (among others, Cowley, Stichelbaut 2012; Hanson, Oltean 2013; Leisz 2013; Magnini et al. 2017; Plini et al. 2017; Gheyle et al. 2018; Stichelbaut, Cowley 2018; Dai Prà, Gabellieri 2020a; Azzalin et al. 2024 for aerial photos; Ballarin et al. 2015; Petrovič et al. 2018; Gobbi et al. 2019; Dai Prà, Gabellieri 2020b; Dai Prà et al. 2022; Magnini et al. 2022; Gašperič 2023; Paradelle et al. 2023; Lo Destro, Ciola 2025; Mora et al. 2025 and Petriccione et al. 2025 for military cartography), while ground photos, panoramic drawings and written documents have received markedly less attention (e.g. Barton 2005; Monti et al. 2016; Nocerino et al. 2018; Dai Prà, Gabellieri 2020c; Plini et al. 2007, 2010). Methods for assessing the spatial accuracy of features digitized from heterogeneous documentation have attracted limited attention throughout.

Spatial (or positional) accuracy can be defined as the degree of closeness between the recorded position of a feature (such as the military features of this research) and its true position in geographic space, where the true value is a reference value that is accepted as true (ISO 2013). In a GIS context the “true position” of a feature can be estimated using geospatial data with the highest possible spatial accuracy, such as orthophotos or LiDAR data taken in a year that is representative of the aims of the research (Ariza-López et al. 2021).

Jenny and Hurni (2011) first established the relevance of positional accuracy for historical maps, and cartometric analysis has since been applied to map series from the early modern period to the twentieth century (Bayer et al. 2010; Jongepier et al. 2016; Narin, Gullu 2022; Marelić 2025; Vaienti et al. 2025; Vantas, Mirkopoulou 2025). Comparable work exists for aerial photography (Walstra et al. 2011; Zhang et al. 2022) and, through monoplottting (a method that enables the creation of maps and precise measurements using individual photographs taken with standard analogue or digital cameras), for terrestrial photographs (Bayr 2021). Within WWI studies, spatial accuracy has been addressed almost exclusively for cartography and aerial imagery, by Sahin et al. (2025) for the Historical Peninsula of Istanbul and by Bozzano et al. (2024) for the Italian Front, while ground photos, panoramic drawings and written documents remain untreated. The need to incorporate accuracy assessment into HGIS database construction has been argued by Tucci and Giordano (2011) and Wong et al. (2012) and applied by Carrion et al. (2016) to medieval fiscal data from Southern Italy.

These contributions address single source types and depend closely on their documentary and geographical contexts. What appears to be missing is a method for estimating the positional accuracy

of WWI military features digitized from different categories of historical source, capable of delivering a rapid semi-qualitative assessment without recourse to detailed topographic or cartometric analysis, and able to rank source types by expected reliability while identifying the factors that condition accuracy.

This study pursues that aim through an HGIS database built for the Asiago Plateau, a sector of the Italian Front in the Venetian Prealps that saw major military operations (Corà, Passarin 2014) and is extensively represented in WWI documentation, which makes it suitable for a local-scale test intended for extension to other contexts and larger regions. The database contains 60,300 features digitized from the five source types, produced by the Austro-Hungarian, British and Italian armies.

The objectives of this study are:

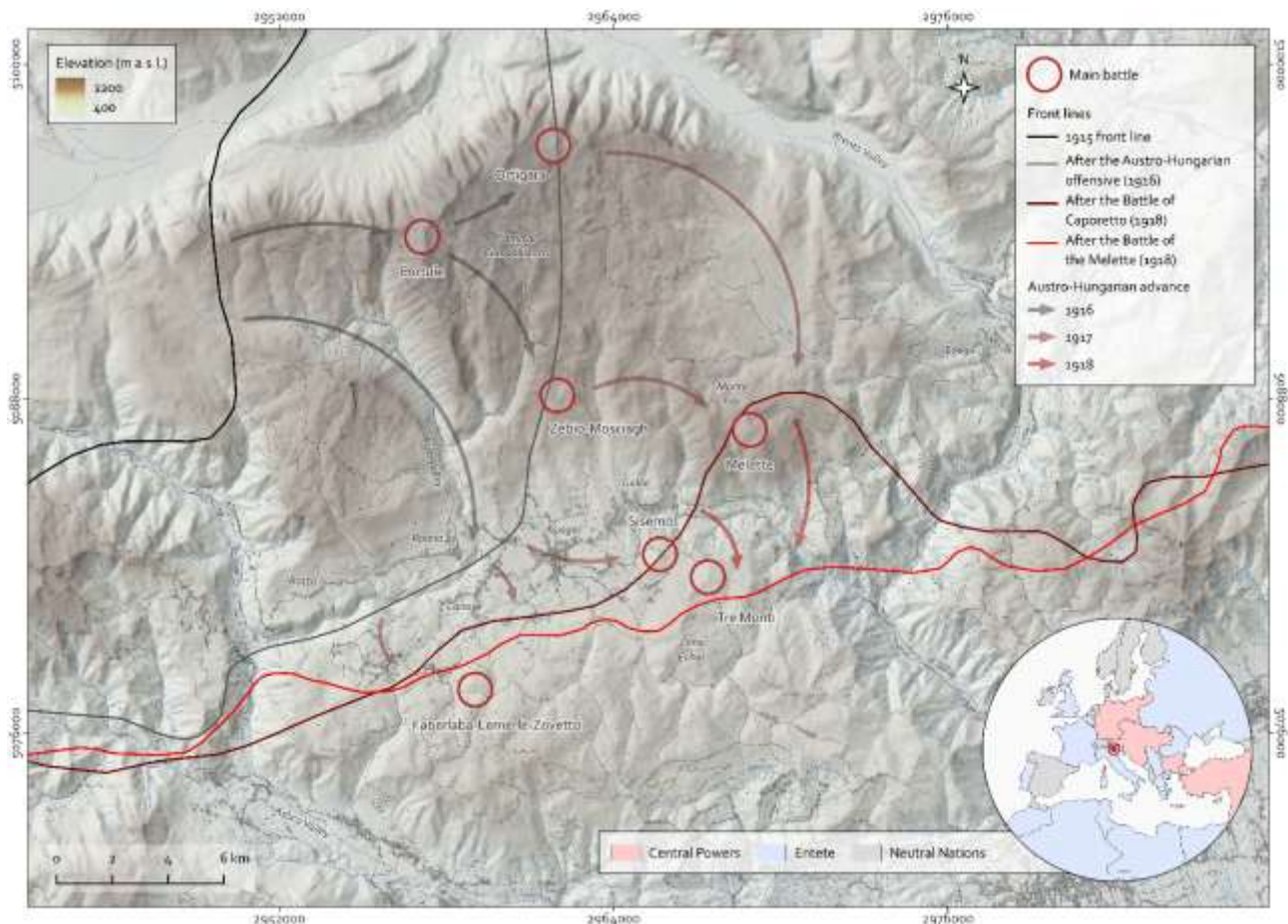
- To perform a qualitative analysis of the five types of sources to examine their main characteristics and to identify the factors that influence the spatial accuracy of GIS features digitized from them. This analysis is based on the military features database developed for the Asiago Plateau, which serves as the study area.
- To conduct a semi-quantitative analysis of the average positional accuracy of the military features in the database, grouping them by source type in order to define a priority scale for historical sources based on their reliability.
- To introduce an Accuracy Level (AL) index for digitized WWI military features: a scale of ordinal values from ≤ 0 to ≥ 10 designed to assess the topographic accuracy of immobile and semi-mobile military features.

2. Historical Context

The study area covers approximately 1,000 km² of the Asiago Plateau, in the province of Vicenza (Veneto, north-eastern Italy), between the Brenta and Astico valleys, comprising the *Sette Comuni* (seven municipalities) of Asiago, Enego, Foza, Gallio, Lusiana Conco, Roana and Rotzo (Fig. 1).

Marginal to the Italian Front at the outbreak of hostilities, the plateau became central during the Austro-Hungarian Spring Offensive of May and June 1916, known in Italy as the *Strafexpedition*, which broke through the Italian lines and shifted the front southward after heavy losses on both sides (Acerbi 2008; Leoni 2019). From late June 1916 Austro-Hungarian forces consolidated an advanced winter line, the *Winterstellung*, which held until November 1917 despite Italian counteroffensives, among them the costly and unsuccessful Battle of Ortigara of June 1917 (Pieropan 2011). The retreat that followed Caporetto in October 1917 displaced the front across the plateau once more, and fighting continued through 1918, including the Battles of the Tre Monti and the Austro-Hungarian offensive of 15 June, until the Italian victory at Vittorio Veneto in October 1918 closed operations in this sector (Vollmann, Brazzale 2012).

Three years of mobile and then static warfare across the same terrain produced a dense stratification of defensive works, which makes the plateau a suitable testing ground for the analysis of positional accuracy across heterogeneous documentation.



Rome, which preserves cartographic and technical documentation produced by Italian military engineering units, 60 Italian tactical maps and 98 Italian aerial photographs were selected. From the Historical Office Archive of the Italian Air Force (*Archivio dell'Ufficio Storico dell'Aeronautica Militare*, AUSAM), 30 Italian aerial photographs were selected. From the *Museo Storico Italiano della Guerra* (MITAG) in Rovereto, 62 aerial photographs taken by the Royal Air Force in Italy were selected.

Written documents and ground photographs from the same archives were collected to support and validate the interpretation of maps and aerial imagery, adding information on defensive lines, military structures and landscape derived from reports produced between 1915 and 1918.

3.2 Methodologies

The methodological guidelines developed here rest on a database of 60,300 vector military features for the Asiago Plateau, composed of points, lines and polygons corresponding to military elements and landscape disturbances. Military elements fall into five macro-categories: armaments, comprising artillery and machine-gun emplacements; logistics and control, comprising water supplies, signals, barracks, shelters, camps, telephone and telegraph lines, warehouses, observation posts and balloons, medical posts and radio stations; supplies, comprising cables, pipes, dumps and ammunition depots; trenches, including barbed wire and walkways; and communication routes, comprising roads, mule tracks, paths, cableways and other infrastructure built or used for purposes related to the conflict (Mora et al. 2025). Landscape disturbances comprise both elements created by explosions or war damage (such as bomb craters and all the effects on the soil of explosive munitions) and elements deliberately created and constructed by humans for military purposes such as dugouts (Hupy, Koehler 2012). The database includes 45,940 artillery craters, 5,695 emplacements, 4,198 km of trenches and walkways, 2,969 km of barbed wire and 857 km of communication routes. The database processing and analysis operations can be divided into three stages, which are described below.

3.2.1 Acquisition and Georeferencing

Following an HGIS methodology (Knowles, Hillier 2008), documentation was acquired in digital form where available and otherwise scanned at 600 dpi on a flatbed scanner, with post-processing where required for mosaicking of incomplete images, colour correction and removal of reflections and noise. The georeferencing process is only possible for graphical representations of the terrain viewed from directly above (or, if oblique, where the angle is not particularly steep): it has therefore not been carried out on ground photographs, panoramic drawings (non-nadir views) and written documents (not graphical representations)

Maps and aerial photographs were georeferenced in QGIS 3.40 using RDN2008 / Zone 12 (E-N), hereafter FUSO12, as the coordinate reference system (CRS; EPSG 7795). This choice addresses two key requirements for geospatial analyses in the Veneto region. First, it relies on a projected rather than a geographic coordinate reference system, allowing accurate distance and area measurements, which are essential for quantifying spatial discrepancies. Second, it accounts for the region's particular location with respect to the reference meridians of the ROMA40 coordinate system (EPSG 3003 and 3004). ROMA40 is based on the Gauss conformal projection, divided into 6° longitudinal zones. Italy is mainly covered by two zones (32 and 33), while the Veneto region lies across the 12° meridian, which marks the boundary between zones 32 and 33. This position introduces minor distortions near the zone boundary and creates discontinuities between adjacent zones. Although the FUSO12 projection spans a wider longitudinal extent and produces larger distortions towards its outer margins, Veneto is located close to its central meridian. As a result, FUSO12 provides the most suitable projected reference system for analyses covering the entire region from east to west, ensuring spatial continuity while maintaining acceptable geometric accuracy (Achilli et al. 2013).

A Thin Plate Spline transformation was applied. Historical maps and aerial photographs carry local deformations of heterogeneous origin: paper shrinkage and folding, non-uniform relief displacement and, for maps, the residual effects of the original geodetic framework (Mora et al. 2026). Global

transformations, whether polynomial or projective, distribute residual error across the whole image and preserve overall geometry at the cost of local fit. Since the objective of georeferencing in this research is the accurate placement of the digitized military features rather than the reconstruction of the original cartographic geometry, a local transformation was preferred. Thin Plate Spline constrains the image to the Ground Control Points (GCPs) exactly, which improves fit in the neighbourhood of each control point while leaving deformation unconstrained between sparsely controlled points. Nearest neighbour resampling was used to preserve original pixel values and avoid interpolation artefacts during photointerpretation.

The number of GCPs depends on document type, scale and physical size. Empirical observation during georeferencing of the reference cartographic corpus led to a minimum of 20 GCPs and a mean density of one point per 2.5 ha for aerial photographs, and a minimum of 40 GCPs and a mean density of one point per 2 km² for military cartography. On average, the georeferencing process required approximately 5-10 minutes for every GCP placed.

Because Thin Plate Spline interpolates the control points exactly, residuals computed at the GCPs approach zero and provide no measure of the accuracy of the transformation. Accuracy was therefore assessed through independent check points, identifiable in both the historical document and the reference orthophoto and excluded from the set used for the transformation.

3.2.2 Digitization and Attribute Organization

Military elements and landscape disturbances visible in the historical documents were identified through photointerpretation and converted into vector features by manual digitization, following the approach described in Mora et al. (2026). The attribute table adapts the guidelines proposed by the same authors for historical cartography, omitting fields specific to cartographic documentation, and records the type of source from which the feature was vectorized, its date, the producing organization and its nationality, the type and macro-category of military element represented, any subcategory, and an alphanumeric identification code.

Ground photographs, panoramic drawings and written documents cannot be georeferenced directly and were archived with the same metadata without GIS processing. Features were digitized from them by interpreting the document against the present-day landscape. For ground photographs and panoramic drawings this interpretation was supported by viewshed analysis: a viewshed computed on the 2022 Digital Terrain Model (DTM) from the estimated camera or observation station delimits the terrain visible from that point, which constrains the area within which a feature identified in the image can be placed and excludes candidate locations hidden by relief. The procedure yields no position by itself, but it reduces the set of admissible positions, which matters for sources whose principal weakness is the ambiguity of the depicted area (Vergara et al. 2018).

The digitization process is generally faster than the georeferencing phase, and it required around 1 minute for every point feature and 2-5 minutes for every linear and polygonal feature digitized.

3.2.3 Reference Data and Computation of the Accuracy Error

Features were grouped by source type and overlaid on contemporary geospatial datasets for the Asiago Plateau: orthophotos at 15 cm resolution and a LiDAR-derived DTM at 1 m resolution for 2022, supplied by Etra S.p.A. Società Benefit. Comparison was restricted to areas where elements identified in the historical sources remain detectable, since it is not possible where subsequent landscape transformation has erased them. This restriction introduces a limitation that must be acknowledged: the areas available for comparison coincide largely with those where WWI heritage has been preserved, whether intentionally, through musealization of defensive lines or restoration of significant landmarks, or unintentionally, as with trenches surviving in pasture or in areas where warscapes coexist with post-war landscapes. Preservation of this kind does not appear to have displaced military elements within the preserved areas, but it does condition the composition of the sample, which is drawn from sectors of comparatively low post-war disturbance.

The distance between the true position of a military element and its position as derived from a historical source is defined in this research as the Accuracy Error (AE) (Fig. 2). For linear and polygonal features, measurement points were distributed along each feature at 1 m spacing, and the AE was computed as the mean distance between points along the digitized feature and the corresponding points along the reference feature. AE was computed for approximately 10,000 features derived from the five types of sources ($\approx 2,000$ per source type). For each source type, the mean AE and the range of values were determined.

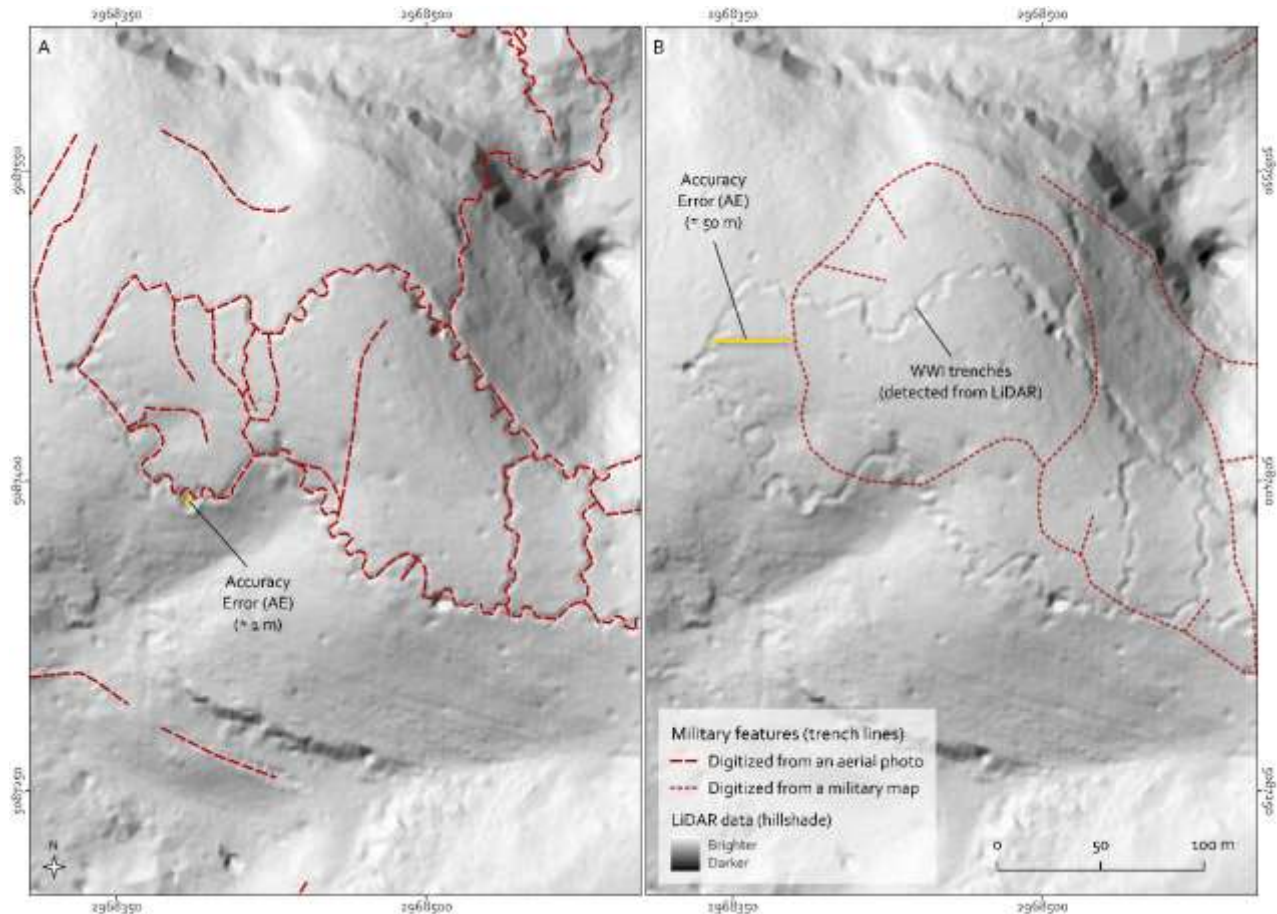


Figure 2. Trench lines digitized from two sources of different accuracy: (A) Italian aerial photograph, 1918 (AUSAM, album 10-11, photo 139_5129, by permission of the Ufficio Storico dell’Aeronautica Militare); (B) Austro-Hungarian map, 1917, 1:25,000 (ASFI, Miscellaneous Military Maps (MMM) archival collection, R 5, 8). AE in yellow; true position from 2022 LiDAR (Etra S.p.A. Società Benefit 2022b).

Interpretation enters this workflow at three successive stages, and the resulting uncertainty is not captured by the AE. The first is the production of the source itself, where the surveyor, cartographer or draughtsman selected, generalized and plotted the elements represented, in cartography and panoramic drawings alike. The second is georeferencing, where the operator chooses the number, position and distribution of the GCPs, and where different choices applied to the same document yield measurably different results. The third is photointerpretation and digitization, where the operator identifies an element, assigns it a category and traces its geometry, decisions that vary with familiarity with the documentary and territorial context.

These three levels of interpretation are cumulative and hard to separate from the intrinsic properties of the source. The second and third belong to the workflow rather than to the document, and they are therefore treated here as limitations of the method and excluded from the factors used to construct the Accuracy Level index, which estimates the expected accuracy of a feature from the characteristics of the source from which it derives.

4. Qualitative Analysis of the Sources

4.1 Aerial Photos

Aerial photos proved the most spatially accurate source for digitizing WWI military features. Their strength lies in high positional precision and in the clarity with which they render landscape elements (Gheyle et al. 2018); under optimal conditions, discrepancies with present-day orthophotos fall below one metre. Their limits lie in discontinuous spatial coverage and in the interpretative effort required where features are faint or partially obscured. Where aerial photos are unavailable or unsuitable because of poor preservation, low readability or missing data, other sources should be preferred.

Positional accuracy is controlled by four groups of factors. The first is image geometry: aerial photos are central projections affected by radial distortion increasing with distance from the nadir, so that in mountainous terrain relief displacement produces systematic shifts related to elevation differences. Inclination of the optical axis compounds this effect, since many WWI photos were taken under oblique conditions at low altitude, producing variable scale within the frame. Camera characteristics (focal length, lens quality, negative size) govern both distortion and ground resolution, while flight altitude interacts with all of these in a non-linear way: lower altitudes increase resolution and amplify relief displacement and perspective effects, and the reverse holds at higher altitudes. Across the corpus analysed here, lower flights consistently yielded larger scale and greater detail.

The second group concerns the material condition of the document, where dirt, moisture, tears, scratches, burns, fingerprints or missing portions may displace features by several tens of metres. The third concerns georeferencing, where the number, distribution and quality of GCPs determine whether a high-quality image achieves sub-metre accuracy or accumulates errors of comparable magnitude. The fourth concerns comparability with present-day data, which can be divided into three cases: the feature remains visible, and direct comparison confirms maximum reliability; the feature survives as residual traces in marginal areas such as pastures or uncultivated land, allowing partial validation; the feature has disappeared, and geometric reliability can be assessed only through stable landscape elements such as historic buildings, persistent infrastructure or terrain morphology, with correspondingly lower reliability.

An example of comparison between a good-quality aerial photo taken in 1918 and an orthophoto taken in 2022 can be seen in Figure 3.

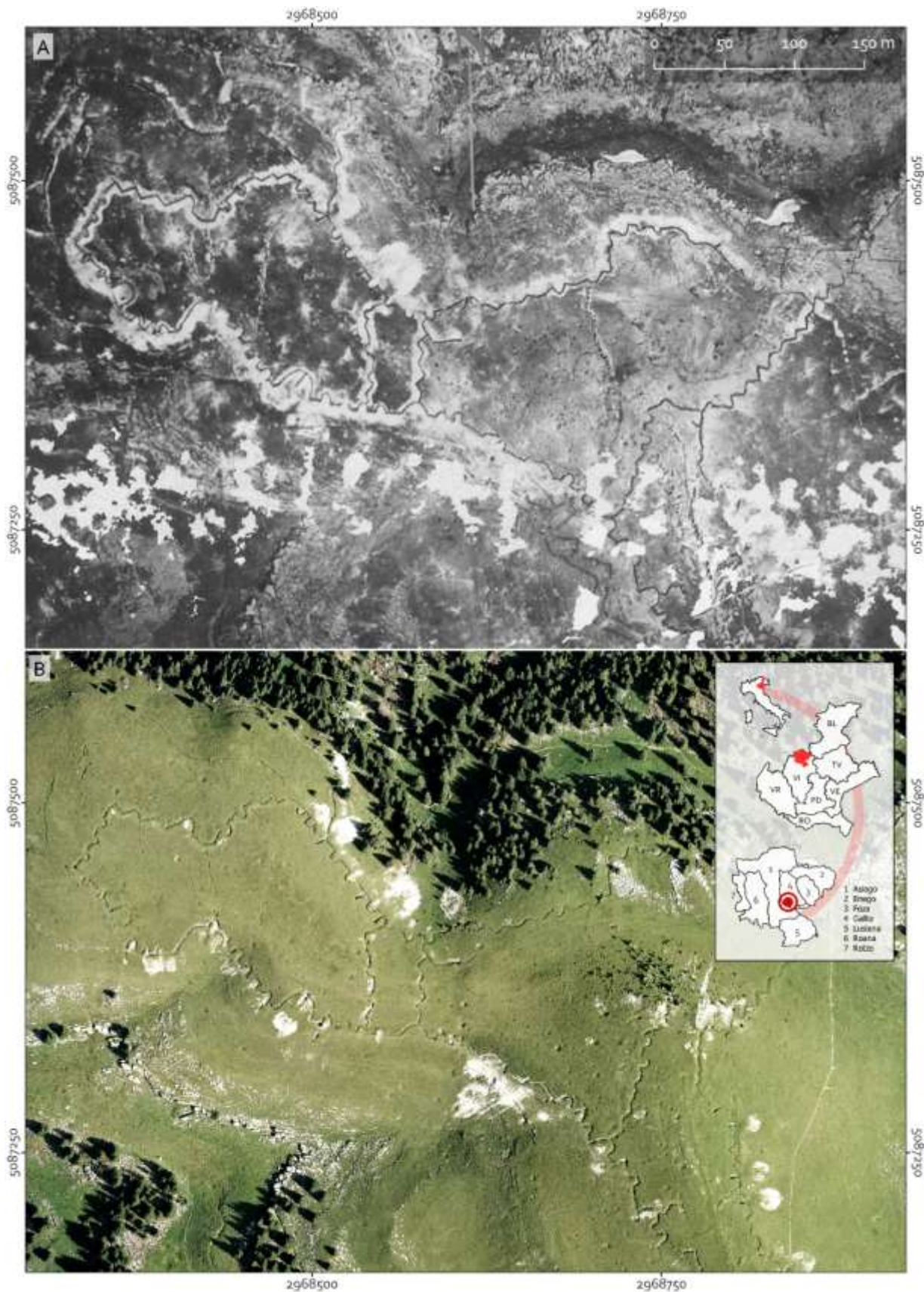


Figure 3. (A) Italian aerial photograph, 1918 (AUSAM, album 10-11, photo 139_5129, by permission of the Ufficio Storico dell'Aeronautica Militare); (B) 2022 Etra's orthophoto (Etra S.p.A. Società benefit 2022a) of the same area, trenches still visible.

4.2 Military Cartography

Military cartography is the most reliable source for large areas and for sectors not covered by aerial photography, typically marginal or rear zones. Scale governs its use: maps at 1:25,000 or larger support detailed mapping, while maps below 1:100,000 serve as primary source only for extensive study areas and at lower accuracy (Dai Prà et al. 2022). Legends often allow additional attributes to be attached to digitized features, describing the nature of the corresponding element (75 mm cannon battery, carriage road, traversed trench), its status (active, abandoned, under construction) or its hierarchical position (first-line trench, battalion command post, main road). Dai Prà and Gabellieri (2020b) classified WWI military cartography into five broad types: (i) tactical maps, (ii) panoramas and basemaps, (iii) engineering maps, (iv) maps for use by allies, and (v) espionage maps. This research used the two that permit digitization of military elements: tactical maps, produced daily to record the situation of troops, artillery and defensive works, and engineering maps, which document the road network, infrastructure and construction status of defensive lines.

The same element digitized from maps of different origin, date and scale generates features that diverge considerably (Figs 4 and 5). Scale is the dominant factor, with positional accuracy decreasing progressively as scale decreases. Date of production and material quality act as they do for aerial photos, the former as a proxy for representativeness of the final wartime configuration, the latter through preservation state, graphic or scale errors, mismatches between joined sheets and errors introduced during digital processing. The nationality of the producer matters because Italian, Austro-Hungarian and British cartographic traditions applied distinct survey methods, standards and levels of precision.

Three further factors are specific to cartography. Map production is a multi-step workflow of survey, reconnaissance, interpretation, drafting and reproduction (Chasseaud 2013), each stage introducing error, particularly in rapidly updated tactical maps compiled from unverified information. Cartographic generalization simplifies, displaces or exaggerates elements to preserve readability at a given scale, so that a plotted position may reflect a representational choice rather than a location, and digitization converts such displacements into measurable positional error. Geodetic reference systems and projections differ by army, and their transformation into a modern CRS introduces systematic errors of several metres or more, compounded by georeferencing, where flexible methods such as Thin Plate Spline may generate local deformations in areas of sparse or uneven GCP coverage.

Historical cartography also reflects graphic experimentation and authorial interpretation, each map being shaped by its author, commissioning authority, purpose and context (Azzari 2010). These properties do not affect AE directly, yet they supply interpretative clues for evaluating geospatial reliability when a database of military features is assembled.

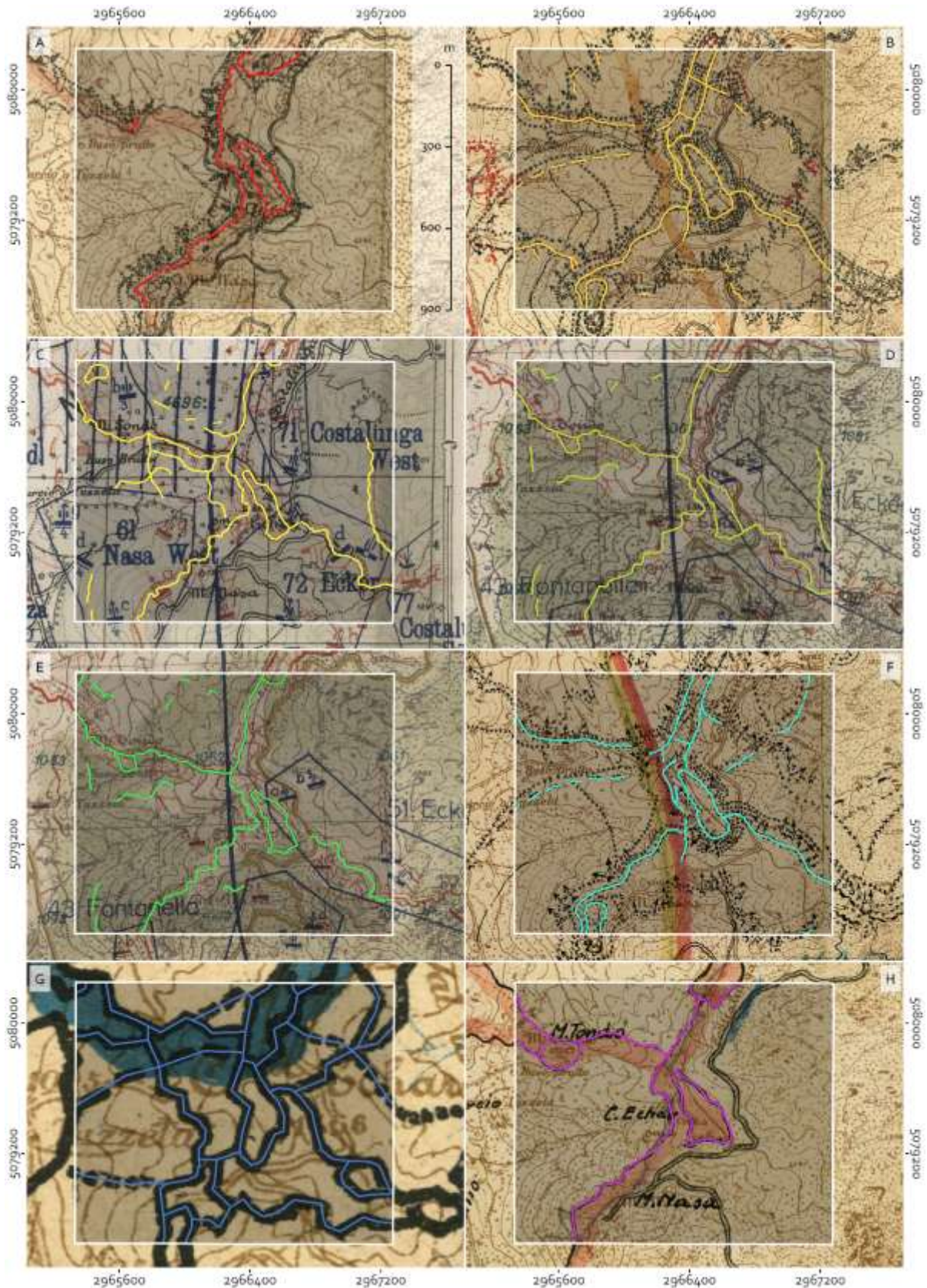


Figure 4. Example of linear military features (trench lines) superimposed on their source map: (A) Italian military map, scale 1:25,000, 1916 (ISCAG, WWI archival collection, B4, F4). (B) Italian military map, scale 1:25,000, 1918 (ISCAG, WWI, B742, F1). (C) Austro-Hungarian tactical map, scale 1:25,000, 1918 (ASFI, MMM, R 4, 208). (D) Austro-Hungarian tactical map, scale 1:25,000, 1918 (ASFI, MMM, R4, 218). (E) Austro-Hungarian tactical map, scale 1:25,000, 1918 (ASFI, MMM, S199, 14). (F) Italian military map, scale

1:25,000, 1918 (ISCAG, WWI, B15, F2). (G) Italian tactical map, scale 1:100,000, 1918 (ISCAG, WWI, B39, F6). (H) Italian tactical map, scale 1:50,000, 1917 (ISCAG, WWI, B15, F2). Source: Author's elaboration.

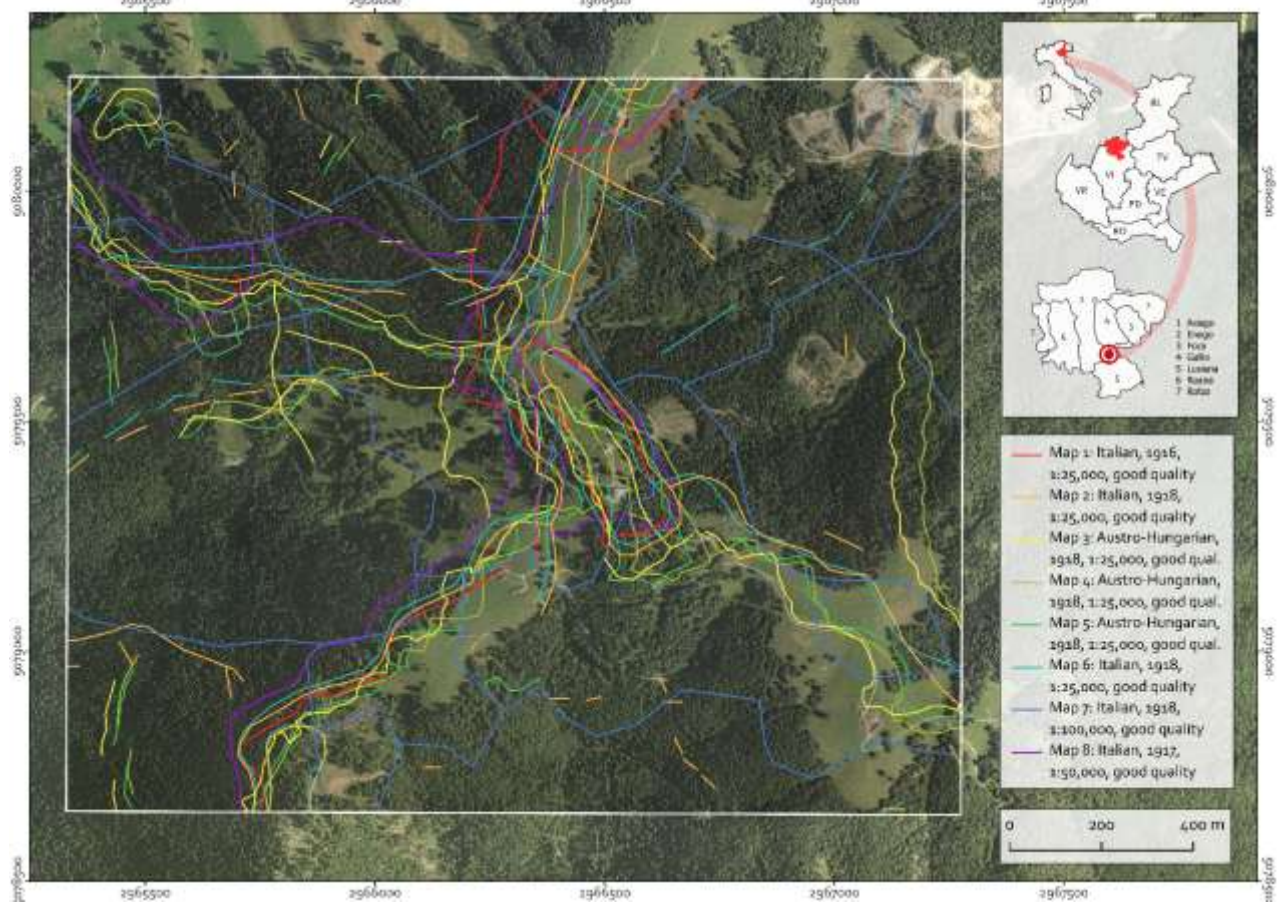


Figure 5. Overlap of the linear military features visible in Figure 4, digitized from eight different cartographic sources of varying origin, date and scale, but depicting the same location (Cima Echar, Asiago Plateau). Basemap: Etra's 2022 orthophoto (Etra S.p.A. Società benefit, 2022a). Source: Author's elaboration.

4.3 Ground Photos

Ground photos are the most abundant category of WWI visual documentation to have survived (Tomassini 2013). This research considers horizontal or oblique photographs taken from the ground that provide a sufficiently wide view of the war landscape, permit the geographical location of the site to be established and allow the military elements present to be identified; only photographs meeting these three conditions support systematic digitization.

They convey information that aerial photos and medium- or small-scale cartography cannot: construction materials of trenches and fortifications, presence of supplies or ammunition, number and characteristics of troops along a defensive line, elements concealed inside buildings or underground. Comparison with present-day imagery through repeat photography (rephotography) allows landscape change to be measured and supports the conservation of architectural and archaeological heritage (Schaffland, Heidemann 2022).

Their main limits are geometric. Ground photos are not vertical images and cannot be georeferenced directly in GIS, which introduces perspective distortion and restricts the observer's field of view, so that complementary viewshed analysis is generally required. The portion of landscape captured by a single frame is often too narrow to situate the depicted element within a broader territorial framework. Monoplotting offers a partial solution by projecting terrestrial photographs onto a DTM, and the accuracy of the resulting data has been assessed in landscape-change research, with mean point displacements of the order of 1.5 m under favourable conditions (Bayr 2021). Its application to WWI corpora, however, where camera stations are unknown and the terrain has been reshaped by the conflict itself, remains to be tested and falls outside the scope of this study. In fact, historical ground

photos present a level of interpretative difficulty similar to that of aerial photos, due to factors such as poor image quality or possible damage to the physical medium. This adds a further layer of limitations even when using the monoplotted technique, which has been tested primarily on digital and colour images.

Overall spatial accuracy therefore remains lower than that of aerial photos and historical cartography.

4.4 Panoramic Drawings

Panoramic drawings are a rarer source, generally available for mountainous areas or regions of complex geomorphology (Fig. 6). Military elements appear in bright colours, typically red for enemy positions, over a black-and-white base drawing, reproducing the symbology of tactical cartography. Unlike ground photos they often cover extensive areas, at times affording a 360° view, and they reproduce the perspective from known observation points, approximating what an observer would have seen when the document was produced (Barton 2005). This makes them valuable for reconstructing the areas under observation during a battle and for landscape studies addressing the historical dimension of warsapes. The use of panoramic drawings proves particularly effective in historical analyses when combined with viewshed analysis of the corresponding areas (Fig. 7): once the vantage point and line of sight have been identified, this enables the elements of the drawing to be linked more precisely to their corresponding geospatial features.

The principal limitation of panoramic drawings is shared with ground photos, since the non-nadir perspective introduces errors related to distortion, shadows and areas out of view. A second limitation derives from the interpretative nature of the document, because the elements shown result from human interpretation and may occupy positions within the drawn space that do not correspond to their location on the ground. AE is consequently larger than for ground photos, where the position of elements corresponds more closely to reality despite oblique viewing.

Their advantage lies in representing a three-dimensional landscape already interpreted through a symbology shared with cartography, which suits them to analysing the altimetric dimension of wartime landscapes, since elevation differences, slopes and exposures are frequently legible. Indication of major peaks and landmarks allows the view to be located within its geographical context with reasonable reliability, although precise georeferencing remains impossible.

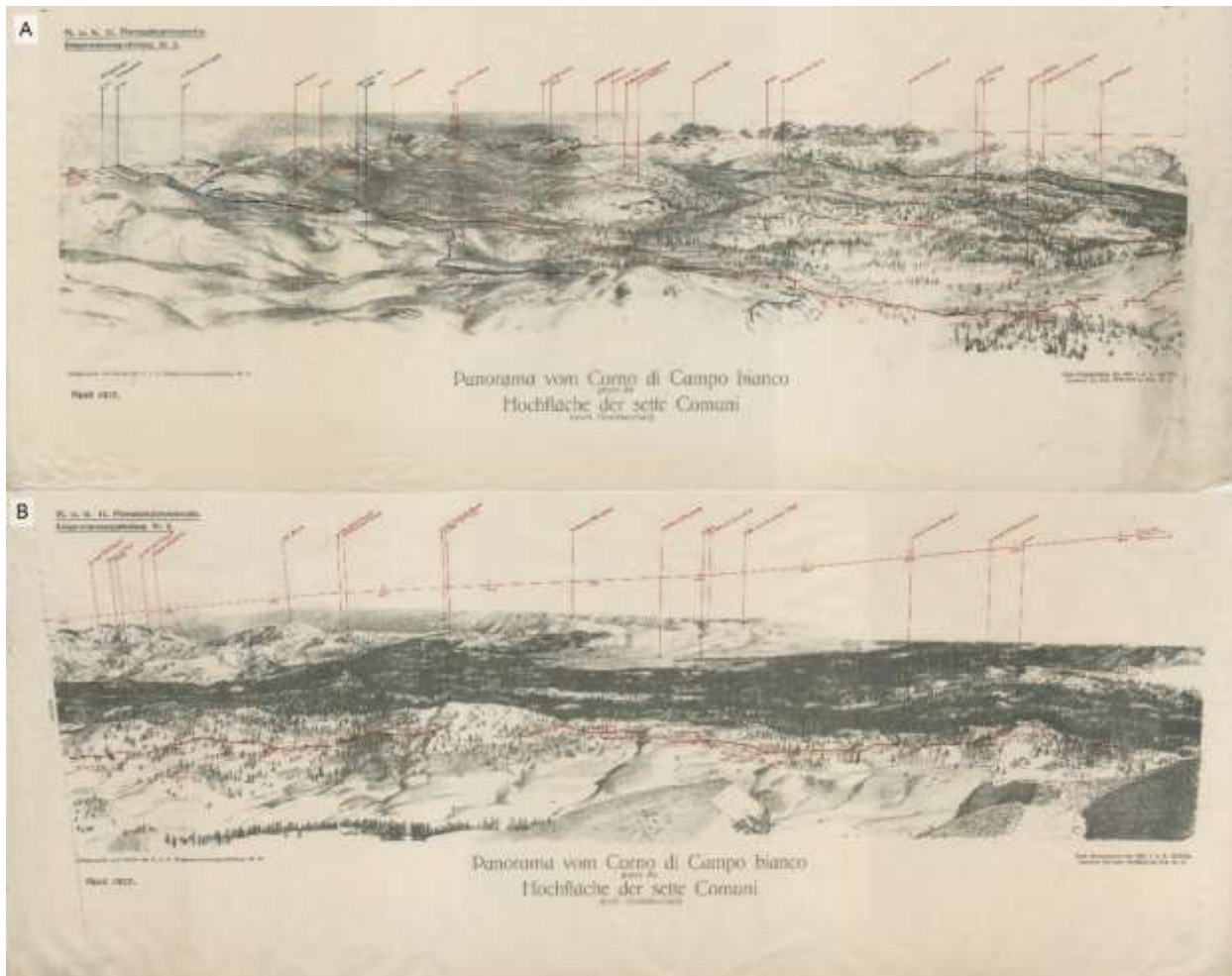


Figure 6. Example of a panoramic drawing, produced in April 1917 by the Austro-Hungarian Army Command Surveying Department (*k.u.k. Armeekommando Kriegsvermessungsabteilung*) (ASFI, MMM archival collection, R 1, 332): view north-east (A) and south-east (B) from Corno di Campobianco.

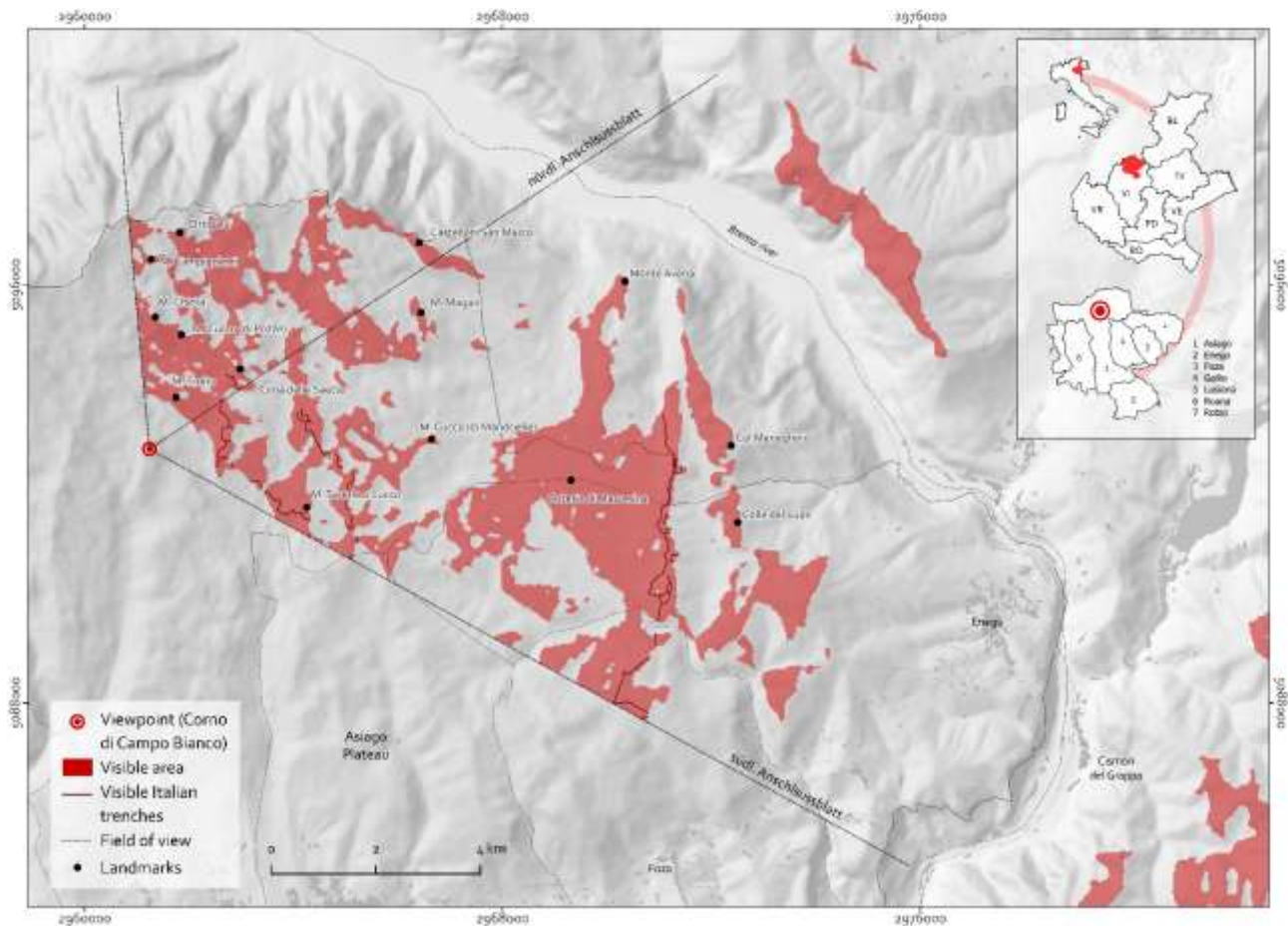


Figure 7. GIS processing of the drawing in Figure 6: areas and trenches visible in the drawing, with the peaks and landmarks it marks. Basemap: Etra 2022 LiDAR (Etra S.p.A. Società Benefit 2022b).

4.5 Written Documents

Where visual sources are unavailable, written documents supply usable spatial information. The term covers a broad corpus of military, legal, administrative and private materials whose common feature is that they describe or refer to one or more military elements in relation to their territorial context: military reports detailing the arrangement of defensive lines, often through local toponyms, and diaries or letters mentioning the position of a trench or emplacement, whether as their subject or incidentally.

The level of detail varies with the nature of the document, its author and its communicative purpose, and positional accuracy varies accordingly, remaining low overall. Textual description cannot reach the precision of visual sources, where the relation between an element and its geospatial context is deducible from the image; geolocation from text requires interpretation by the reader and yields poor results when performed by users unfamiliar with the spatial context. Only certain document types describe the landscape in terms detailed enough to narrow a location even to a macro-area such as a battlefield or a valley, and geolocation is frequently impossible.

5. Semi-Quantitative Analysis and Priority Scale of Sources

5.1 Semi-Quantitative Analysis

Comparison of the database against the 2022 orthophoto and LiDAR datasets allowed the mean AE and its range to be determined for each source type (Tab. 1). Values were computed on the approximately 10,000 features described in the methodology section and should be read as case-specific outcomes, reflecting the combined effect of the factors previously discussed rather than intrinsic properties of each source category.

Aerial photos yield a mean AE of ≈ 2 m. Documents in optimal condition fall to ≈ 0.5 m, while earlier photographs of comparable quality rise to ≈ 7 m.

Military cartography yields a mean AE of ≈ 15 m, with scale accounting for most of the dispersion: maps larger than 1:25,000 remain below ≈ 25 m; maps between 1:25,000 and 1:50,000 fall between ≈ 25 and ≈ 50 m; maps between 1:50,000 and 1:100,000 between ≈ 50 and ≈ 150 m; maps smaller than 1:100,000 between ≈ 150 and ≈ 300 m.

Ground photos yield a mean AE of ≈ 100 m. Well-preserved photographs from the final year of the war average ≈ 35 m, slightly damaged images rise to $\approx 150 - \approx 300$ m, and severely damaged images to $\approx 500 - \approx 900$ m. Photographs too deteriorated to permit reliable interpretation yield no geolocation. As for the other visual sources, images predating 1918 show lower accuracy.

Panoramic drawings yield a mean AE of ≈ 250 m, ranging from $\approx 50 - \approx 300$ m for well-preserved documents of 1918 to ≈ 600 m - ≈ 1 km for older or heavily damaged documents such as those of 1916.

Written documents yield a mean AE of ≈ 450 m. Sources containing precise topographic description, such as reconnaissance and aerial reports, engineering reports, or brigade and regimental war diaries, average ≈ 150 m within a range of $\approx 100 - \approx 300$ m. AE rises as spatial references become sparser, until geolocation becomes impossible.

Table 1. Average AEs by document type and their ranges. Averages and ranges are shown for each source type under optimal conditions (i.e. documents in excellent condition, updated with detailed wartime information and comparable with their true position in the present), under adverse conditions (i.e. damaged documents, with a low level of detail, dating from the start of WWI, difficult to read and no longer comparable with their true position) and for all documents taken into consideration (Average AE; Overall range).

Type of source	Average AE			AE range		
	Optimal conditions	Adverse conditions	Overall	Optimal conditions	Adverse conditions	Overall range
Aerial photos	≈ 0.5 m	≈ 7 m	≈ 2 m	$\approx 0.2 - \approx 2$ m	$\approx 5 - \approx 10$ m	$\approx 0.2 - \approx 10$ m
Military cartography	≈ 2 m	≈ 100 m	≈ 15 m	$\approx 1 - \approx 25$ m	$\approx 150 - \approx 300$ m	$\approx 1 - \approx 300$ m
Ground photos	≈ 35 m	≈ 600 m	≈ 100 m	$\approx 20 - \approx 50$ m	$\approx 500 - \approx 900$ m	$\approx 25 - \approx 900$ m
Panoramic drawings	≈ 80 m	≈ 900 m	≈ 250 m	$\approx 50 - \approx 300$ m	≈ 600 m - ≈ 1 km	≈ 50 m - ≈ 1 km
Written documents	≈ 150 m	Geolocation impossible	≈ 450 m	$\approx 100 - \approx 300$ m	Geolocation impossible	≥ 100 m

Source: Author's elaboration.

5.2 Priority Scale of Sources

The values in Table 1 support a ranking of source types by expected accuracy. Aerial photos rank first. Military cartography follows, its position governed by scale and state of preservation. Ground photos rank third: although they cannot be georeferenced directly, they permit direct identification of military elements and an approximate reconstruction of their position, with distortion arising from perspective, shadows and obstructions. Panoramic drawings follow, since the elements they represent result from interpretation by cartographers, photointerpreters or scouts working from aerial imagery or intelligence, and this additional interpretative step lowers positional accuracy below that of ground photos despite their visual similarity. Written documents rank last, carrying no direct geospatial information and yielding only spatially interpretable references.

The ranking assumes comparable preservation, level of detail and date across source types, a condition rarely met. Features digitized from a distorted or poorly preserved aerial photograph may prove less accurate than those derived from a well-preserved large-scale map. To account for this variability, an Accuracy Level (AL) scale was introduced. This scale is designed to estimate the expected accuracy of individual military features by considering not only the type of source, but also the main factors that may influence the overall quality of the data.

6. Accuracy Level (AL) Scale

The Accuracy Level of a digitized WWI military feature can be defined as a semi-qualitative index on an ordinal scale ranging from ≤ 0 to ≥ 10 , aimed at estimating the accuracy of a military feature with respect to the corresponding military element it depicts on a battlefield. Accuracy in this context is defined by the AE: the distance, measured in metres, that can be expected between the military feature digitized in GIS and its “true position” in the present day (visible in orthophotos, satellite images and LiDAR data, or detectable by field surveys). AL and AE are inversely related: the greater the AE (measured in metres), the lower the AL.

The AL scale refers to the accuracy of individual military features and not to the source from which that feature is taken (e.g., the photo or historical map). It was decided to define a scale for individual features rather than a generalized scale for entire original sources, as the latter are often inconsistent, with accuracy that can vary greatly within the same document, depending on the areas depicted and the quality of the depiction. For example, a map may have both areas with features with a high AL and more complex areas (such as mountainous or marginal areas) where the AL of the features is significantly lower.

The scale comprises eleven levels, 10 denoting the highest accuracy and 0 the lowest (Tab. 2). Levels were derived from the mean AE values measured across the database, grouped into exponentially increasing ranges with thresholds set at rounded values, and each range was associated with a nominal class of accuracy.

The AL of a feature is set primarily by the type of historical source and is then adjusted by modifiers derived from five factors, previously analysed (type of historical source, overall quality of the material document, level of detail of the source, date of the document, presence of military elements detectable in present-day data). Type of source fixes the initial value according to the priority scale. Overall material quality lowers it where the document is deformed, weathered, damaged, torn or fragmented. Level of detail is expressed by flight altitude for aerial photos, by scale for cartography and by the quantity and clarity of visible elements for non-vertical sources. Date of the document acts as a proxy for survey practice and for the cumulative stratification of defensive systems, since military elements were rarely erased during the conflict and were more often absorbed into new ones, as when a trench line abandoned by Italian troops was captured and repurposed by Austro-Hungarian forces (Iorio 2016). Presence of corresponding elements in present-day data provides a validation step, and its absence in areas where landscape transformation has erased WWI traces raises uncertainty.

Only these five factors were retained, in order to keep the index applicable across source types. Factors extrinsic to the document, such as scanning and georeferencing, belong to acquisition and post-processing rather than to the properties of the source, and are treated as limitations of the workflow. Further variables would have required case-specific assessment and reduced replicability. The AL accordingly provides a first approximate estimate of expected accuracy, supporting initial evaluation and comparison of data within HGIS workflows without replacing detailed cartometric or topographic analysis.

Values were calibrated on the database described in the methodology section and on field observation in the Asiago Plateau and adjacent areas such as Monte Grappa. The scale therefore describes the conditions of the Italian Front, largely developed at high elevation, and may prove less representative in different geomorphological contexts, such as the defensive lines of the Eastern Front on flat terrain and less rocky substrates.

Table 2. Accuracy Level (AL) scale.

AL	Class	Estimated AE	Description
≥ 10	Maximum	≤ 1 m	Feature highly accurate with respect to its real spatial position
9	Very high	$>1-2$ m	Feature accurate with respect to its real spatial position
8	High	$>2-5$ m	Good accuracy, with residual uncertainty

AL	Class	Estimated AE	Description
7	Medium-high	>5-20 m	Acceptable accuracy, with minor deformations, offsets or sporadic missing data
6	Medium	>20-50 m	Moderately reliable positioning despite deformations, graphic or scale errors
5	Medium-low	>50-150 m	Significant deformations, graphic or scale errors; positioning still informative
4	Low	>150-300 m	Deformations and errors prevent precise geolocation
3	Very low	>300-600 m	Deformations and errors prevent geolocation beyond a broad area
2	Unreliable, constrained area	>600 m-1 km	Only a constrained area of placement can be identified
1	Unreliable, macro-area	>1 km	Only a macro-area, such as a mountain or a valley, can be identified
≤0	Geolocation impossible	-	Spatial position cannot be identified

Source: Author's elaboration.

Figure 8 sets out the procedure for determining the AL from feature metadata. The scheme assigns an initial value by source type and applies modifiers (AL_n) that lower it or leave it unchanged according to the characteristics of the document; the final value combines the initial value with its modifiers. An example of the process used to determine the AL for a set of military features corresponding to trench lines digitized from historical cartography (Fig. 9) is shown in Figure 10. The map considered is a British tactical map produced on 22 September 1918, preserved in good condition and drawn at a scale of 1:25,000 (ASFI, MMM archival collection, R 5, 151 bis).

Features digitized from historical cartography receive an initial AL of 7, corresponding to an estimated AE of >5-20 m. Production in the final year of the war leaves the value unchanged, as does the good state of preservation. The level of detail, expressed by the 1:25,000 scale, applies a -1 modifier and lowers the AL to 6, corresponding to an estimated AE of >20-50 m. The corresponding elements are legible in both orthophotos and LiDAR, so no further modifier applies. GIS measurement of the actual AE for the trench system in the study area yields a mean of approximately 30 m, within the range predicted by the assigned level.

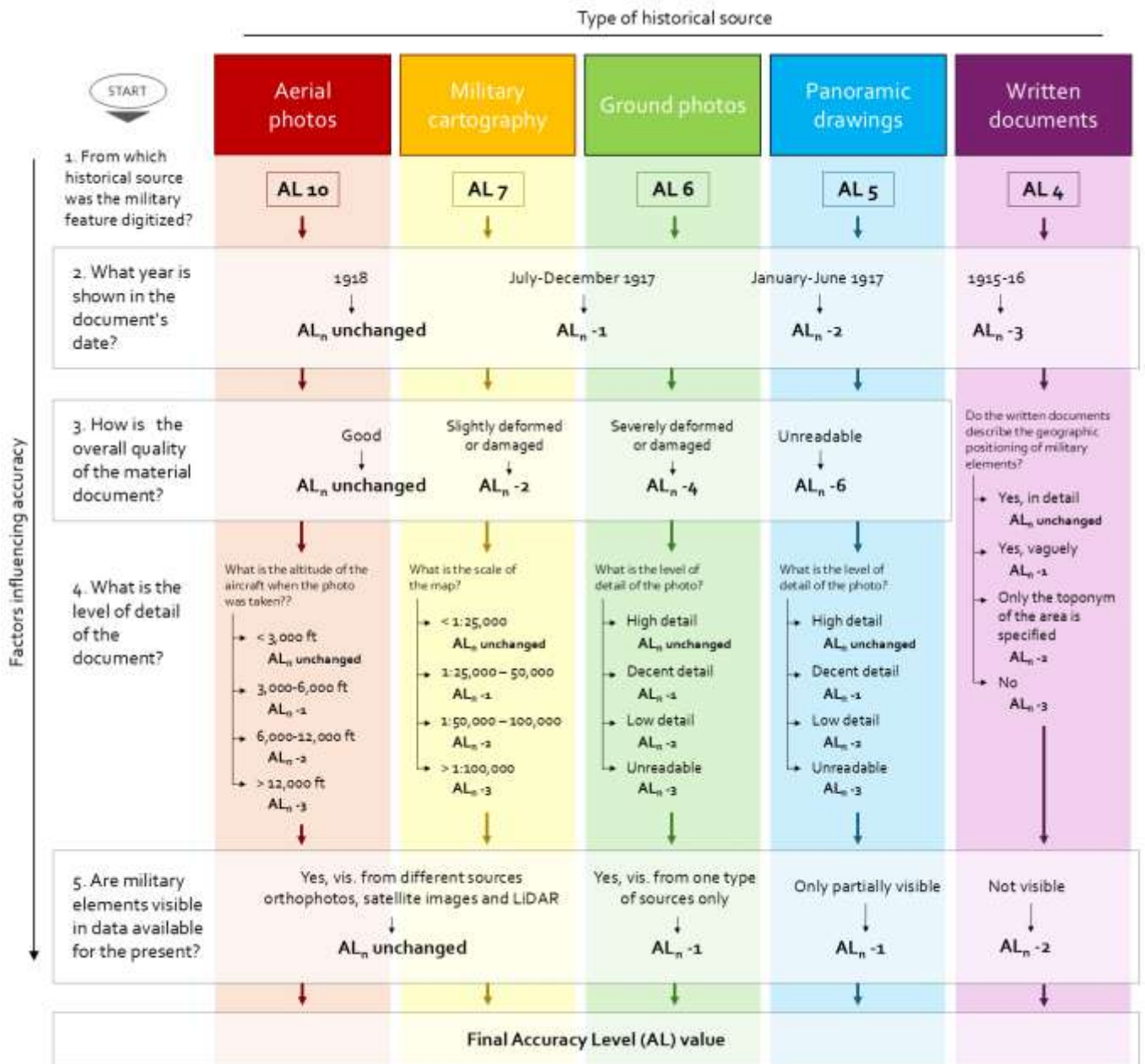


Figure 8. Accuracy Level determination scheme. Source: Author's elaboration.

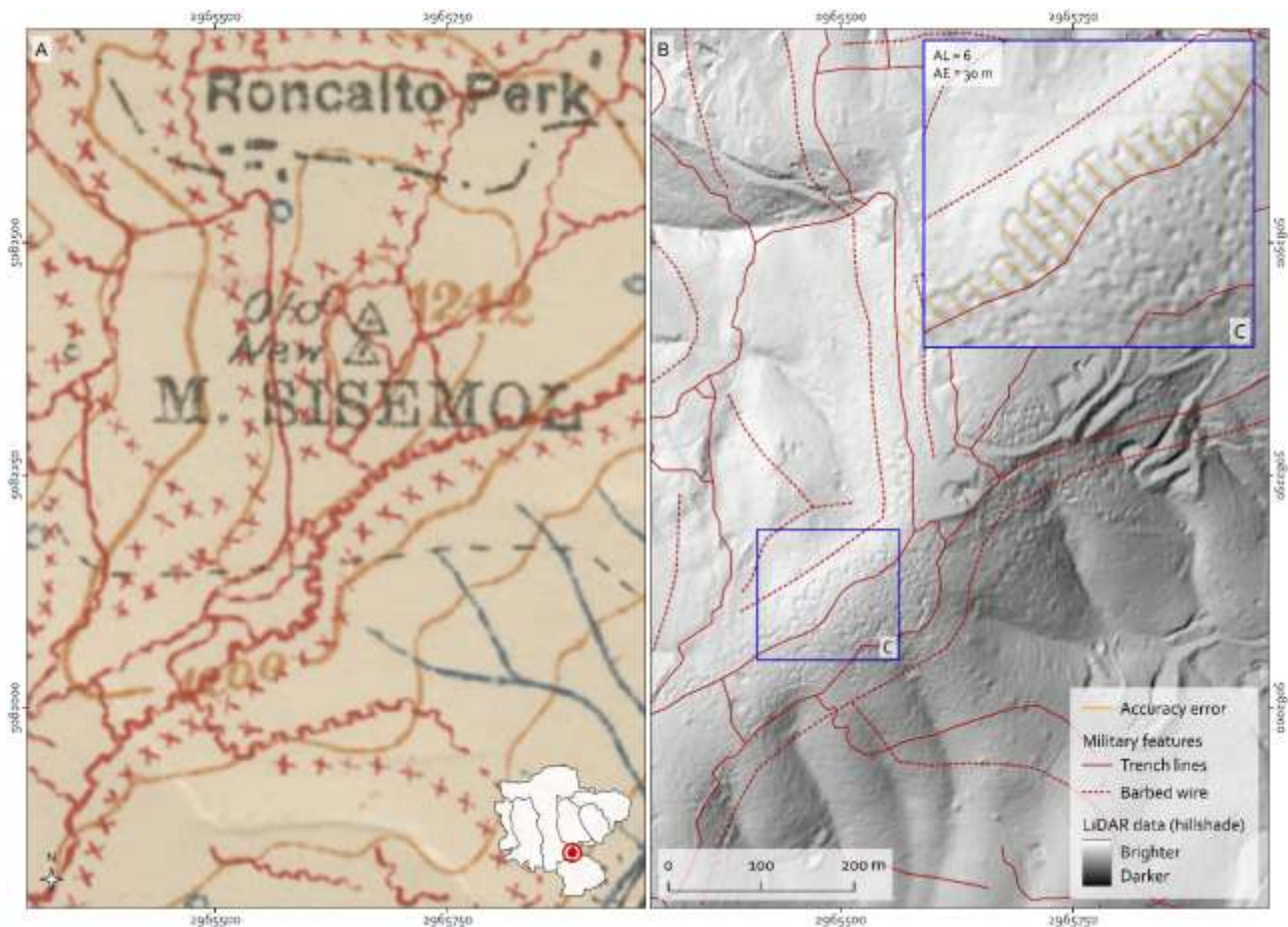


Figure 9. (A) Detail from a British tactical map produced on 22 September 1918, preserved in good condition and drawn to a scale of 1:25,000 (ASFI, MMM archival collection, R 5, 151 bis). Military elements drawn in the map are visible in both orthophotos and LiDAR data of the same area. The detail shows the area of Monte Sisemol, in the municipality of Gallio (Vicenza), on the Asiago Plateau. (B) Military features (trench lines and barbed wire) digitized from the map in A for the Monte Sisemol area, visible via LiDAR (Etra S.p.A. Società Benefit 2022b). The AE measured in GIS between military features and the “true position” of the trench lines is approximately 30 m.

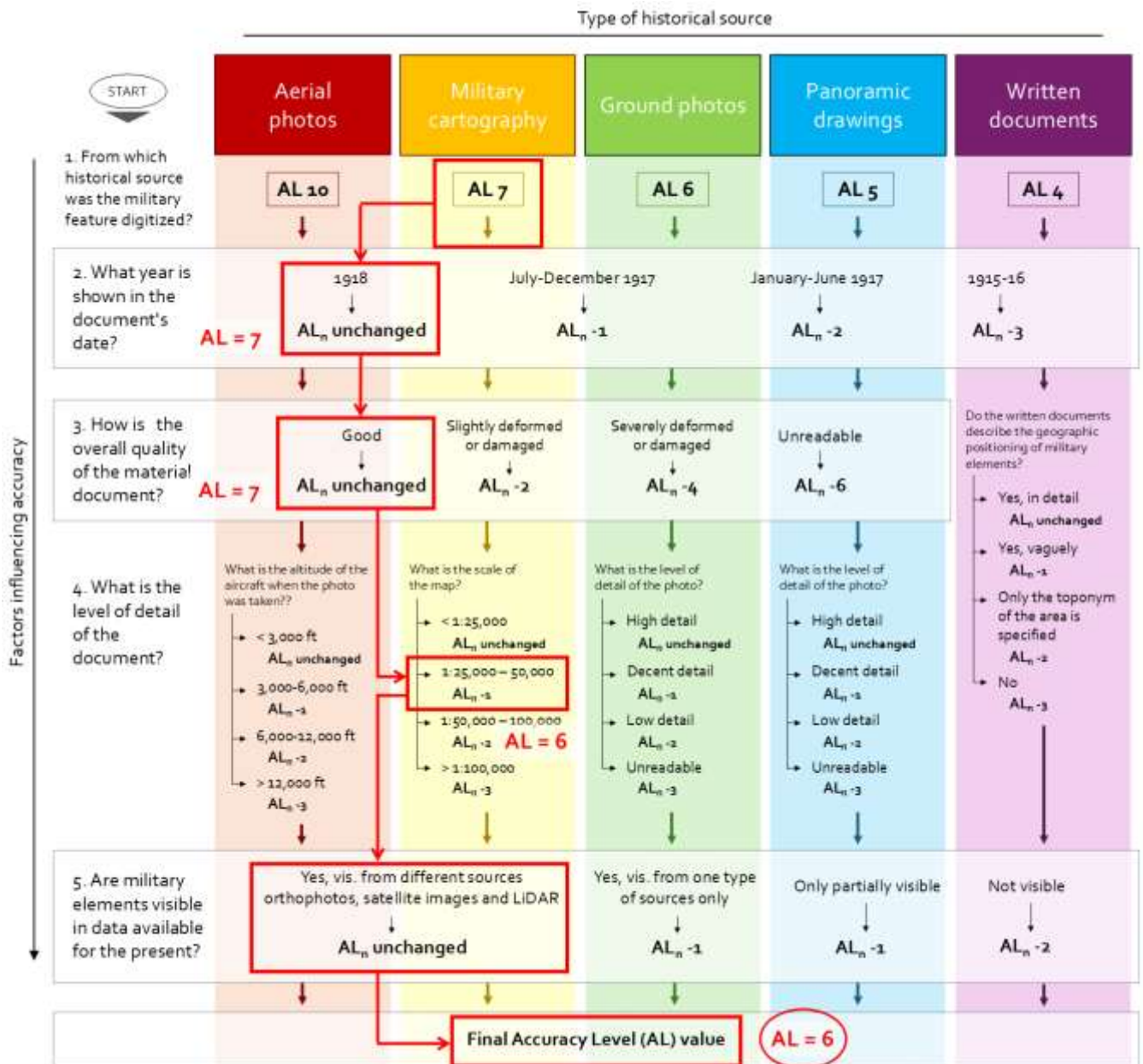


Figure 10. Process for determining the AL of the military features (trenches and barbed wire) shown in Figure 9. The calculated AL is 6, which corresponds to an estimated AE range of >20-50 m. The actual AE is 30 m. Source: Author's elaboration.

7. Conclusions

This study analysed the spatial accuracy of WWI military features digitized in GIS from the five categories of historical document most commonly used in geohistorical research, through a database built for the Asiago Plateau from corpora held in Italian archives.

Qualitative and semi-quantitative analysis identified source type as the dominant factor conditioning accuracy, with differences between categories of the order of hundreds of metres. Material quality and state of preservation follow, with particular weight for maps and aerial photographs. Level of detail, expressed by scale for cartography and by flight altitude for aerial imagery, conditions positional uncertainty in turn, while date of production exerts a more limited influence, acting as a proxy for survey practice and for the cumulative stratification of defensive systems. Comparison against present-day orthophoto and LiDAR data proved necessary for validating and correcting positional error.

A priority scale of sources was established on this basis, ranking aerial photos first, followed by military cartography, ground photos, panoramic drawings and written documents. An Accuracy Level scale from ≤ 0 to ≥ 10 was then constructed to estimate the expected accuracy of individual features and their mean distance from the corresponding true position, combining the priority scale with the factors that condition the quality of each document. Application of the index to a test case returned an estimate consistent with the AE measured directly in GIS.

The study has three main limitations. The variety of sources analysed entails secondary factors that the index does not incorporate, among them relief displacement in aerial photographs, whose exclusion keeps the AL applicable across source types at the cost of precision within each. Interpretation enters the workflow at the stages of source production, georeferencing and digitization, and its contribution to positional error is not separable from the intrinsic properties of the documents. The analysis rests on a local case study within a limited sector of the front, and the method requires testing on further corpora before it can be regarded as transferable. The study accordingly offers preliminary guidelines for researchers approaching these sources for geospatial processing rather than an exhaustive treatment of the five categories.

Three developments follow. The method can be extended to sectors of the front with different geohistorical characteristics, such as the Karst, where terrain and substrate differ substantially from the high-elevation conditions on which the scale was calibrated. The factors conditioning the AL can be investigated further, with a view to identifying variables not covered here. Practical applications follow from the determination of positional accuracy itself, since establishing where features documented in historical sources are likely to lie supports the preservation of cultural and archaeological war heritage (e.g. Magnini et al. 2022), public planning, and the preventive assessment of risk from unexploded ordnance (e.g. Bondesan et al. 2026).

References

- Acerbi, E. (2008). *Strafexpedition (maggio-giugno 1916). Fatti, memorie, immagini, ricordi dell'offensiva in Trentino ed altipiani*. Valdagno, Rossato.
- Achilli, V., Fabris, M., Menin, A., Targa, G., De Gennaro, M., Milan, P., Trivelloni, U., Zampieri, A., Baroni, L., Maseroli, R. (2013). Il problema della discontinuità fra fusi cartografici: una soluzione pensata per la Regione Veneto utilizzabile anche in altre realtà. In *Atti della XVII Conferenza Nazionale ASITA*. Federazione ASITA, pp. 3-10.
- Ariza-López, F., Rodríguez-Avi, J., Robledo Ceballos, J., García-Balboa, J.L. (2021). *Guide for the positional accuracy assessment of geospatial data*. Mexico City, Pan American Institute of Geography and History.
- Azzalin, G., Milanese, M., Magnini, L. (2024). “Sa vida pro sa Patria”: Archeologia della Brigata Sassari sull’Altopiano dei Sette Comuni. In *I Convegno italiano di archeologia dell’età contemporanea*. Bari, Edipuglia, pp. 15-30.
- Azzari, M. (2010). Use, prospects and problems of old cartography in digital format. *Bollettino dell’Associazione Italiana di Cartografia*, 138, pp. 217-224.
- Ballarin, M., Balletti, C., Gottardi, C. (2015). Automatic Systems for Digitizing Historical Maps. *e-Perimtron*, 10(1), pp. 21-29.
- Barton, P. (Ed.) (2005). *The Battlefields of the First World War: The Unseen Panoramas of the Western Front*. Oxford, Osprey Publishing.
- Bayer, T., Potůčková, M., Čábelka, M. (2010). Cartometric Analysis of Old Maps on the Example of Vogt’s Map. In Gartner, G., Ortig, F. (Eds.). *Cartography in Central and Eastern Europe*. Lecture Notes in Geoinformation and Cartography. Berlin, Heidelberg, Springer, pp. 509-524. DOI: https://doi.org/10.1007/978-3-642-03294-3_33
- Bayr, U. (2021). Quantifying historical landscape change with repeat photography: an accuracy assessment of geospatial data obtained through monoplottting. *International Journal of Geographical Information Science*, 35(10), pp. 2026-2046.

- Bondesan, A., Ehlen, J. (Eds.) (2022). *Military Geoscience: A Multifaceted Approach to the Study of Warfare*. Cham, Springer.
- Bondesan, A., Petriccione, M., Mora, L. (2026). A GIS-based multi-criteria geospatial workflow for mapping the hazard, exposure and risk of explosive remnants of war in twentieth-century conflict landscapes: A case study from northeastern Italy. *International Journal of Disaster Risk Reduction*, 143, 106322.
- Bozzano, M., Sguerso, D., Zatelli, P., Zendri, D., Besana, A. (2024). Accuracy Evaluation for Plan-Reliefs and Historical Maps Created during WWI in Northern Italy. *ISPRS International Journal of Geo-Information*, 13(3), 101. DOI: <https://doi.org/10.3390/ijgi13030101>
- Carrion, D., Migliaccio, F., Minini, G., Zambrano, C. (2016). From historical documents to GIS: A spatial database for medieval fiscal data in Southern Italy. *Historical Methods: A Journal of Quantitative and Interdisciplinary History*, 49(1), pp. 1-10.
- Chasseaud, P. (2013). *Mapping the First World War: The Great War through Maps from 1914-1918*. London, HarperCollins.
- Corà, V., Passarin, M. (2014). *Guerra sull'altopiano*. Sommacampagna, Cierre Edizioni.
- Cowley, D.C., Stichelbaut, B.B. (2012). Historic Aerial Photographic Archives for European Archaeology. *European Journal of Archaeology*, 15(2), pp. 217-236. DOI: <https://doi.org/10.1179/1461957112Y.0000000010>
- Dai Prà, E., Gabellieri, N. (2020a). Cartografia, aerofotogrammetria e intelligence dell'Esercito Italiano durante la Grande Guerra. *Gnosis. Rivista italiana di intelligence*, 26(1), pp. 71-81.
- Dai Prà, E., Gabellieri, N. (2020b). Imago proelii. La cartografia storica della Prima Guerra Mondiale dal Museo Storico della Terza Armata: spigolature per una analisi tipologica e semiologica. *Bollettino della Società Geografica Italiana*, 3(1), pp. 59-79.
- Dai Prà, E., Gabellieri, N. (2020c). Mapping the First World War Forgotten Material Heritage: A Multi-proxy and GIS-based Proposal for the Trentino Alps. In *Proceedings FORTMED 2020: International Conference on Fortifications of the Mediterranean Coast Granada Valencia*, Editorial Universitat Politècnica de València.
- Dai Prà, E., Gabellieri, N., Bailo, M.B. (2022). The World War I Tactical Maps of the Italian Army: Proposals for a Typological Classification, an Interpretation of Symbols and a Digital Analysis of the Cartographies in the Historical Archive of the Third Army. In Bondesan, A., Ehlen, J. (Eds.). *Military Geoscience: A Multifaceted Approach to the Study of Warfare*. Cham, Springer, pp. 125-143. DOI: https://doi.org/10.1007/978-3-030-79260-2_8
- Espenhorst, J. (2016). A Good Map Is Half The Battle! The Military Cartography of the Central Powers in World War I. In Liebenberg, E., Demhardt, I.J., Vervust, S. (Eds.). *History of Military Cartography*. Cham, Springer, pp. 83-130. DOI: https://doi.org/10.1007/978-3-319-25244-5_5
- Etra S.p.A. Società Benefit (2022a). Ortofoto 2022. *Ortoimmagini relative al territorio di competenza Etra*. Cittadella (PD), Etra S.p.A. Società Benefit.
- Etra S.p.A. Società Benefit (2022b). *LiDAR 2022. Dati altimetrici LiDAR relativi al territorio di competenza Etra*. Cittadella (PD), Etra S.p.A. Società Benefit.
- Gašperič, P. (2023). A new standardized methodology for analyzing cartographic information on old maps. *Acta Geographica Slovenica*, 63(2), pp. 23-49. DOI: <https://doi.org/10.3986/AGS.10867>
- Gheyle, W., Stichelbaut, B., Saey, T., Note, N., Van den Berghe, H., Van Eetvelde, V., Van Meirvenne, M., Bourgeois, J. (2018). Scratching the surface of war. Airborne laser scans of the Great War conflict landscape in Flanders (Belgium). *Applied Geography*, 90, pp. 55-68.
- Gobbi, S., Ciolli, M., La Porta, N., Rocchini, D., Tattoni, C., Zatelli, P. (2019). New Tools for the Classification and Filtering of Historical Maps. *ISPRS International Journal of Geo-Information*, 8(10), 455. DOI: <https://doi.org/10.3390/ijgi8100455>
- Hanson, W.S., Oltean, I.A. (Eds.) (2013). *Archaeology from Historical Aerial and Satellite Archives*. New York, Springer.
- Hupy, J.P., Koehler, T. (2012). Modern warfare as a significant form of zoogeomorphic disturbance upon the landscape. *Geomorphology*, 157-158, pp. 169-182.

- Iorio, A. (2016). *Il riciclo strategico: memorie della Grande Guerra e stratificazioni del paesaggio veneto contemporaneo*. Roma, Aracne.
- Isnenghi, M., Rochat, G. (2014). *La Grande Guerra 1914-1918*. Bologna, Il Mulino.
- ISO (2013). *ISO 19157: Geographic information - Data quality*. Geneva, International Organization for Standardization.
- Jenny, B., Hurni, L. (2011). Studying cartographic heritage: Analysis and visualization of geometric distortions. *Computers & Graphics*, 35(2), pp. 402-411.
- Jongepier, I., Soens, T., Temmerman, S., Missiaen, T. (2016). Assessing the Planimetric Accuracy of Historical Maps (Sixteenth to Nineteenth Centuries): New Methods and Potential for Coastal Landscape Reconstruction. *The Cartographic Journal*, 53(2), pp. 114-132. DOI: <https://doi.org/10.1179/1743277414Y.00000000095>
- Knowles, A.K., Hillier, A. (Eds.) (2008). *Placing History: How Maps, Spatial Data, and GIS Are Changing Historical Scholarship*. Redlands, ESRI Press.
- Leisz, S.J. (2013). An Overview of the Application of Remote Sensing to Archaeology During the Twentieth Century. In Comer, D.C., Harrower, M.J. (Eds.). *Mapping Archaeological Landscapes from Space*. New York, Springer, pp. 11-19.
- Leoni, D. (2019). *La guerra verticale. Uomini, animali e macchine sul fronte di montagna (1915-1918)*. Torino, Einaudi.
- Lo Destro, C., Ciola, M. (2025). Historical GIS of strategic-level maps from World War I: A Geo-Historical Enhancement Project for Archival Research. In Borgogno-Mondino, E., Zamperlin, P. (Eds.). *Geomatics for Green and Digital Transition*. Cham, Springer, pp. 23-38.
- Magnini, L., Bettineschi, C., De Guio, A. (2017). Object-based Shell Craters Classification from LiDAR-derived Sky-view Factor. *Archaeological Prospection*, 24(3), pp. 211-223. DOI: <https://doi.org/10.1002/arp.1565>
- Magnini, L., Rovera, G., De Guio, A., Azzalin, G. (2022). A Digital and Archaeological Perspective of the World War One Veneto-Trentino Front Line Trench Systems in Northern Italy. In Bondesan, A., Ehlen, J. (Eds.). *Military Geoscience: A Multifaceted Approach to the Study of Warfare*. Cham, Springer, pp. 83-106. DOI: https://doi.org/10.1007/978-3-030-79260-2_6
- Marelić, T. (2025). Cartometric Analyses: Methodological Issues and Their Significance for the History of Cartography and Historical Studies in General. In Faričić, J., Marelić, T. (Eds.). *Early Modern Nautical Charts of the Adriatic Sea*. Singapore, Palgrave Macmillan, pp. 223-248. DOI: https://doi.org/10.1007/978-981-96-8046-7_9
- Monti, M., Arvizzigno, G., Lombardo, D., Maino, G. (2016). Sul restauro digitale di foto storiche. In Gallo, G., Stanco, F. (Eds.). *Proceedings of ArcheoFOSS: Free, libre and open source software e open format nei processi di ricerca archeologica*. Oxford, Archaeopress, pp. 77-79.
- Mora, L., Piovan, S.E., Ferrarese, F., Petriccione, M., Hodgson, M.E., Bondesan, A. (2025). Mapping the marks of war: a Historical GIS approach to digitalize WWI military cartography of the Sette Comuni di Asiago area (Vicenza, Italy). In Borgogno-Mondino, E., Zamperlin, P. (Eds.). *Geomatics for Green and Digital Transition*. Cham, Springer, pp. 3-22. DOI: https://doi.org/10.1007/978-3-031-91144-6_1
- Mora, L., Piovan, S.E., Ferrarese, F., Petriccione, M., Hodgson, M.E., Bondesan, A. (2026). A framework for a World War I military historical GIS database. *International Journal of Cartography*, pp. 1-29. DOI: <https://doi.org/10.1080/23729333.2025.2553482>
- Narin, O.G., Gullu, M. (2022). Evaluating the Planimetric Accuracy of a Historical Map (Europe and the Mediterranean Sea by Piri Reis): A New Method and Cartographic Analysis. *The Cartographic Journal*, 58(4), pp. 341-352. DOI: <https://doi.org/10.1080/00087041.2021.1956064>
- Nocerino, E., Menna, F., Toschi, I., Morabito, D., Remondino, F., Rodríguez-Gonzálvez, P. (2018). Valorisation of history and landscape for promoting the memory of WWI. *Journal of Cultural Heritage*, 29, pp. 113-122.

- Paradelle, N., Laslier, M., Decocq, G. (2023). Automatic extraction of former WWI battlefields from ancient maps. *Remote Sensing for Agriculture, Ecosystems, and Hydrology XXV*, Proc. SPIE 12727, 127270H, pp. 96-112. DOI: <https://doi.org/10.1117/12.2684009>
- Petriccione, M., Bondesan, A., Ferrarese, F., Gallo, F.L., Mora, L., Levorato, C., Busoni, S. (2025). GIS-based assessment of World War I UXO occurrence probability through military maps and aerial imagery on the Grappa Massif (NE Italy). In Borgogno-Mondino, E., Zamperlin, P. (Eds.). *Geomatics for Green and Digital Transition*. Cham, Springer, pp. 61-76. DOI: https://doi.org/10.1007/978-3-031-91141-5_5
- Petrovič, D., Trajkovski, K.K., Kokalj, Ž. (2018). Different visualizations and used data sources of the mountain battlefield on the Soča/Isonzo front line. *International Journal of Cartography*, 4(3), pp. 336-347. DOI: <https://doi.org/10.1080/23729333.2018.1512185>
- Pieropan, G. (2011). *Storia della Grande Guerra sul fronte italiano. 1915-1918*. Milano, Mursia.
- Piovan, S. (2020). *The Geohistorical Approach: Methods and Applications*. Cham, Springer.
- Pirina, C. (2020). *Dietro il paesaggio della Grande Guerra*. Siracusa, LetteraVentidue.
- Plini, P., De Santis, V., Salvatori, R. (2007). GIS per ricostruire eventi storici. *GEOmedia*, 11(1).
- Plini, P., De Santis, V., Salvatori, R., Di Franco, S. (2010). Storia, memoria e geografia: un GIS storico sulle operazioni dell'esercito italiano nella Campagna di Russia (1941-1943). *Bollettino dell'Associazione Italiana di Cartografia*, 139-140, pp. 9-22.
- Plini, P., Di Franco, S., Salvatori, R. (2017). Geography of WWI Sites Along the Italian Front by Means of GIS Tools. In Cefalo, R., Zieliński, J.B., Barbarella M. (Eds.). *New Advanced GNSS and 3D Spatial Techniques*. Cham, Springer, pp. 229-235. DOI: https://doi.org/10.1007/978-3-319-56218-6_18
- Pollard, T., Barton, P. (2013). The Use of First World War Aerial Photographs by Archaeologists. A Case Study from Fromelles, Northern France. In Hanson, W.S., Oltean, I.A. (Eds.). *Archaeology from Historical Aerial and Satellite Archives*. New York, Springer, pp. 87-103. DOI: https://doi.org/10.1007/978-1-4614-4505-0_6
- Sahin, C., Ergun, B., Bilucan, F. (2025). Landmark Base Point Approach to Positional and Coastal Accuracy Analysis for Historical Map Before WWI: A Case Study 1836 Moltke and 1914 German Blue about in Historical Peninsula of İstanbul. *Arabian Journal for Science and Engineering*, 50(1), pp. 249-267. DOI: <https://doi.org/10.1007/s13369-024-09074-7>
- Schaffland, A., Heidemann, G. (2022). Heritage and Repeat Photography: Techniques, Management, Applications, and Publications. *Heritage*, 5(4), pp. 4267-4305. DOI: <https://doi.org/10.3390/heritage5040220>
- Stichelbaut, B., Cowley, D. (Eds.) (2018). *Conflict Landscapes and Archaeology from Above*. London, Routledge.
- Tomassini, L. (2013). "Conservare per sempre l'eccezionalità del presente". Dispositivi, immaginari, memorie della fotografia nella Grande Guerra, 1914-18. *Annali della Fondazione Ugo La Malfa. Storia e Politica*, XXVIII, pp. 341-368.
- Tucci, M., Giordano, A. (2011). Positional accuracy, positional uncertainty, and feature change detection in historical maps: Results of an experiment. *Computers, Environment and Urban Systems*, 35(6), pp. 452-463.
- Vaianti, B., Di Lenardo, I., Kaplan, F. (2025). Segmentation and Clustering of Local Planimetric Distortion Patterns in Historical Maps of Jerusalem. *ISPRS International Journal of Geo-Information*, 14(3), 132. DOI: <https://doi.org/10.3390/ijgi14030132>
- Vantas, K., Mirkopoulou, V. (2025). Supervised Learning for Positional Accuracy Improvement of Historical Maps: A Systematic Comparison and Validation. *Transactions in GIS*, 29(4), e70076. DOI: <https://doi.org/10.1111/tgis.70076>
- Vergara, M.N., Bondesan, A., Ferrarese, F. (2018). GIS analysis of the trafficability determined by slope in the eastern Tyrol front (WWI, Eastern Alps): a military history reading. *Cartography and Geographic Information Science*, 45(6), pp. 477-494. DOI: <https://doi.org/10.1080/15230406.2017.1399828>

- Vollmann, A., Brazzale, F. (2012). *Grande guerra. Britannici sull'altopiano dei Sette Comuni*. Valdagno, Rossato.
- Walstra, J., Chandler, J.H., Dixon, N., Wackrow, R. (2011). Evaluation of the controls affecting the quality of spatial data derived from historical aerial photos. *Earth Surface Processes and Landforms*, 36(7), pp. 853-863. DOI: <https://doi.org/10.1002/esp.2111>
- Wong, D.W., So, B.K.L., Zhang, P. (2012). Addressing quality issues of historical GIS data: an example of Republican Beijing. *Annals of GIS*, 18(1), pp. 17-29. DOI: <https://doi.org/10.1080/19475683.2011.647074>
- Zhang, S., Barrett, H.A., Baros, S.V., Neville, P.R.H., Talasila, S., Sinclair, L.L. (2022). Georeferencing Accuracy Assessment of Historical Aerial Photos Using a Custom-Built Online Georeferencing Tool. *ISPRS International Journal of Geo-Information*, 11(12), 582. DOI: <https://doi.org/10.3390/ijgi11120582>